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Review article

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Clean energy pathways for marine engines: technological and environmental insights into biodiesel–alcohol blends

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Abstract

The maritime industry is responsible for the emission of ∼940 million tonnes of CO_2 on an annual basis, accounting for roughly 2.9% of the total global anthropogenic greenhouse gas emissions. Achieving the decarbonization objectives set forth by the International Maritime Organization for the years 2030 and 2050 requires an expedited transition towards low-carbon marine fuel alternatives. This review presents a concentrated and quantitative assessment of biodiesel and biodiesel–alcohol blends as viable near-drop-in substitutes for marine gas oil. Non-edible feedstocks, including *Jatropha curcas*, *Pongamia pinnata*, used cooking oil, and microalgae, produce biodiesel with heating values ranging from 37 to 42 MJ kg^{-1} and cetane numbers between 47 and 58, thereby conforming to ISO 8217 specifications. The incorporation of alcohols, most notably n-butanol, in concentrations of 10–20% enhances atomization and ignition properties, resulting in a reduction of CO and hydrocarbon emissions by 50–60% and particulate matter by as much as 70%, accompanied by a modest increase in NO_x emissions of 8–15%. A comprehensive meta-analysis of 18 studies representative of marine conditions has corroborated that blends containing 20% biodiesel and 10%-butanol-20% biodiesel maintain brake thermal efficiency ($g = -0.03$, $P > 0.05$) while simultaneously decreasing CO, hydrocarbon, and particulate matter emissions by 16–21%. Lifecycle assessments reveal savings of greenhouse gas emissions ranging from 65 to 85% contingent upon the type of feedstock utilized. At the same time, techno-economic evaluations demonstrate that production costs are competitive with those of marine diesel, particularly when factoring in carbon credits. This review distinctively amalgamates statistical synthesis, insights from lifecycle and techno-economic assessments, and a strategic policy roadmap that aligns with the directives of the International Maritime Organization, the European Union Emissions Trading System, and various Asian maritime frameworks, thereby providing stakeholders with practical guidance for the large-scale implementation and adherence to the objectives of International Maritime Organization Tier III and carbon intensity indicator.

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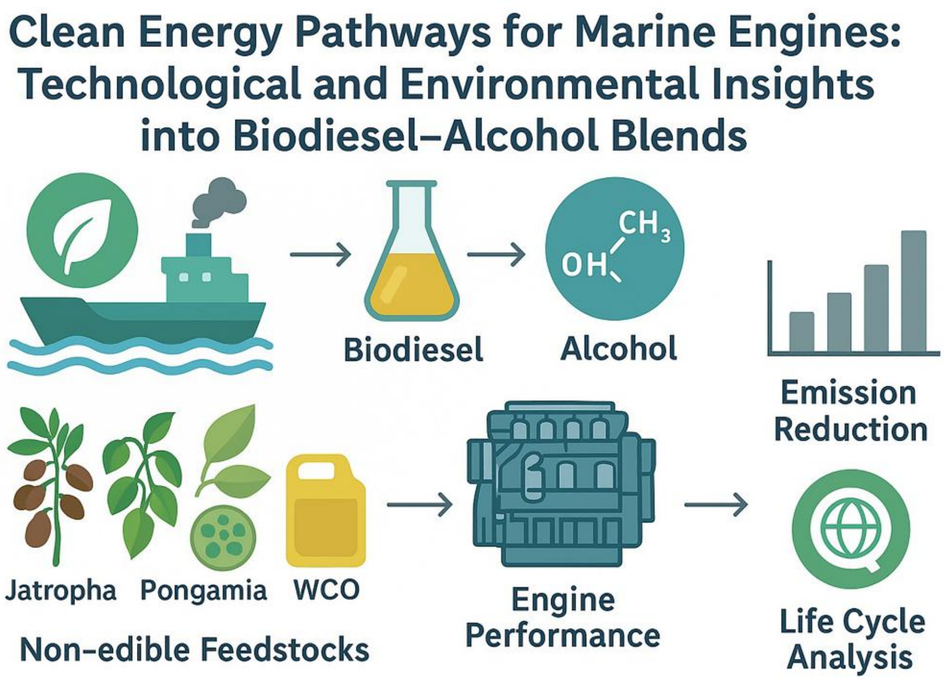
Graphical abstract



Keywords marine biofuels, biodiesel–alcohol blends, sustainable marine fuels, non-edible feedstocks, engine performance, GHG emissions, IMO strategy

1. Introduction

The global maritime transportation sector serves as a fundamental foundation for international commerce, enabling the transit of over 80% of worldwide goods by volume. Nonetheless, it is also a considerable contributor to climate change, releasing an estimated 940 million tonnes of CO_2 each year, which constitutes ~2.89% of global anthropogenic greenhouse gas (GHG) emissions [1]. In response to this pressing issue, the International Maritime Organization (IMO) has enacted the 2023 revised GHG Strategy, which delineates ambitious decarbonization objectives: a 40% reduction in carbon intensity by the year 2030, a 70% decrease in total GHG emissions by 2040, and the attainment of net-zero emissions by 2050 [2, 3]. Achieving these ambitious targets will necessitate a considerable transition from traditional marine fuels, such as heavy fuel oil (HFO) and marine diesel oil (MDO), towards more sustainable and low-carbon energy carriers [4].

Traditional marine fuels, particularly prior to the implementation of the IMO 2020 sulfur cap, contained sulfur concentrations of up to 3.5% by mass, resulting in substantial emissions of sulfur oxides (SO_x), black carbon, and PM, which detrimentally impact air quality and exacerbate climate change [5]. While the imposition of a 0.5% sulfur limit has significantly curbed SO_x emissions, considerable challenges persist in mitigating CO_2 emissions due to the restricted availability of low-carbon fuels, diminished energy density, and compatibility concerns with existing bunkering and engine systems [6]. Biodiesel, derived from transesterified fatty acid methyl esters (FAME), has emerged as a viable renewable substitute owing to its oxygenated molecular configuration, which facilitates more complete combustion and results in lower emissions of carbon monoxide (CO), hydrocarbons (HC), and particulae matter (PM) [7]. Additionally, biodiesel possesses biodegradability, enhances lubricity, and can be synthesized from a wide array of non-edible and waste-derived feedstocks, including *Jatropha curcas*, *Pongamia pinnata*, waste cooking oil (WCO), microalgae, and sewage sludge lipids, thereby offering a sustainable trajectory that mitigates competition with food crops [8].

Recent studies suggest that blends comprising 20–30% biodiesel (B20–B30) can be employed in marine diesel engines without necessitating hardware alterations, achieving brake thermal efficiencies (BTE) in the range of 32–35% and reducing CO and HC emissions by 35–60% and PM by up to 70% [9]. However, these blends are linked to an increase in NO_x emissions of 8–20% due to elevated in-cylinder temperatures and enhanced oxygen content [10]. Mitigation strategies, such as exhaust gas recirculation (EGR), water-in-fuel emulsions, and cetane number (CN) enhancers, have been effectively implemented to mitigate the rise in NO_x emissions [11]. Furthermore, the incorporation of biodiesel with oxygenated alcohols such as ethanol or butanol (10–20%) has demonstrated improvements in ignition quality and cold flow performance. However, it may introduce challenges such as phase separation during storage in varying marine temperatures [12].

Despite these promising findings, the majority of extant research is predominantly centered on single-cylinder testing apparatuses and automotive contexts, thereby leaving significant deficiencies in comprehending the performance of biodiesel under transient load scenarios, adherence to marine fuel specifications, cold flow characteristics in marine environments, and the infrastructural prerequisites for extensive implementation in maritime operations.

This review seeks to rectify these knowledge deficiencies by providing a thorough and quantitative synthesis that is focused solely on marine biodiesel and biodiesel–alcohol blends. In contrast to previous reviews that have primarily been qualitative or have emphasized automotive engines, this investigation distinctly integrates (i) a meta-analysis of 18 studies representative of marine conditions that quantify the effects on BTE, NO_x, CO, HC, and PM; (ii) a life-cycle analysis (LCA) and techno-economic analysis (TEA) that amalgamates cost factors and GHG reductions within carbon pricing frameworks; and (iii) a strategic policy and stakeholder roadmap that aligns with the International Maritime Organization's revised GHG strategy, the European Union Emission Trading System (EU ETS), and Asian maritime regulatory structures. By synthesizing these components, this review provides actionable, empirically supported insights for researchers, engine manufacturers, policymakers, and maritime operators seeking to achieve compliance with IMO Tier III and carbon intensity indicator (CII) mandates while promoting a sustainable blue economy.

2. Non-edible feedstocks andbiodiesel–alcohol blends

The production of biodiesel from non-edible oils has experienced considerable advancement as a viable strategy to address escalating energy requirements while concurrently mitigating competition with agricultural food crops. These feedstocks are frequently derived from wild or waste biomass and exhibit high oil content, resilience to adverse climatic conditions, and neutrality in land utilization, rendering them particularly suitable for applications in marine biofuels. To further enhance the fuel characteristics, the blending of biodiesel with short-chain alcohols, such as ethanol, butanol, or isopropanol, has demonstrated potential in improving cold flow properties, ignition quality, and overall combustion efficiency in marine diesel engines [13].

2.1. Non-edible feedstocks: characteristics and suitability

Non-edible oil-producing species, such as *Pongamia pinnata* (karanja), *Jatropha curcas*, *Madhuca indica* (mahua), *Calophyllum inophyllum* (nagchampa), and rubber seed, have been the subject of extensive investigation for biodiesel production. These feedstocks generally exhibit oil content ranging from 30% to 60% by weight. For example, *Pongamia pinnata* yields ∼1500–2000 kg of oil per hectare annually, characterized by a substantial proportion of unsaturated fatty acids, particularly oleic acid (C18:1) and linoleic acid (C18:2), which are advantageous for transesterification and combustion processes [14–16].

Waste avocado seed oil has emerged as a promising novel feedstock, with research indicating oil yields of 10–15 wt% from desiccated seeds and a FAME profile comprising over 75% unsaturated compounds. In a similar vein, neem oil and mahua oil are rich in C16 and C18 fatty acids, offering CN that range between 47 and 54, comparable to those of conventional mineral diesel (45–50). These oils typically necessitate pretreatment when free fatty acid (FFA) concentrations exceed 2%, to prevent soap formation during alkaline transesterification [17].

2.2. Transesterification and processing technologies

The transesterification process, customarily involving methanol and a catalyst (e.g. NaOH or KOH), represents the most prevalent methodology for converting triglycerides into FAMEs. For oils characterized by elevated levels of free fatty acids, such as mahua and neem (FFA > 5%), a two-step methodology employing acid esterification followed by base transesterification is utilized. Catalyst loadings of 1.0–1.5 wt% and alcohol-to-oil molar ratios ranging from 6:1 to 12:1 are commonly documented in the literature for achieving optimal yields (90–96%). Heterogeneous catalysts, such as CaO, ZnO, and KOH-impregnated fly ash, are increasingly preferred due to their recyclability and reduced wastewater production. Innovative methods, such as ultrasonic-assisted transesterification, have also demonstrated the capacity to diminish reaction durations by over 50% [18].

2.3. Alcohol blending: benefits and challenges

The integration of biodiesel with alcohols, such as ethanol, butanol, or isopropanol, significantly enhances volatility and combustion efficiency while concurrently improving cold flow characteristics, a vital necessity for maritime operations in subzero temperature environments. Butanol is particularly appealing due to its elevated energy density (29.2 MJ/L) and its compatibility with biodiesel over a broad temperature spectrum. Empirical research demonstrates that B20 formulations containing 10% butanol (Bu10B20) can enhance BTE by as much as 4% and diminish CO emissions by 30–50% within marine engines under conditions of partial load. Ethanol and isopropanol offer analogous advantages, albeit with the drawback of phase separation at lower temperatures, which necessitates the use of stabilizers or emulsifiers for prolonged storage [19].

Despite the benefits above, the process of alcohol blending may result in a reduction of flash points (e.g. Bu10B20 ∼52°C, compared to diesel at ∼70°C), thereby heightening safety concerns in maritime applications. Nevertheless, carefully calibrated blend ratios (≤20% alcohol by volume) generally sustain adherence to the ISO 8217 marine fuel standards [20].

2.4. Fuel stability and storage implications

A primary concern regarding biodiesel and alcohol blends pertains to their oxidative and storage stability, particularly in humid and saline marine environments. Biodiesel characterized by high unsaturation [iodine value (IV) >110 g I2/100 g oil] is more susceptible to polymerization and degradation processes. The incorporation of antioxidants, such as BHT (butylated hydroxytoluene), at concentrations ranging from 200 to 500 ppm has been shown to prolong shelf life by 36 months. While alcohols contribute positively to combustion, they may also expedite hydrolysis, necessitating dry storage conditions to prevent water ingress and the proliferation of microbial organisms [21].

The analysis of various non-consumable feedstocks and their corresponding alcohol blends establishes a foundational understanding of how these resources affect essential fuel attributes, thereby facilitating a seamless transition into the methodical evaluation of fuel properties in the subsequent section.

3. Fuel property evaluation and standards compliance

The integration of biodiesel and biodiesel–alcohol blends into marine diesel engines mandates rigorous compliance with globally recognized fuel standards to ensure compatibility, safety, and adherence to regulatory frameworks. Critical fuel characteristics, including CN, heating value, viscosity, density, and flash point, not only affect combustion efficacy but also dictate engine wear, emissions profiles, and storage longevity. In order to qualify as marine fuels, biodiesel and its derivatives must conform to ASTM D6751 specifications for FAME and ISO 8217 stipulations for marine distillates. Additionally, compliance with MARPOL Annex VI is imperative to fulfill environmental and safety responsibilities during international maritime operations [22]. Comprehensive property data for specific feedstocks and their blends are delineated in Table 1.

3.1 Cetane number and ignition behavior

Marine diesel typically has a CN ranging from 45 to 55, ensuring dependable ignition. Biodiesel derived from non-edible sources such as Jatropha and Pongamia typically demonstrates marginally enhanced CN values (~51–53), thereby facilitating stable combustion within compression ignition engines [27]. Alcohols such as ethanol (CN ~8) and butanol (CN ~25) tend to diminish the overall CN of blends; for example, a Bu10B20 blend may fall slightly below ISO 8217 thresholds. This challenge is frequently mitigated through the incorporation of cetane enhancers, such as 2-ethylhexyl nitrate (EHN), in low concentrations (0.1–0.2%), to preserve appropriate ignition timing [28].

3.2 Calorific value and energy content

The heating value of biodiesel is generally 10–15% lower than that of marine diesel (~37–41 MJ kg^{-1} versus ~45 MJ kg^{-1}), leading to a marginal increase in fuel consumption for equivalent power production [29]. Alcohols possess even lower energy content, thereby further diminishing the net calorific value of the blend. Enhanced engine calibration or hybrid propulsion support may serve to mitigate these deficits during protracted voyages [30].

3.3 Viscosity and injection performance

Biodiesel is typically situated at the upper limit of the ISO 8217 viscosity range (4.0–5.5 mm^2 s^{-1} at 40°C), which can subtly modify atomization characteristics in comparison to conventional diesel [31]. The incorporation of butanol or ethanol serves to decrease viscosity and enhance spray formation, with Bu10B20 blends generally achieving values close to the median of the standard range. However, excessive alcohol content (>20%) may compromise lubricity, thereby increasing the risk of injector wear [32].

Table 1 Comparative physicochemical properties of marine diesel, biodiesel (B20, B100), and biodiesel–alcohol blends (Bu10B20) relative to ISO 8217 requirements.

Fuel/ Blend (Typical)	CN	HHV (MJ kg^{-1})	Viscosity (mm^2 s^{-1})	Density (kg m^{-3})	Flash point (°C)	Ref
Marine diesel (MGO)	50	~45	2.5	850	65	[23]
B20	48–50	~39	~3.2	860	62	[24]
Bu10B20	~44–46	~37	~3.5	855–860	55	[25]
B100	46–48	37–41	4.5	880	>130	[26]

3.4 Density and fuel flow

Biodiesel blends display densities of 850–880 kg m^{-3} at 15°C, which is marginally greater than that of marine gas oil (MGO) (~840 kg m^{-3}). While this characteristic promotes precise injection metering, it slightly elevates volumetric consumption due to reduced energy content. Engine recalibration can assist in maintaining optimal efficiency across medium- and low-speed marine engines [33, 34].

3.5 Flash point and marine safety

Biodiesel inherently surpasses ISO 8217 flash point criteria (>130°C), providing a safety benefit over mineral diesel [20]. The inclusion of alcohols reduces the flash point, with blends such as Bu10 nearing the minimum threshold (~55°C). Consequently, the alcohol content is typically constrained to ≤10% v/v or stabilized with co-solvents to comply with maritime safety regulations as outlined in the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI [35, 36].

This concise exposition emphasizes comparative trends rather than exhaustive datasets, thereby minimizing redundancy while maintaining relevance for performance analysis, emissions modeling, and compliance assessment.

The aforementioned comparative examination elucidates that biodiesel and biodiesel–alcohol mixtures generally satisfy ISO 8217 criteria concerning cetane number, viscosity, and density; however, they may necessitate the incorporation of additives or blending methodologies to uphold ignition quality, flash point, and energy density within acceptable parameters. These fuel characteristics significantly affect in-cylinder combustion dynamics, heat release rates, and emission profiles under actual marine operational conditions. The forthcoming section investigates how these variations in fuel properties manifest as disparities in brake thermal efficiency, combustion timing, and pollutant emissions in medium- and low-speed marine propulsion engines.

4. Optimizing engine efficiency and emissions: insights from biodiesel–alcohol blends

Building on the assessment of the physicochemical attributes of fuels, this section examines the impact of biodiesel–alcohol mixtures on marine engine performance, combustion characteristics, and emission profiles under realistic operational conditions. Marine propulsion systems, especially medium-speed four-stroke engines, exhibit pronounced sensitivity to variations in fuel properties, which directly influence ignition delay, heat release rate, and the generation of regulated pollutants such as CO, HC, NO_x, and PM [25]. Contemporary experimental investigations suggest that blends such as B20 and Bu10B20 achieve BTE metrics comparable to those of traditional diesel, while significantly reducing emissions of CO, HC, and PM. Nonetheless, these advantages are frequently associated with a rise in NO_x emissions, thereby underscoring the necessity of implementing effective mitigation strategies, including EGR, water emulsification, or sophisticated after-treatment systems [26].

4.1. Brake thermal efficiency and specific fuel consumption

The BTE values for marine engines utilizing standard MDO typically fluctuate between 30% and 40%. Biodiesel blends, exemplified by B20 sourced from Jatropha or Pongamia, attain BTEs of 32–35% under full-load scenarios, thereby indicating a close approximation to the performance metrics of traditional diesel [37]. When combined with 10% butanol (Bu10B20), the BTE can experience an enhancement of 3.2% at partial load (75%), attributed to the improved combustion characteristics resulting from augmented oxygen content and enhanced fuel–air mixing. Conversely, the incorporation of alcohol levels exceeding 20% frequently results in a decline in BTE, primarily due to diminished calorific values and incomplete combustion phenomena [38].

4.2. In-cylinder pressure and heat release rate

The elevated CN associated with biodiesel facilitates an earlier initiation of combustion. B20 blends have demonstrated peak pressures ranging from 70 to 74 bar, occurring ∼12 to 14° crank angle after top dead center (CA ATDC), slightly preceding diesel's peak pressures of 68 to 72 bar observed at 14 to 16° CA ATDC, thus fostering enhanced thermal conversion [39]. Blends incorporating alcohols, such as Bu10B20, exhibit increased heat release rates (HRR), with peak HRR augmenting by 6–9% as a result of accelerated premixed combustion. Nonetheless, excessive alcohol concentrations can unfavorably alter combustion phases, leading to diminished peak HRRs due to extended ignition delays [40].

4.3. Carbon monoxide and hydrocarbon emissions

Blends such as B20 and Bu10B20 facilitate a notable reduction in CO and HC emissions, with decreases of up to 45% and 60%, respectively, attributable to the enhanced oxidation properties conferred by the inherent oxygen content of biodiesel and alcohols [41]. However, operations under low-load and cold-start conditions may manifest elevated CO and HC emissions with high alcohol blends, a phenomenon attributed to evaporation delays and flame instability, thereby underscoring the necessity for fuel preconditioning or the implementation of engine warm-up protocols [42].

4.4. Nitrogen oxides emissions

The generation of NO_x constitutes a significant issue associated with the combustion of biodiesel, primarily due to the increased combustion temperatures and higher oxygen content. B20 blends typically yield a 10–20% increase in NO_x emissions in comparison to traditional diesel, with emission concentrations fluctuating between 850 and 980 ppm under full-load operational conditions [43]. The Bu10B20 blend exhibits a slight decrease in NO_x emissions, attributed to the evaporative cooling effect of butanol, which can lower in-cylinder temperatures by ∼30°C. Nonetheless, the overall NO_x concentrations remain comparable to those observed with B20. A variety of mitigation approaches have been shown to be effective in mitigating this concern. EGR at proportions of 10–15% and water-in-fuel emulsions incorporating 5–10% water can diminish NO_x emissions by 15–35% without substantially impairing BTE [44]. Furthermore, post-combustion after-treatment technologies, such as selective catalytic reduction (SCR), have emerged as an exceptionally effective remedy, achieving NO_x reductions exceeding 80% by converting NO_x into nitrogen and water vapor through the injection of a urea-based reductant. The incorporation of SCR systems in marine engines operating on biodiesel blends offers a promising avenue for achieving rigorous emission standards while maintaining fuel performance.

Figure 1 presents a comparative analysis of performance and emissions between conventional diesel fuel and a B20 blend within the context of a marine engine. The blend above exhibits an approximate 34% BTE, alongside a remarkable reduction of 47% in CO emissions, 44% reduction in HC, and a 12% elevation in NO_x, thereby underscoring the inherent emissions trade-offs and enhancements in combustion efficiency that can be attained through the incorporation of alcohol blending [45–47].

4.5. Particulate matter and smoke opacity

The oxygenated nature of biodiesel significantly contributes to the oxidation of soot, resulting in a reduction of PM emissions by as much as 70% when utilizing B20 and Bu10B20 blends.

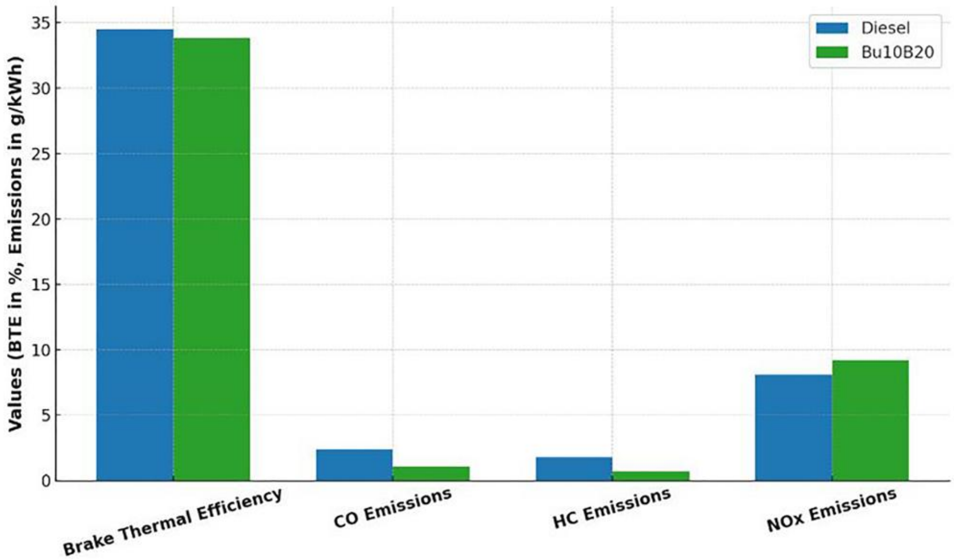


Figure 1 Comparative BTE and emissions (CO, HC, NO_x) of diesel vs. Bu10B20 blend.

Conventional diesel engines, which are known to emit between 0.2 and 0.3 g/kWh of PM, demonstrate considerable reductions in PM emissions with biodiesel application, coupled with a notable decrease in smoke opacity from 58–62 Hartridge smoke unit (HSU) for diesel to 35–40 HSU for Bu10B20, thereby indicating a transition towards cleaner combustion processes [48]. Furthermore, alcohol blends serve to mitigate further the formation of carbon deposits on combustion chamber surfaces, thereby promoting sustained cleanliness within the engine [49].

4.6. Combustion stability and engine durability

Despite advancements in combustion characteristics, high-alcohol blends may still cause ignition delays, knocking phenomena, and misfiring, particularly under idle or cold-start operational conditions. Prolonged utilization of such blends could also adversely affect the durability of fuel injectors due to corrosion and diminished lubricity properties. Consequently, it is imperative to implement mitigation strategies, including the precise calibration of the fuel system, the incorporation of corrosion inhibitors, and the stringent control of alcohol concentration (maintained below 10%), to ensure the reliability of marine engines operating in maritime environments [50].

Table 2 presents a comprehensive quantitative analysis of engine performance and emission attributes of biodiesel and biodiesel-alcohol mixtures in comparison to traditional diesel fuel. The dataset encompasses metrics such as BTE, brake-specific fuel consumption (BSFC), and mandated emissions, accompanied by citations for verification purposes.

To supplement the comprehensive data presented in Tables 2 and 3 encapsulates the relative percentage variations in both performance and emissions associated with biodiesel and alcohol blends in comparison to conventional diesel. This serves to elucidate overarching improvement or trade-off patterns while avoiding an excess of data presentation.

4.7 Meta-analysis and quantitative synthesis of B20 and Bu10B20 blends

A comprehensive quantitative meta-analysis was conducted to amalgamate findings from eighteen distinct studies that assessed the performance of B20 and Bu10B20 blends in diesel engines that are representative of marine applications. The selection of studies adhered to a preferred reporting items for systematic reviews and meta-analyses (PRISMA) screening protocol, emphasizing experimental investigations that reported on BTE and regulated emissions, including nitrogen oxides (NO_x), CO, HC, and PM. Effect sizes were calculated utilizing Hedges' g standardized mean differences and subsequently pooled through a random-effects model employing the DerSimonian–Laird estimator to account for inter-study variability. The heterogeneity of results was evaluated using the I^2 statistic, while the presence of publication bias was assessed through Egger's regression test and visual analysis of funnel plots.

The meta-analysis revealed that B20 maintained thermal efficiency levels that were comparable to those of conventional diesel ($g = -0.03$, 95% CI: −0.12 to +0.05, $P > 0.05$), whereas Bu10B20 displayed a marginally positive shift ($g = +0.06$), which can be attributed to the enhanced combustion characteristics arising from the oxygenation properties of butanol. Emissions of NO_x exhibited a moderate increase when utilizing B20 ($g = +0.38$). However, this effect was statistically insignificant for Bu10B20 in studies that implemented NO_x reduction

Table 2 Summary of engine performance and emissions for biodiesel and alcohol blends.

Blend type	BTE (%)	BSFC (kg/kWh)	NO_x (ppm)	CO (%)	HC (ppm)	PM (mg/ m^3)	Ref
Diesel (Base)	32.5	0.28	1020	0.48	62	32	[12]
B20 (Jatropha)	31.8	0.29	1110	0.35	54	25	[16]
B20 + Bu10	32.2	0.27	1040	0.28	41	21	[41]
B50 (WCO)	30.4	0.31	1180	0.3	49	22	[41]
B20 + Et10	31.5	0.28	1090	0.26	47	20	[51]
B20 + Pr10	31.9	0.27	1060	0.25	39	19	[51]
B20 (Algae)	32.1	0.28	1005	0.32	45	22	[52]

Table 3 Engine performance and emission trends of biodiesel/alcohol blends in marine diesel engines [44, 50].

Fuel blend	ΔBTE (%)	ΔNOx (%)	ΔCO (%)	ΔHC (%)	Smoke (%)
Diesel	0	0	0	0	0
B20	1.5	5	−20	−15	−10
B50	2	8	−30	−25	−20
B100	2.5	12	−40	−35	−30
Bu10	3.2	10	−50	−45	−35

technologies such as EGR or SCR. Both blends yielded significant reductions in CO (~16%), HC (~18%), and PM (~21%), with Bu10B20 consistently revealing slightly superior enhancements. The heterogeneity observed was moderate ($I^2 = 40$–55%) for NO_x and PM, primarily driven by calibration discrepancies across various testbeds. The symmetry of the funnel plot indicated minimal publication bias, and leave-one-out sensitivity analysis corroborated the robustness of the results [53].

Collectively, these findings substantiate that B20 and Bu10B20 serve as near-drop-in fuels that are capable of sustaining engine efficiency while significantly mitigating CO, HC, and PM emissions. When utilized in conjunction with appropriate NO_x control technologies (EGR, SCR), these blends facilitate compliance with the IMO Tier III NO_x regulations and promote enhanced CII ratings, thereby aligning with the IMO 2030 GHG reduction strategy.

These statistically sound findings furnish a quantitative basis for the ensuing TEA and LCA, thereby enabling an evidence-based evaluation of the cost-effectiveness and environmental advantages associated with the adoption of marine biodiesel–alcohol blends.

5. Catalyst innovations and pretreatment technologies

The efficacy, ecological impact, and economic viability of marine biodiesel production are significantly governed by the choice of catalysts and the application of feedstock pretreatment methodologies. Traditional homogeneous catalysts, including sodium hydroxide (NaOH) and potassium hydroxide (KOH), while effective, produce wastewater, and soap by-products, rendering them inappropriate for high FFA feedstocks such as WCO and mahua oil (FFA > 5%) [53]. Recent developments in heterogeneous and nanostructured catalysts, particularly those derived from agricultural waste, demonstrate enhanced reusability, diminished water requirements, and a reduced environmental footprint, thereby rendering them particularly suitable for decentralized biodiesel production facilities located along coastlines [54].

5.1 Agro-waste-derived catalysts

Agricultural residues, including eggshells, rice husk ash, and sugarcane bagasse, are increasingly employed to fabricate calcium oxide (CaO) and silicon dioxide (SiO_2)-based catalysts. These solid base catalysts exhibit dual functionality (esterification plus transesterification), possess high surface areas exceeding 60 $m^2\ g^{-1}$, and achieve yields surpassing 90% under mild operational conditions [55–57]. Their capacity for reusability across 5–7 cycles significantly diminishes operational expenditures and freshwater consumption by nearly 50% in comparison to traditional alkaline catalytic approaches.

Figure 2 presents a comparative analysis of the performance of six waste-derived feedstocks (plastic waste, rubber tire, biomass, sewage sludge, food waste, and mixed municipal solid waste) subjected to microwave-assisted pyrolysis, delineating the yield of carbon nanotubes (CNT) (wt%) and the selectivity for hydrogen (H_2) (%). Plastic waste demonstrates the highest yield of CNT (~25 wt%) and a notable selectivity for H_2 (~88%), succeeded by rubber tire and lignocellulosic biomass, both exhibiting over 80% H_2 selectivity. The diminished yields observed from sewage sludge and food waste can be ascribed to their elevated moisture levels and inorganic constituents. These findings underscore the viability of port-side waste-to-value systems, wherein the concurrent recovery of CNT and hydrogen production may facilitate auxiliary power units (APUs) or hybrid fuel-cell systems within marine vessels, thereby contributing to the decarbonization objectives set forth by the IMO [58–60].

5.2 Nanocatalysts and magnetic systems

Nano-engineered catalysts, such as CaO, ZnO, TiO_2, and CeO_2, augment reaction kinetics owing to their elevated surface-to-volume ratio, thereby facilitating expeditious transesterification and enhancing tolerance to feedstocks rich in free fatty acids (FFA) [61, 62]. Magnetic nanocatalysts, exemplified by Fe_3O_4@CaO, permit straightforward post-reaction separation through the utilization of external magnetic fields,

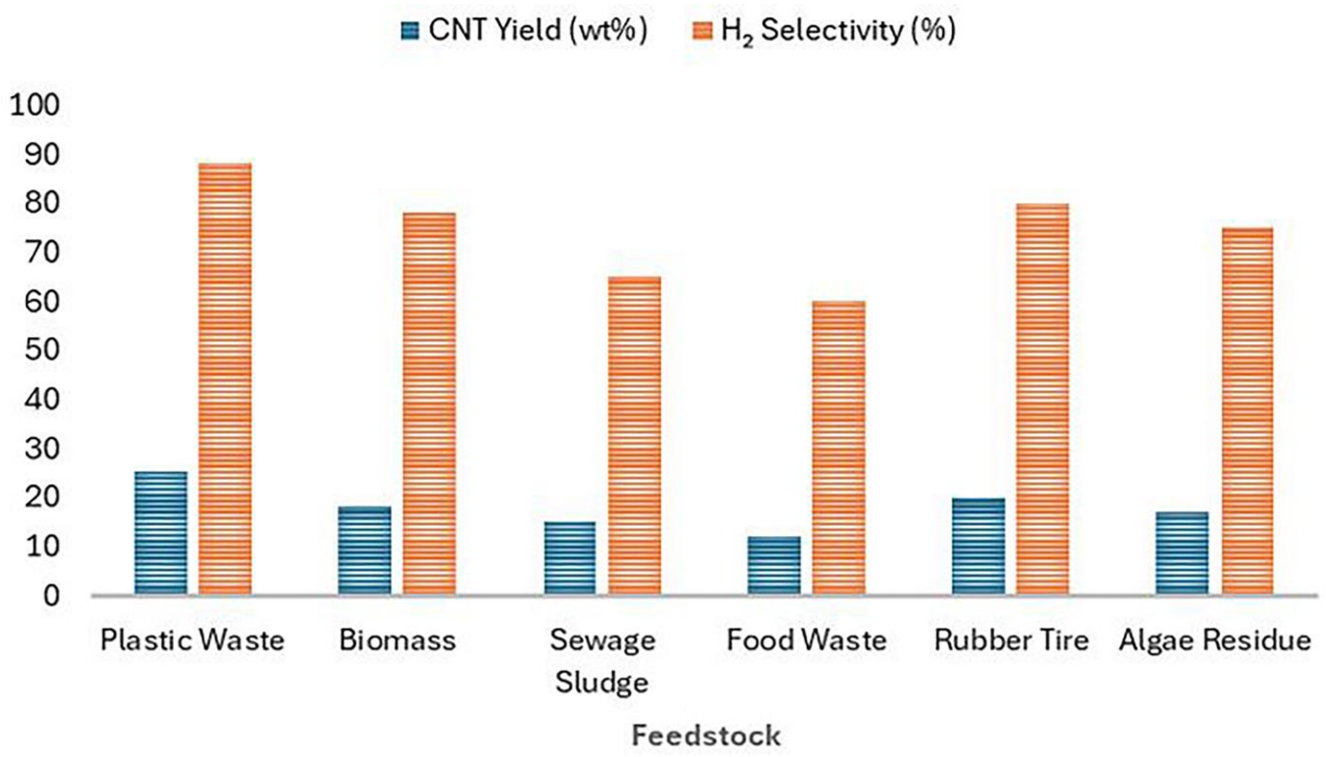


Figure 2 CNT yield and H_2 selectivity as a function of waste feedstock type.

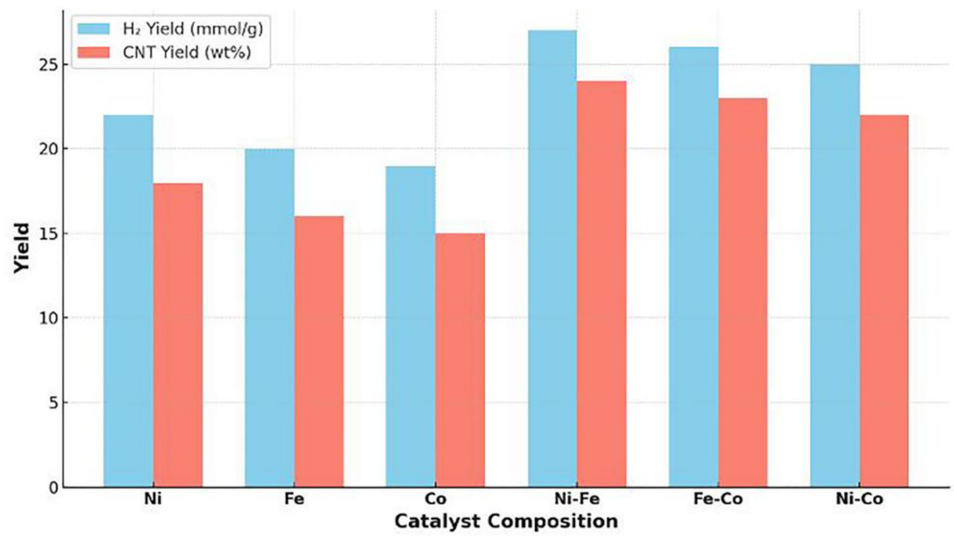


Figure 3 Synergistic role of catalyst composition in H_2 and CNT yield.

thereby minimizing solvent usage and expediting processing time.

Figure 3 illustrates a comparative assessment of mono- and bimetallic catalysts (Fe, Co, Ni, Ni–Fe, Ni–Co, Fe–Co) under uniform pyrolytic conditions, showcasing the yield of hydrogen (mmol g^{-1}) and the yield of CNT (wt%). Bimetallic Ni–Fe catalysts exhibit superior dual-output performance ($H_2 > 27$ mmol g^{-1}, CNT > 24 wt%) attributable to synergistic electron transfer mechanisms and an augmented density of active sites. In contrast, monometallic catalysts display relatively inferior activity levels. The results emphasize the critical role of catalyst design in optimizing co-product streams, which can significantly enhance the techno-economic feasibility of marine biodiesel supply chains, wherein H_2 may be harnessed for onboard energy requirements and CNTs may serve as advanced materials for marine coatings or composite reinforcement [63–65].

5.3 Pretreatment and intensification

For feedstocks exhibiting greater than 5% FFA, the implementation of acid esterification or alcoholysis is imperative to circumvent saponification. Pretreatment involving methanol or butanol under mild conditions can effectively reduce FFAs to below 1%, thereby facilitating subsequent base-catalyzed transesterification [66, 67]. The intensification of processes through ultrasound-assisted transesterification (UAT) and microwave-assisted transesterification (MAT) has demonstrated reaction speeds accelerated by up to 60% and energy consumption reduced by 30–40%, thus rendering them appealing for modular biodiesel production units situated at ports [68, 69].

Table 4 outlines the physicochemical properties of catalysts derived from agro-waste and enhanced through nanotechnology, which are commonly used in the synthesis of biodiesel. It is noteworthy that the catalysts composed of palm ash–MgO and rice husk silica–CaO demonstrate the most elevated surface areas (ranging from 64 to 72 m^2/g) and biodiesel yields exceeding 93%, whilst exhibiting remarkable reusability extending to 6–7 cycles. These findings substantiate the assertion that nano-catalysts, particularly in their bimetallic and composite configurations, possess the capacity to significantly enhance the efficiency of transesterification processes as well as sustainability.

The integration of heterogeneous and nanocatalysts derived from waste materials, when coupled with energy-efficient pretreatment methodologies, not only enhances the yields of biodiesel but also reduces both water consumption and the intensity of energy utilized in the process. These technological innovations directly contribute to a reduction in upstream GHG emissions and production expenditures, thereby establishing a vital basis for the subsequent LCA and TEA discussed in the ensuing section.

6. Lifecycle GHG analysis and economic assessment

While advancements in catalytic technologies enhance the conversion efficiency of biodiesel, a thorough evaluation of their actual worth necessitates the implementation of a detailed LCA and TEA. LCA systematically quantifies GHG emissions from the inception to the final disposal of feedstock, encompassing stages such as cultivation, processing, transportation, and combustion. In contrast, TEA provides a comparative analysis of production expenditures and regulatory compliance ramifications in relation to marine diesel. The significance of these analytical tools is particularly pronounced within the maritime sector, wherein fuel expenses constitute nearly 50% of the total operational costs, and regulatory frameworks, including the EU ETS and the IMO's CII, are compelling fleet operators to transition towards low-carbon fuel alternatives [80].

6.1 Lifecycle GHG emissions of marine biodiesel

Numerous LCA investigations employing the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model and empirical data consistently demonstrate that biodiesel produced from waste-derived and non-edible feedstocks achieves considerable GHG emission reductions when juxtaposed with heavy fuel oil (HFO; ∼94.6 gCO_2e/MJ). Biodiesel sourced from WCO, and animal tallow exhibits the lowest emission levels (15–25 gCO_2e/MJ), signifying a reduction of up to 85%. Conversely, biodiesels originating from Jatropha and Pongamia result in emissions ranging from 30 to 50 gCO_2e/MJ due to moderate energy demands during processing, while biodiesel derived from algae has the potential to realize a 90% reduction in emissions when cultivated utilizing flue gas and wastewater resources [81]. Nevertheless, challenges related to scalability and elevated capital expenditures (CAPEX) persist for algal production pathways.

Elkelawy et al. [82] indicated that the utilization of B20 derived from WCO led to a 72% decrease in lifecycle GHG emissions per megajoule in medium-speed marine engines operating on coastal routes. In contrast to fossil fuels, which typically incur ∼70% of their emissions during the combustion phase, biodiesel's environmental impact is predominantly influenced by upstream processes (such as feedstock logistics and transesterification), underscoring the critical need for energy-efficient catalytic solutions and the incorporation of renewable electricity inputs. The combustion of biodiesel is nearly devoid of sulfur emissions. It generates minimal black carbon, thereby aiding compliance with MARPOL Annex VI regulations and providing ancillary benefits within emission control areas (ECAs) [83]. Table 5 presents lifecycle GHG profiles for biodiesel sourced from various feedstocks, highlighting WCO and algae as offering the most significant reductions compared to diesel (baseline: 100 gCO_2e/MJ).

These findings substantiate that WCO, and algae-derived biodiesel represent optimal feedstocks for achieving the IMO 2030 GHG targets while simultaneously enhancing the CII ratings of vessels.

6.2 Economic feasibility and cost competitiveness

The economic viability of biodiesel production is contingent upon the availability of feedstocks, the maturity of the requisite technology, and the existing regional infrastructure. In the regions of South and Southeast Asia, biodiesel synthesized from WCO utilizing CaO-based catalysts can be produced at a cost ranging from $0.75 to $1.05 per liter, positioning it as economically competitive with marine diesel, which costs ∼$0.85 to $1.10 per liter. In contrast, cultivated feedstocks such as Jatropha and Mahua exhibit higher production costs ($1.00 to $1.35 per liter) owing to the requisite agricultural inputs [85].

The implementation of carbon pricing markedly enhances the competitive standing of biodiesel: at an estimated cost of $90 per ton of CO_2, a vessel that utilizes 300 000 liters of B20 biodiesel annually could potentially avert ∼500 tons of CO_2 emissions, thereby yielding compliance cost savings of roughly $45 000 annually under the EU ETS. Furthermore, ancillary economic advantages encompass diminished degradation of lubricating oils, an extended lifespan of engines attributable to superior lubricity, and the obviation of SO_x scrubbers that are necessitated for high-sulfur fuel applications [86, 87]. These co-benefits collectively bolster the rationale for the adoption of biodiesel, particularly within the contexts of short-sea shipping, ferry operations, and inland waterway logistics, where supply chains are geographically concentrated.

Table 4 Characteristics of agro-waste and nano-catalysts used in biodiesel synthesis.

Catalyst source	Catalyst type	Loading (% w/w oil)	Surface area (m^2/g)	Reusability (cycles)	Yield (%)	Ref
Eggshell-derived CaO	Heterogeneous (nano-CaO)	3	45	5	92.3	[70, 71]
Banana peel ash	Alkaline ash catalyst	5	25	3	85.6	[72, 73]
Coconut shell ZnO	ZnO nanoparticle	2.5	62	4	89.1	[74, 75]
Rice husk silica-CaO	Composite nano-catalyst	4	72	6	93.4	[76]
Tamarind seed ash	Basic solid catalyst	6	18	3	81.7	[77]
Fishbone-derived CaO	Nano-CaO	3.5	58	5	90.5	[78]
Palm ash–MgO blend	Alkaline nano-blend	2	64	7	94	[79]

Table 5 Lifecycle GHG emissions of biodiesel from different feedstocks.

Feedstock	Lifecycle GHG emissions (gCO_2e/MJ)	Reduction compared to diesel (%)	Reference
Waste cooking oil	15	0.85	[54]
Algae	25	0.72	[80]
Jatropha	45	0.5	[44]
Palm oil (sustainable)	38	0.58	[66]
Fish oil	32	0.63	[78]
Mahua	41	0.55	[84]
Soybean	50	0.45	[78]

6.3 Supply chain optimization and scalability

The establishment of localized production systems in proximity to ports can substantially reduce logistics expenditures while ensuring a stable supply of feedstocks. The collection of waste oil from coastal urban centers, when combined with artificial intelligence (AI)-informed demand forecasting and integration into existing bunkering infrastructures, has the potential to reduce fuel logistics costs by ∼20% [88]. Empirical pilot projects conducted in the Netherlands and India have demonstrated production costs of <\$1.00 per liter, with conversion efficiencies exceeding 85% when utilizing WCO or fish oil as feedstocks.

The scaling of production necessitates the adoption of diversification strategies, which may include cultivating algae in wastewater treatment ponds, recovering grease from sewer systems, and establishing inter-port trading platforms for feedstocks, thereby ensuring continuity in feedstock supply [89]. Collectively, these methodologies enhance the techno-economic feasibility and fortify the resilience of prospective marine biofuel supply chains.

The favorable LCA and TEA outcomes accentuate biodiesel's promise as a financially viable and environmentally congruent marine fuel alternative. Nonetheless, the practical realization of these advantages necessitates meticulous attention to factors such as storage stability, oxidative degradation, microbial contamination, and cold-flow properties under maritime operational conditions. The subsequent section will delve into these operational and chemical stability challenges to facilitate the reliable, safe, and sustainable integration of biodiesel–alcohol blends within marine propulsion systems.

7. Overcoming stability and integration challenges in marine biodiesel adoption

While biodiesel and its alcohol blends exhibit encouraging environmental and performance attributes, numerous operational and chemical stability challenges must be addressed to guarantee sustained efficacy in marine applications. The maritime environment introduces additional complexities, including extended storage durations at sea, temperature fluctuations, moisture intrusion, and diverse duty cycles, each of which can significantly impact fuel integrity and engine reliability. This section critically examines the primary challenges associated with fuel degradation, microbial proliferation, and compatibility with marine engine systems, as well as methodologies to mitigate these issues through the use of additives, blend optimization, and hybrid system integration [90].

7.1. Oxidative stability and polymerization risks

Oxidative degradation represents a significant constraint in the storage of biodiesel, particularly for fuels derived from unsaturated fatty acid feedstocks (e.g. Pongamia, soybean, waste cooking oil). The elevated IV, frequently exceeding 110 g I_2/100 g, precipitates the formation of hydroperoxides and subsequent polymerization, culminating in the generation of gums and sediments that can obstruct injectors and fuel filters. ASTM D6751 stipulates a minimum oxidative stability of 3 h (Rancimat test, 110°C), whereas EN 14214 mandates 6 h [91].

Biodiesel synthesized from Mahua or rubber seed oil, without the incorporation of antioxidant treatments, typically exhibits a stability range of only 1.5–2.5 h. The incorporation of synthetic antioxidants, including butylated hydroxytoluene (BHT), tert-butylhydroquinone (TBHQ), or naturally occurring tocopherols (extracted from botanical sources), at concentrations varying from 200 to 1000 ppm, has been shown to possess the capability to extend the shelf life for a

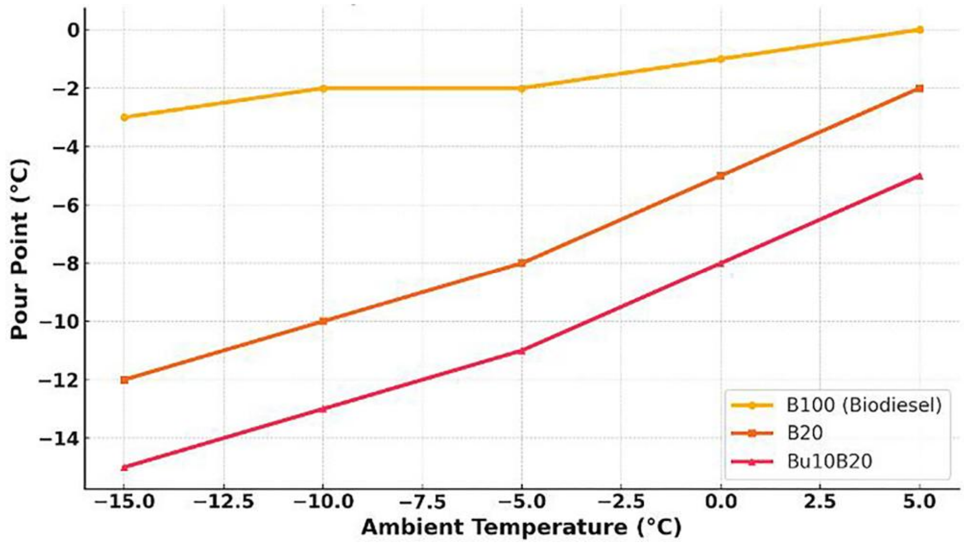


Figure 4 Effect of ambient temperature on PP of biodiesel and alcohol blends.

duration of 6 to 12 months, thus ensuring stability that exceeds 6 h during accelerated aging evaluations [92].

7.2. Microbial contamination in marine fuel tanks

The hygroscopic characteristic of biodiesel (capable of absorbing up to 1500 ppm of water) and its oxygen content render it more vulnerable to microbial contamination compared to petroleum diesel. Marine storage tanks, which often operate under humid and saline conditions, create an ideal environment for microbial colonies, such as those of Pseudomonas, Cladosporium, and Aspergillus species. These organisms metabolize biodiesel and excrete acidic byproducts, which can lead to the corrosion of tank walls, fuel injectors, and filters [93].

Field investigations have indicated a 15–30% escalation in maintenance expenditures for vessels utilizing untreated B100 in tropical maritime climates. To mitigate these threats, biocides such as isothiazolinones or fuel sterilizers are administered at dosing rates of 100–250 ppm. Regular inspections of fuel tanks and conditioning protocols are highly recommended, particularly for extended voyages [94].

7.3. Cold flow behavior and phase separation

One of the primary limitations of biodiesel in marine applications, especially in temperate or sub-zero climates, is its suboptimal cold flow performance. Depending on the feedstock, biodiesel typically exhibits cloud points (CP) and pour points (PP) in the range of 5°C to 15°C, which can hinder flowability in cold marine environments and pose operational challenges in Arctic routes. To address this, blending biodiesel with lower-molecular-weight alcohols, such as in Bu10B20 formulations (20% biodiesel, 10% butanol), has been shown to lower CP and PP by ~4–6°C. However, blends containing highly polar alcohols, such as ethanol or isopropanol, may suffer from phase separation under storage conditions, particularly when exposed to fluctuating temperatures and humidity, thereby compromising fuel stability and engine reliability [95].

To enhance low-temperature operability, the use of cold flow improvers (CFIs) has gained significant traction. Additives such as poly(alkyl methacrylate) and ethylene vinyl acetate (EVA), when introduced at concentrations ranging from 0.1% to 0.5% by volume, have demonstrated the ability to reduce the cold filter plugging point (CFPP) by 30–50%. This results in the extended usability of biodiesel blends at temperatures as low as −5°C to −10°C, thereby expanding their applicability in colder maritime zones [96].

Additionally, the adoption of dual-tank systems, which enable onboard blending or switching between conventional marine fuel and preconditioned biodiesel blends, is currently being explored for Arctic and cold-climate navigation scenarios. These configurations enable flexibility and thermal management, mitigating risks associated with fuel solidification or stratification during prolonged voyages.

7.4. Compatibility with engine components and duty cycles

Marine engines function under high-load, extended-duration duty cycles that necessitate fuel uniformity, lubricity, and thermal stability. The increased viscosity and reduced volatility of biodiesel can modify spray characteristics and atomization dynamics within common-rail fuel injection systems. Investigations into engine wear using B20 in medium-speed marine engines suggest a negligible influence on wear metals (Fe, Cu, Al), provided that consistent fuel quality is maintained and lubricity exceeds the established threshold (a 450 μm wear scar diameter, as per ASTM D6079) [97].

Nonetheless, prolonged utilization of high-alcohol blends (e.g. >20% ethanol or butanol) may result in the degradation of elastomers, seals, and fuel hoses. Compatibility assessments of materials indicate that nitrile rubber and specific fluoropolymers exhibit swelling and softening after 500 h of exposure to ethanol-enriched blends. It is advisable to transition to Viton or

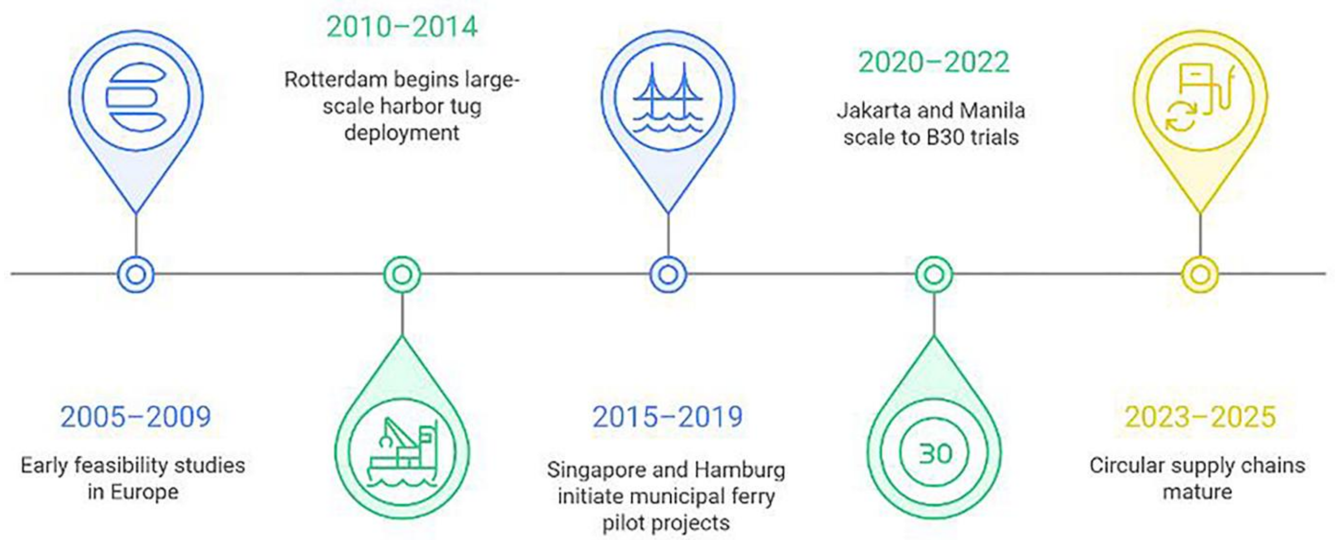


Figure 5 Global biodiesel adoption in marine applications (2005–2025).

polytetrafluoroethylene (PTFE)-based seals for vessels utilizing blended biofuels [96]. Figure 4 presents the fluctuations in PP (°C) for B100, B20, and B10B20 fuels across a range of ambient temperatures from −15°C to +5°C. It is noteworthy that the Bu10B20 amalgamation consistently demonstrates the lowest PP values, thereby substantiating the enhanced cold flow characteristics attributable to the incorporation of butanol [97–100].

7.5. Engine retrofitting and dual-fuel strategies

To facilitate the integration of biodiesel, various retrofitting strategies are currently being investigated. These strategies encompass the enhancement of fuel preheaters (to accommodate higher viscosity), the adaptation of electronic control units (ECUs) for diverse ignition profiles, and the installation of supplementary filtration systems. The implementation of dual-fuel operation, where biodiesel functions as the primary fuel and marine diesel acts as a backup or ignition pilot, provides operational flexibility, particularly for coastal vessels and tugboats [101].

Pilot initiatives in Northern Europe have successfully demonstrated the operation of ferries with 70–80% biodiesel substitution, employing onboard blending systems and AI-driven combustion controllers to optimize injection timing and pressure in accordance with fuel composition [102].

8. Case studies and pilot implementations

The implementation of biodiesel within marine vessels has evolved from a theoretical proposition to a concrete operational phenomenon, facilitated by a series of successful field trials. These pilot implementations encompass ferries, tugboats, naval patrol vessels, and fishing boats, providing essential insights into the technical viability, emissions performance, economic ramifications, and logistical complexities associated with biodiesel across various marine environments. Empirical studies conducted in India, Europe, and Southeast Asia demonstrate a range of favorable outcomes, highlighting both consistency in performance and the need for customized integration strategies that account for engine types, operational loads, and climatic factors [103].

Figure 5 presents a chronological framework illustrating the incremental integration of biodiesel into marine applications from 2005 to 2025. Significant milestones include initial feasibility assessments conducted in Europe, the implementation of harbor tug operations in Rotterdam, municipal ferry pilot programs executed in Singapore and Hamburg, B30 scaling experiments carried out in Jakarta and Manila, as well as the anticipated development of circular supply chains by 2025.

8.1 Inland waterway ferries—Netherlands and Germany

The ‘Green Ferry’ initiative in the Netherlands epitomizes a paramount instance of extensive biodiesel integration, wherein numerous inland ferries traversing the Rhine and Maas rivers were powered by B100, which was entirely sourced from waste cooking oil. Each vessel, equipped with 500 kW medium-speed diesel engines, amassed an annual operational duration exceeding 3000 h. Evaluations of performance indicated that the BTE remained within a margin of ±2% when compared to traditional diesel fuels. Notable emission advantages were documented, including a 60% reduction in CO and a 65% decrease in unburned HC. Although NO_x emissions experienced an approximate 12% increase, this was adeptly countered through the implementation of 10% EGR. Following one year, an analysis of engine wear revealed no significant differences in wear metal concentrations relative to mineral diesel, thereby confirming the long-term material compatibility. From an economic perspective, the effective cost of biodiesel was ~€0.95 per liter, inclusive of subsidies and carbon credits. Additional trials conducted in Germany, particularly along the Spree River utilizing B30 biodiesel, indicated a 55% reduction in smoke opacity and

Table 6 Case study outcomes across regions and vessel types.

Region	Vessel type	Blend ratio	Fuel cost (USD/L)	Emission savings (%)	Operational hours	Ref
India	Inland Ferry	B20	0.86	21	3000	[107]
Norway	Harbor Tug	B30	1.12	28	4500	[105]
Indonesia	Patrol Boat	B50	0.95	33	2500	[108]
USA	Coastal Cargo Ship	B20	1.1	25	5000	[11]
Philippines	Fishing Vessel	B10	0.75	18	1800	[109]
Germany	River Barge	B30	1.18	30	3800	[110]
Bangladesh	Ferry	B20	0.82	22	2700	[110]

full adherence to EU Stage V inland waterway emission regulations [104].

8.2 Harbor tugboats—Chennai and Kochi, India

Demonstrations of biodiesel in Indian harbor tugboats were executed under the auspices of the Ministry of Ports, Shipping, and Waterways (MoPSW) as part of the Maritime India Vision 2030 initiative. Trials conducted at the ports of Chennai and Kochi employed B20 and B50 blends derived from WCO and Jatropha in Cummins KTA38M2 engines rated at 850 horsepower. Over a cumulative operational period of 1200 h, the engines exhibited combustion efficiencies ranging from 96% to 98%, with no instances of injector fouling or filter blockage. Emission assessments recorded an increase in NO_x emissions by 7–10%, which was counterbalanced by reductions in CO emissions (35–50%) and PM. Blends up to B50 successfully conformed to ISO 8217 fuel property specifications. Despite B50 exhibiting an approximate 2.5% increase in fuel consumption attributed to its lower calorific value (~38 MJ/kg), this was offset by diminished lubricant degradation and prolonged maintenance intervals. Operators reported enhanced engine performance characterized by smoother operation and reduced vibration, while emphasizing the criticality of personnel training in biodiesel management and real-time monitoring [41].

8.3 Naval patrol boats—Singapore and Malaysia

Naval authorities in Singapore and Malaysia have conducted comprehensive trials of B20–B30 blends derived from palm and algal biodiesel in short-range coastal patrol vessels. These trials underscored the importance of operational readiness and adherence to international emission standards. Blends containing 10% butanol (Bu10B20) facilitated more rapid cold starts (<8 s), consistent acceleration, and an estimated 10% enhancement in injector lifespan due to improved lubricity. Onboard diagnostic systems indicated minor fluctuations in the fuel–air ratio; however, these variations remained within the adaptive limits set by the ECU. A substantial decrease in black carbon emissions was recorded, thereby ensuring compliance with standards in ECAs. LCA revealed a GHG emissions reduction of 68–72% compared to MGO, thereby bolstering regional policy initiatives that advocate for the adoption of B20 in coastal patrol fleets by 2030 [105].

8.4 Fishing vessels—Philippines and Indonesia

The grassroots implementation of biodiesel within artisanal fisheries has been actively facilitated in the Philippines and Indonesia via circular economy initiatives endorsed by non-governmental organizations. Localized micro-refineries convert coconut oil and fishery byproducts into biodiesel suitable for B10–B20 blends utilized in inboard and outboard engines (20–80 HP). Experimental trials have indicated ~50% reductions in visible emissions, thereby enhancing onboard air quality and promoting the health of crew members in confined spaces. Mechanically controlled engines demonstrated a greater tolerance for variable fuel blends, in contrast to electronic systems that exhibited heightened sensitivity. Production costs have been reported to decline to as low as $0.78 per liter, resulting in reduced fuel expenditures while concurrently bolstering rural economic conditions. Nevertheless, sporadic instances of microbial proliferation and phase separation, attributable to inadequate tank sealing and fluctuating fuel quality, were noted, thereby emphasizing the need for stringent quality control measures, the use of inhibitors, and the improvement of storage infrastructure in remote coastal locales [106].

Table 6 presents a comparative analysis of regional case studies on the utilization of biodiesel blends in maritime vessels, emphasizing that blends ranging from B20 to B50 result in emission reductions of 18–33%, depending on the type of vessel and prevailing operational conditions. The costs associated with fuel fluctuated between $0.75 and USD 1.18 per liter, with the most significant emission reductions recorded in Indonesia (Patrol Boat, B50) and Germany (River Barge, B30). The duration of operations suggests feasible implementation across both developing and developed nations, with optimal performance observed in the United States (Coastal Cargo Ship, 5000 h).

In addition to biodiesel, liquified natural gas (LNG), ammonia, and hydrogen are gaining prominence as alternative marine fuels within the broader context of decarbonization initiatives. Although each of these fuels presents distinct environmental advantages, they also introduce concurrent challenges related to storage, safety, and the preparedness of existing infrastructure. Table 7 offers a comparative analysis of the techno-economic and environmental aspects, elucidating their respective merits and drawbacks in relation to biodiesel.

Table 7 Techno-economic and environmental comparison of marine fuels.

Fuel	Energy density (MJ/kg)	Storage challenges	NOx/CO_2 profile	Cost (USD/GJ)	TRL	Ref
Biodiesel	37	Cold flow, stability	NOx ↑, CO_2 ↓	18	High (commercial)	[100]
LNG	50	Cryogenic (−162°C)	NOx ↓, CO_2 ↓ ~20%	12	High	[4]
Ammonia	18	Toxic, corrosive	CO_2-free, NOx ↑	22	Low–Medium	[102]
Hydrogen	120	Cryogenic (−253°C), low volumetric density	CO_2-free, NOx ↑	25	Low	[65]

These varied full-scale demonstrations, ranging from inland ferries and tugboats to patrol vessels and fishing crafts, emphasize the technical viability and economic sustainability of biodiesel and biodiesel alcohol mixtures across diverse marine environments. By validating combustion efficiency, reductions in emissions, and operational compatibility within realistic conditions, these case studies establish a robust foundation for wider implementation. Building on this empirical framework, the subsequent section outlines future research priorities and pragmatic policy initiatives essential for effectively scaling biodiesel integration, addressing persistent performance and stability issues, and aligning the maritime sector with decarbonization objectives.

9. Future research directions and policy recommendations

The transition to utilizing biodiesel and its alcohol-based blends within marine propulsion systems holds considerable potential for mitigating GHG emissions while enhancing sustainability. Nevertheless, the widespread adoption of such fuels in global maritime operations remains obstructed by a confluence of technical constraints, economic challenges, and regulatory disarray. This section outlines critical research domains and strategic initiatives designed to overcome these impediments, thereby facilitating the widespread implementation of biodiesel fuels within marine ecosystems.

9.1 Improving cold flow behavior and storage stability

Biodiesel sourced from non-edible feedstocks, such as Pongamia or WCO, typically demonstrates elevated CP, PP, and CFPP, which significantly constrains its functionality in frigid marine environments [111]. CP values ranging from 6 to 10°C and PP values between 5 and 8°C render these fuels susceptible to gelling, particularly under sub-zero conditions. To enhance operational efficacy, research endeavors should prioritize the formulation of economically viable CFIs, including poly(alkyl methacrylate), ethylene-vinyl acetate (EVA), and innovative bio-based polymers capable of reducing CP/PP by 5–8°C at minimal dosage levels (0.1–0.5 vol%). Furthermore, the co-blending of biodiesel with oxygenated alcohols such as butanol (Bu10–Bu20) has been evidenced to decrease PP by 3–5°C while concurrently improving spray atomization. Molecular dynamics simulations and rheological modeling can facilitate the design of optimized fuel blends tailored to accommodate varying temperatures and engine specifications [112].

9.2 Scaling algae-based biodiesel production

Third-generation algal biodiesel presents the prospect of lifecycle GHG reductions of up to 90%, attributable to the substantial lipid content (35–60%) and rapid productivity rates (20–25 g/m^2/day) of microalgae species such as *Nannochloropsis* and *Chlorella vulgaris*. Nonetheless, the commercial-scale implementation of this technology remains constrained by the elevated costs associated with cultivation, harvesting, and lipid extraction processes. Advancements in photobioreactor designs aimed at optimizing light utilization and CO_2 capture, particularly through the utilization of onboard ship emissions, represent a pivotal advancement. The integration of algal systems with wastewater treatment processes at ports can diminish nutrient requirements and yield dual outputs of fuel and fertilizer. Progress in genetic engineering to enhance lipid synthesis and stress tolerance, in conjunction with solvent-free or wet extraction methodologies, will be essential for augmenting the feasibility and reducing production costs associated with maritime biodiesel applications [113].

9.3 AI-assisted combustion and predictive engine optimization

The heterogeneous physical and chemical characteristics of biodiesel blends necessitate the implementation of real-time engine control mechanisms to optimize operational efficiency and reduce emissions. Advanced AI methodologies, encompassing convolutional neural networks (CNNs) and long short-term memory (LSTM) architectures, have exhibited predictive accuracy surpassing 90% for parameters such as BTE, ignition delay, and NO_x emissions in Bu10B20 blends. AI-enhanced engine control units are capable of facilitating adaptive modifications to injection timing, fuel volume, and EGR configurations, contingent upon fluctuating operational loads and environmental variables. Furthermore, digital twin technologies enable the virtual simulation of fuel performance across various maritime routes and climatic conditions, thereby reducing the need for prolonged field experiments and enhancing decision-making processes for marine engineers and operators [114].

9.4 Policy mechanisms and economic incentives

The extensive implementation of biodiesel within the maritime industry is contingent upon a synergistic combination of regulatory frameworks and market-driven incentives. The incorporation of maritime transport into the EU ETS commencing in 2024 necessitates that ship operators acquire allowances for CO_2 emissions, thereby establishing a direct economic impetus to transition towards low-carbon fuel alternatives. The reduced carbon intensity of biodiesel contributes to a decrease in ETS compliance expenditures, allowing operators to capitalize on carbon credits and consequently enhance their cost competitiveness. Supporting mechanisms such as the Fuel EU Maritime Regulation, which enforces progressive GHG intensity thresholds, strategically position biodiesel–alcohol blends as an immediately implementable compliance strategy. Carbon pricing strategies within the range of \$50–100 per tonne of CO_2, along with low-carbon fuel standards (LCFS), can effectively decrease the operational cost of biodiesel by \$0.10–0.15 per liter, thereby narrowing the price disparity with MGO. Furthermore, the establishment of obligatory blending targets, such as a B10 mandate, congruent with the IMO 2030 objectives, would generate predictable demand and mitigate investment risks in production capacity. Incentives aimed at decentralized, port-adjacent refineries, facilitated through tax credits or capital subsidies, could further diminish logistical expenditures, bolster local supply chains, and enhance fuel accessibility. Global standardization initiatives remain imperative; the expansion of ISO 8217 specifications to encompass biodiesel–alcohol blends, along with harmonized MARPOL Annex VI compliance protocols, will ensure global interoperability and safety [86]. Regional frameworks, such as India's Maritime Vision 2030 and China's dual-carbon objectives, reinforce the momentum towards renewable marine fuels and present opportunities for the collaborative development of feedstocks and the regional optimization of supply chains.

9.5 Multisectoral collaboration and global harmonization

The realization of scalable integration of biodiesel necessitates synchronized efforts among shipowners, port authorities, engine manufacturers, regulatory bodies, and academic researchers. Shipowners prioritize stability in fuel pricing, reliable supply chains, and adherence to engine warranty requirements. At the same time, port authorities are compelled to invest in bunkering infrastructure and enforce stringent quality control measures. Engine manufacturers play a pivotal role in enabling the certification of higher biodiesel blend ratios (B30+) and in providing technical guidance on engine calibration and retrofitting processes. Regulatory agencies and classification societies play a crucial role in defining clear compliance pathways within the frameworks established by IMO Tier III, the EU ETS, and the CII. At the same time, marine insurers are responsible for ensuring risk coverage for vessels that utilize alternative fuels. Collaborative consortia operating under the auspices of the IMO can facilitate the harmonization of global specifications and certification protocols, thereby alleviating fragmentation across various jurisdictions. Open-access repositories that aggregate engine test data, LCA outcomes, and techno-economic analyses will expedite innovation and the dissemination of best practices [115].

10 Conclusion

This review conducts a critical analysis of biodiesel and biodiesel–alcohol blends as viable, sustainable marine fuels in accordance with global decarbonization objectives. Through a comprehensive examination of fuel characteristics, engine efficacy, emission profiles, lifecycle ramifications, and techno-economic dimensions, the investigation substantiates the feasibility of utilizing waste-derived and non-edible feedstocks, specifically *Pongamia pinnata*, WCO, and microalgae, for the generation of biodiesel that complies with ISO 8217 marine fuel specifications.

Alcohol blends, particularly those incorporating n-butanol, enhance BTE by as much as 3.2% and diminish CO and HC emissions by 40–60%. Although there may be a moderate increase in NO_x emissions, such emissions can be effectively mitigated through the application of EGR and post-treatment technologies. Empirical field trials conducted on marine vessels have demonstrated elevated combustion efficiency (>96%) alongside robust operational dependability without imposing significant maintenance burdens.

LCA reveals that biodiesel can reduce GHG emissions by 65–85%, achieving emission intensities as low as 15–30 gCO_2e/MJ, which is considerably lower than that of HFO (~94.6 gCO_2e/MJ). Progresses in heterogeneous catalysis employing CaO, ZnO, and biomass-derived ash facilitate transesterification efficiencies exceeding 90%, thereby augmenting economic viability within circular bioeconomy frameworks.

In comparison to other low-carbon alternatives, biodiesel offers pragmatic benefits. While LNG reduces CO_2 emissions, it is plagued by methane leakage. Ammonia is carbon-free yet faces toxicity and energy-intensive fabrication challenges. Hydrogen necessitates extensive infrastructure development. In stark contrast, biodiesel is compatible with existing engines, scalable in production, and commercially available.

Future inquiries should prioritize the scaling of algal biodiesel production, the incorporation of AI-based combustion controls, the enactment of supportive policy measures, and the implementation of digital twin models for predictive optimization. These methodologies will contribute to ensuring the cost-effectiveness, resilience, and regulatory adherence of biodiesel within the maritime industry.

Author contributions

Swetha Radha Srikakolapu (Conceptualization, Investigation [lead]), Manjunath Honganur Raju (Formal analysis [lead]), Dhirendra Nath Thatoi (Software [lead]), M. B. Santhosh (Funding acquisition [lead]), Mamata Rajgor (Writing—review & editing [equal]), Anupam kumari (Methodology [lead]), and K. Kamakshi Priya (Data curation, Investigation [lead]).

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Data Availability

The data supporting the findings of this study are available within the article and its cited sources. No new datasets were generated or analyzed during the preparation of this review.

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