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Beyond Road Biodiesel: Qualifying Palm-Derived FAME and Hydrotreated Vegetable Oil for Marine Propulsion, Fuel-System Reliability and Well-to-Wake Decarbonization

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ABSTRACT

Maritime decarbonization increasingly relies on liquid renewable fuels capable of serving existing diesel propulsion systems. Yet applying road-sector experience to vessels risks overlooking prolonged storage, moisture exposure, fuel-system architecture and operational load variation. This qualitative literature review critically compares palm-derived fatty acid methyl esters (FAME) and hydrotreated vegetable oil (HVO) through an integrated analysis of fuel chemistry, equipment compatibility, combustion performance, operational reliability and well-to-wake (WTW) greenhouse-gas accounting. The evidence indicates that FAME and HVO are not interchangeable: oxygenated FAME may require enhanced control of oxidation, moisture and cold-flow behavior, whereas paraffinic HVO can offer different stability advantages while still posing density, lubricity and injection-calibration questions. Marine trials provide evidence of feasibility for certain fuels and blends, but do not establish unrestricted applicability across fleets. Lifecycle outcomes depend decisively on feedstock provenance, land-use change, peat emissions, production energy, renewable hydrogen and allocation assumptions. The review proposes a six-gate Marine Palm-Fuel Qualification and Decarbonization Framework spanning feedstock identity, marine-fuel standards, equipment approval, voyage reliability, WTW verification and continuing surveillance. It concludes that practical marine adoption should proceed through vessel-specific, evidence-based qualification paired with transparent lifecycle and traceability audits, rather than generic biofuel mandates or claims of automatic carbon neutrality.

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Introduction

Background and Scientific Motivation

Decarbonizing existing commercial ships is not equivalent to choosing a fuel for a new road vehicle. A vessel must maintain propulsion and electrical services over lengthy routes, frequently with few opportunities to replace off-specification bunker fuel or damaged components. Marine engines vary from high-speed auxiliary units to immense slow-speed two-stroke propulsion machinery, while onboard treatment arrangements were often developed around petroleum distillates or residual grades. Renewable liquids are attractive because they may preserve parts of the existing fuel and distribution infrastructure. Nevertheless, compatibility is a conditional engineering statement: it depends on a precise fuel batch, engine model, filtration arrangement, operating temperature, maintenance regime and approved blend fraction. Recent maritime transition studies accordingly place operational fit alongside emissions and economics rather than assuming that one alternative fuel can serve the entire fleet [1-4].

Southeast Asia is central to this question because palm-oil production, esterification industries and increasingly complex refinery systems create a regional feedstock and blending opportunity. The attraction of palm-derived fuels arises partly from supply-chain proximity to important shipping lanes and port networks. However, the same geographical concentration demands unusually careful distinctions between palm fruit oil, palm fractions, processing residues and qualifying waste streams. These materials have different economic opportunity costs, competing uses and direct or indirect greenhouse-gas consequences. The word “palm-derived” therefore describes a family of technical and sustainability pathways, not a single fuel with a universal carbon factor. A credible review must connect changes in the molecules entering the vessel with the processes and land systems that produced those molecules, while acknowledging uncertainties in coproduct allocation and counterfactual land use [5-8].

The reference point should be the ship service actually delivered, not a favorable laboratory test alone. A reduction in engine-out particulate mass is relevant for air quality but cannot prove a WTW climate benefit; conversely, a low upstream carbon footprint provides no assurance that a ship can operate through a cold season without filter plugging or unplanned maintenance. This divergence is particularly significant for the comparison between fatty acid methyl esters and hydrotreated vegetable oil. FAME preserves oxygen within ester molecules, whereas correctly produced HVO consists predominantly of hydrocarbon structures shaped by hydrotreating and sometimes isomerization. Consequently, both fuels can ignite in compression-ignition engines, but their storage risks, fluid properties and material interactions are not identical. Evaluations of marine fuels must preserve these differences in both modeling and shipboard decisions [9-11].

Problem Statement and Contribution

A substantial literature has emerged around alternative fuels, carbon accounting, marine policy and engine combustion. Yet those streams frequently address different scales: an engine experiment may report exhaust outcomes over hours; a storage experiment may examine changes over months; a lifecycle analysis may model feedstock scenarios over decades. Their results cannot be combined meaningfully unless the boundary and evidence level of each are explicit. A second gap is the limited number of studies following palm-derived fuels through complete vessel qualification, including bunker sampling, acceptance tests, long-term performance, degradation events, maintenance records and auditable WTW claims. This article therefore asks whether FAME and HVO represent two distinct routes to conditional marine deployment, and under which technical and environmental conditions either route is defensible [12-15].

The contribution is a qualitative thematic synthesis rather than another unqualified ranking of energy carriers. The review develops a six-gate Marine Palm-Fuel Qualification and Decarbonization Framework (MPF-QDF) that treats provenance, fuel specifications, engine and equipment permission, voyage performance, lifecycle evidence and surveillance as separable checks. It further identifies a practical hierarchy of research evidence, distinguishing observations from ocean-going ships from bench tests, automotive diesel experiments and simulations. Such a hierarchy matters because apparent agreement among papers can conceal differences in load, injection settings, ambient temperatures, blend ratios and emissions measurement boundaries. The framework aims to improve research design, onboard decision making and the credibility of marine decarbonization claims without implying that every palm supply pathway is environmentally desirable [16-19].

Literature Review

Conceptual Foundations: Reliability and Carbon Performance

A liquid becomes technically viable as a marine fuel only when it satisfies several interacting objectives. Chemical acceptability concerns composition, contaminants and stability; mechanical acceptability concerns the response of tanks, pumps, seals and high-pressure injection parts; operational acceptability concerns the preservation of propulsion availability and manageable maintenance demands. Environmental acceptability concerns more than smokestack carbon dioxide: it encompasses greenhouse gases associated with the feedstock, conversion process, fuel distribution and actual ship operation. Decision-support research on alternative marine fuels therefore favors multidimensional criteria rather than a single indicator such as minimum life-cycle carbon intensity or market price. The literature also cautions that policy targets can influence commercial preferences faster than the underlying long-duration reliability evidence develops [20-22].

The notion of "drop-in" fuel deserves particular scrutiny. Hydrocarbon composition may permit an HVO product to mix readily with petroleum diesel, but this does not establish that a low-density paraffinic fuel has the identical volumetric delivery, injection response, lubricity or seal behavior of the previous fuel. Likewise, FAME may pass a relevant blend specification while presenting operational risks related to oxidation or high saturated-ester crystallization under a colder voyage profile. It is more rigorous to speak of conditional drop-in use within an approved operating envelope than to promise universal substitution. Fuel and engine designers must consider the interaction between composition, fuel temperatures, injection strategy, filtration and the cumulative exposure of elastomers to mixtures. Laboratory observations help formulate these questions but cannot determine fleetwide permissions by themselves [23,24].

Conversion Chemistry of Palm-Derived FAME and HVO

FAME is normally produced by transesterifying triglyceride feedstocks with a short-chain alcohol, commonly methanol, followed by separation, washing or alternative purification and product verification. The resulting esters retain oxygen, and their individual chain lengths and degrees of unsaturation influence melting behavior, viscosity, cetane quality and oxidation response. Palm oil is relatively rich in palmitic and oleic fractions; the significance for marine use is not simply that it is "saturated" but that the final ester distribution may contain high-melting components that crystallize under unsuitable cold-flow conditions. Feedstock blending, fractionation, additives and fuel mixing can change the outcome, making generic descriptions of palm FAME inadequate. The exact fuel composition and climate envelope should be documented when comparing reported storage, filtration and combustion [25-27].

HVO follows a different manufacturing logic. Catalytic treatment removes oxygen from oils, fatty acids and related feedstocks, using hydrogen and producing paraffinic hydrocarbons that can be further isomerized to improve low-temperature properties. This conversion changes the principal risk profile: resistance to several oxidation processes can be more favorable than for FAME, while density, energy per liter, lubricity and specific injection behavior may require attention. The severity of hydrotreating, catalyst configuration, hydrogen source and isomerization strategy all affect process energy needs and final fuel characteristics. Crucially, the chemical name HVO does not establish that the product was made from palm oil; used cooking oil, animal fats and various lipid residues may feed similar units. Feedstock attribution must therefore rely on auditable chain-of-custody data and process accounting [28-30].

Figure 1 summarizes why these production paths cannot be collapsed into a single "biodiesel" category. Although both may originate from palm-derived lipids, oxygen removal creates an HVO hydrocarbon product whereas esterification preserves FAME oxygenated functionality. This difference leads to distinct handling and qualification questions downstream.

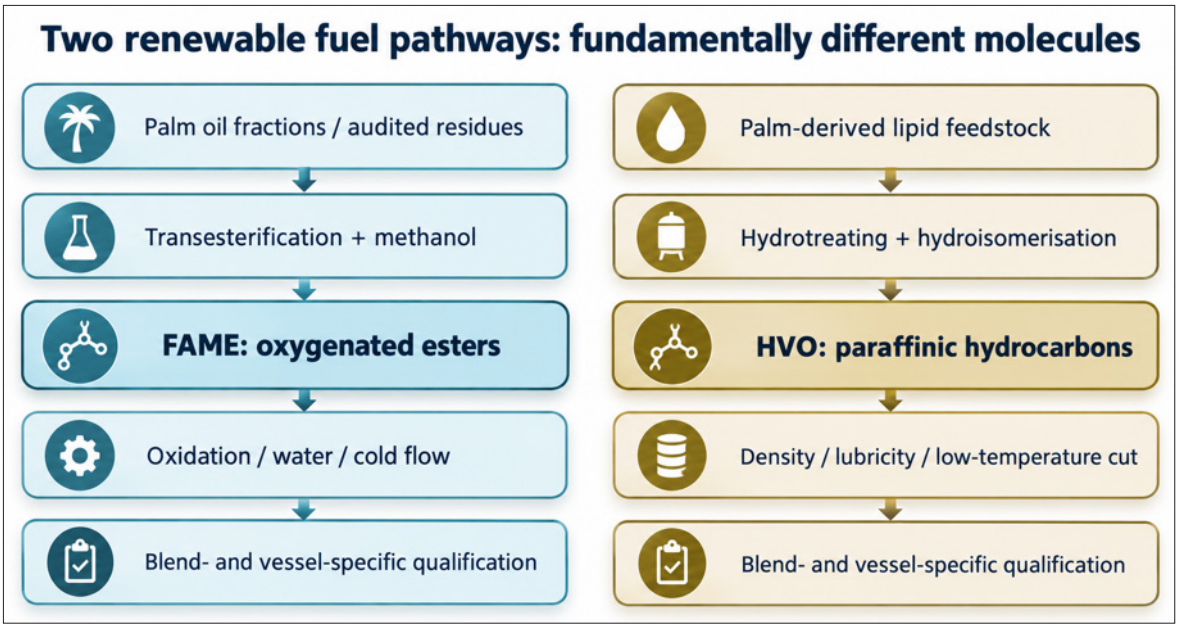


Figure 1: Palm-Derived FAME and HVO Production Pathways and Their Distinct Marine-Fuel qualification issues. Conceptual Synthesis by the Authors

The figure also emphasizes that differences in product chemistry remain meaningful after blending with marine gas oil. Blend notation should specify whether it refers to FAME content, total bio-derived material or a mixture that also includes HVO, because these descriptors are not automatically interchangeable. A supplier may demonstrate a correct blend percentage but still need to show adequate oxidation stability, cold-flow response and contamination control under the intended storage period. Refineries and bunker operators should retain batch-level evidence linking the feedstock, processing route, analytical certificate and delivery to the receiving vessel. In research, the same discipline would allow investigators to compare fuel effects rather than inadvertently comparing dissimilar batches or unspecified co-additives.

Fuel Properties as Mechanisms, Not a Simple Checklist

Cetane quality influences ignition delay, but its relationship to efficiency and pollutant emissions is mediated by injection timing, pressure, mixing and load. Density determines the mass of fuel delivered for a given volume; viscosity influences injection and leakage behavior; and lower heating value changes the amount of fuel needed to deliver equivalent shaft work. Since marine bunkering and engine control may use volumetric quantities, comparisons should specify whether results are expressed by mass, volume, energy or useful transport service. Paraffinic HVO can exhibit strong ignition quality while producing a lower density than conventional diesel, whereas FAME blends may have energy-content and viscosity changes that affect consumption and spray characteristics. A favorable value for one characteristic cannot compensate automatically for weaknesses in another [31].

Cold-flow behavior is especially important for palm-derived FAME because saturated ester fractions can form solid phases at conditions that are not extreme in global shipping. The practical concern is not only whether a sample has a nominal cloud point but also whether slow cooling, prolonged holding and filtration geometry trigger a loss of deliverable fuel. Blending can improve or worsen performance depending on the exact components and relative ratios. Recent computational work links cold-flow predictions to FAME distribution, confirming the value of a molecularly explicit approach; however, predictions require confirmation by relevant analytical methods and operational testing. HVO also varies in cold-flow response according to its hydrocarbon distribution and isomerization severity, so the term "renewable diesel" alone is insufficient documentation.

Lubricity and material compatibility form another pair of distinct but coupled properties. Some ester-containing fuel blends offer useful lubricating behavior, yet changes in fuel polarity may affect swelling, extraction and mechanical integrity of elastomeric components. Palm-biodiesel experiments with nitrile rubber demonstrate that material compatibility needs testing against the specific fuel composition and exposure conditions, not merely the source crop. HVO generally differs in solvency and polarity from FAME and can require lubricity management depending on the finished product and system specification. In a marine setting, overlooked changes in seals or high-pressure equipment could turn an otherwise favorable emissions result into an availability problem. Qualification should therefore test the actual materials deployed in the target vessel.

Standards, Safety and Sustainability Concepts

ISO 8217:2024 specifies multiple marine distillate and residual fuel grades and explicitly encompasses petroleum-derived hydrocarbons, renewable or synthetic hydrocarbons, and FAME only in the grades and blends permitted by the standard (ISO, 2024). It is nonetheless a product specification, not an unconditional engine warranty or a universal authorization to substitute any renewable fuel percentage. Buyers and suppliers must select the applicable grade and verify parameters, while shipowners should review manufacturer instructions, class guidance, relevant safety management procedures and the fuel systems already installed. No single standard can predict the behavior of every mixture throughout a voyage. Operational acceptability therefore requires a combination of documented fuel characteristics, equipment approval and marine-context monitoring rather than a certificate alone [32,33].

Lifecycle thinking adds an independent conceptual boundary. Tank-to-wake describes energy use and emissions from fuel use onboard, while well-to-wake adds upstream cultivation or collection, land-

use change where applicable, conversion, energy supply, storage and distribution. Published marine fuel assessments show how conclusions shift with the functional unit, electricity assumptions, co-product treatment and choice of alternative pathway. The literature also distinguishes greenhouse-gas inventories from broader sustainability attributes, such as biodiversity, labor, local air quality and land governance. A robust palm-fuel evaluation must therefore include explicit carbon accounting together with non-carbon safeguards, rather than treating the latter as hidden inside a favorable numerical CO2-equivalent result [34-36].

The International Maritime Organization's 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels formally separate well-to-tank, tank-to-wake and well-to-wake accounting and address verification and sustainability considerations (IMO, 2024). Their use is complementary to ISO 8217 fuel-quality verification: the ISO specification addresses the delivered fuel, whereas IMO lifecycle guidance addresses the origin and accounting of climate impacts. Neither document should be presented as a substitute for vessel-specific approval, nor should an unverified production scenario be presented as a measured carbon intensity.

Methodology

Design and Selection Logic

This study applies a qualitative literature review (QLR) with critical narrative synthesis. It is not a systematic literature review, does not use PRISMA, and does not present search-result counts or pooled effect sizes. The design is chosen because the available evidence is highly heterogeneous: primary ship trials, marine-engine studies, engine simulation, fuel-analysis experiments, elastomer tests and greenhouse-gas lifecycle models answer different questions with incompatible outputs. A qualitative design makes it possible to trace mechanisms and expose assumptions without implying that numerical averages across these designs would be meaningful. Its central unit of analysis is the evidenced relationship among fuel composition, marine operating context, equipment condition and environmental boundary.

The documentary foundation gives priority to peer-reviewed work published between 2020 and 2026 in energy, engineering, maritime research, environmental science and lifecycle assessment journals. Thematic literature identification uses combinations of concepts such as "marine diesel," "biodiesel," "FAME," "HVO," "renewable diesel," "palm oil," "cold flow," "oxidation stability," "elastomer," "injection," "well-to-wake" and "land-use change." References are screened conceptually for relevance and provenance, rather than through formal systematic inclusion statistics. ISO 8217:2024 is used as a normative specification separate from the journal corpus. Studies employing other biofeedstocks or other marine fuels enter the review only where they support an explicit comparative mechanism or assessment method [37,38].

Evidence Classification and Interpretive Synthesis

A source is assigned an evidence context before its claims are interpreted. Category A covers direct shipboard operation and onboard monitoring; category B covers marine engine and fuel-system tests under controlled conditions; category C covers related automotive or stationary-engine and bench-scale evidence; category D covers modeling, scenarios or secondary synthesis. Categories are not numerical quality scores: a carefully performed laboratory study may be the best source for an oxidation mechanism, whereas a sea trial is more directly informative about onboard operability. What matters is matching the conclusion to the experimental context. In particular, numerical studies of HVO combustion cannot be described as sea-going demonstrations, and road-engine findings should be presented as transferable hypotheses requiring marine validation.

The synthesis was organized around four themes: fuel chemistry and batch identity; equipment reliability and fuel handling; engine combustion and regulated exhaust species; and WTW greenhouse-gas integrity. Contradictory observations were examined by identifying differences in fuel blend, load, temperature, engine architecture, aftertreatment, measurement method and carbon-accounting assumptions. Findings were then mapped onto practical decision gates and vessel categories. This approach deliberately avoids treating publication frequency as evidence of operational consensus, because repeated reviews may derive from the same limited primary experiments. It also avoids treating a favorable carbon intensity value under one supply chain as a universal palm-fuel result [39,40].

Limitations of the Interpretive Approach

A narrative design offers explanatory integration but cannot make statistical claims about average effect sizes or exhaustively quantify every existing publication. The journal literature also has an inherent imbalance: small-engine laboratory results are easier to produce than multiyear vessel data, and lifecycle inventories often draw on modeled or proprietary supply-chain information. This review mitigates these concerns by distinguishing direct measurements from simulations, separating petroleum comparators from alternative-fuel scenarios and emphasizing conditional rather than categorical judgments. All equations and proposed gates are analytical aids, not a claim to have generated original engine, field or lifecycle datasets. Recommendations should therefore be tested through prospective, vessel-specific qualification protocols [41].

Results: Thematic Findings

Theme I — Fuel Composition and Stability

The literature consistently establishes that FAME and HVO have different oxygen chemistry and cannot share every handling assumption. Oxygenated esters are vulnerable to composition-dependent oxidative change and can interact with absorbed or entrained water in ways that motivate careful storage management. Palm-derived FAME research documents measurable changes in oxidation-related indicators and demonstrates the relevance of additive selection and analytical monitoring. HVO is predominantly paraffinic, yet commercial HVO-containing blends still require long-term storage assessment because the complete mixture, rather than the neat HVO fraction, determines degradation pathways. Tests comparing coastal and highland conditions underscore that climatic and storage context can influence outcomes. The marine decision variable is therefore the tested supplied batch under realistic residence time, rather than an idealized neat-fuel property.

Differences in energy delivery also resist oversimplification. Lower volumetric energy content can increase the liters delivered per unit of output, while high cetane quality can change ignition and heat-release profiles. When reports express fuel consumption by different denominators, apparently conflicting results may be methodological rather than fundamental. The fuel properties measured by Bullermann and colleagues support treating renewable blends as formulation-dependent products whose behavior changes with blending. HVO-specific engine studies likewise demonstrate sensitivity to injection conditions, combustion regimes and baseline engine tuning, although their non-marine settings limit direct extrapolation. A fuel-quality comparison intended for ship procurement should include temperature-dependent density and

viscosity, relevant blend composition, ignition performance and usable energy per volume.

Evidence from palm-based FAME and alternative ester mixtures also shows why additives need scrutiny. An antioxidant that improves a laboratory oxidation metric is not automatically approved for a marine fuel system or shown to remain effective over an entire bunker storage interval. Similarly, alcohol co-blending may improve certain combustion or low-temperature properties, but introduces its own volatility, miscibility, material and regulatory questions. A road-engine study of palm FAME with n-butanol is useful as a hypothesis-generating experiment, not proof of safe marine bunkering. The correct result of the synthesis is consequently an engineering testing agenda rather than a blanket endorsement of chemical manipulation.

Theme II — Marine Fuel-System Reliability

The reliability chain starts before the engine: onboard fuel tanks, transfer lines, settling or service tanks, purification equipment and filters may be exposed to fuel for a large share of the voyage. For FAME-containing blends, water management is important because water ingress and persistent moisture can promote contaminant growth and contribute to corrosive or deposit-related failures under suitable conditions. Oxidation products may affect deposit formation and filter loading. These mechanisms are not guaranteed to occur in every fuel; their significance depends on contaminants, temperature, storage duration and the maintenance system. They nevertheless justify explicit acceptance testing, routine fuel sampling, tank cleanliness checks and monitoring of filter differential pressure instead of relying on pre-bunkering paperwork alone [42].

The microbiologically influenced corrosion literature adds a distinct mechanism that is often overlooked in otherwise favorable fuel-compatibility discussions identify the water–fuel interface and microbial biofilms as relevant loci for localized corrosion in biodiesel-containing storage systems; these observations concern storage mechanisms, not demonstrated failure frequencies across marine fleets. As a result, shipboard qualification should combine water-bottom surveillance, representative microbial sampling where indicated, corrosion inspection and predefined remedial thresholds with conventional filter and chemical-quality checks [43].

HVO can avoid some ester-associated oxidative and moisture-related mechanisms, but it should not be described as mechanically risk-free. A shift toward low-density paraffinic fuel may affect volume-based metering, pumping or injection calibration, while lubricity can become relevant for components that depend on the fuel for wear protection. The effects are equipment-specific, and suitable additives or approved blending may mitigate them. Studies of marine renewable fuels and HVO engine behavior support this differentiated view, but long-term comparative shipboard reliability records remain scarce. Engineers should document hardware materials, control strategies, operating temperatures and historical maintenance before attributing a change in pump wear or injector deposits to any single fuel characteristic.

Seal and hose compatibility is a clear example of why one material test cannot answer every vessel question. Exposure tests on nitrile rubber with palm-biodiesel blends reveal that physical and mechanical response may change with ester content, but onboard components can include diverse elastomers, aging histories and coexposure to cleaning agents. Intermittent fuel switching may also matter because a component conditioned by one fuel could respond differently to another formulation. Thus the transferable finding is methodological: bench-test actual ship materials in actual fuel blends, include elevated and reduced temperatures where appropriate, and inspect components during trial operation. Marine maintenance decisions must be based on observed leakage, wear and filter behavior rather than universal compatibility assertions.

Fuel purification arrangements create another context-specific complication. Centrifugal separators designed for particular density differences and sediment profiles may not behave the same when the fuel formulation changes. Similarly, blending FAME into marine distillate should not be assumed compatible with residual-fuel treatment practices simply because all products circulate through a vessel's bunker infrastructure. Where an operator proposes a new fuel, the qualification dossier should include transfer pump performance, separation settings, filter ratings, sampling points, heating temperatures and contingency provisions. Studies of marine diesel systems emphasize the value of ship-specific practices, yet they rarely furnish a standardized long-term failure-rate comparison across palm FAME and HVO. That absence itself is a result: operability evidence is not equivalent to quantified reliability assurance [44].

A recent marine-engine durability assessment reinforces the need to examine maintenance effects beyond short combustion campaigns. Faitar et al. discuss the potential effects of biofuel properties on fuel-handling equipment and marine engine components; however, their engineering assessment should not be mistaken for a prospective multi-vessel failure-rate dataset. The relevant contribution is a component-by-component hazard inventory that operators can translate into measurable checkpoints and incident reporting, not a universal predictive reliability coefficient for either renewable fuel [45].

Theme III — Combustion Performance and Exhaust Emissions

Experimental results from marine engines demonstrate possible reductions in selected exhaust components, but they also reveal variation across engines and operating conditions. Research involving a two-stroke marine engine with onboard measurements offers more direct operational evidence than extrapolation from automotive platforms; reviews spanning propulsion and auxiliary engines show why the design of the engine and test cycle must be reported. Fuel-bound oxygen, ignition quality, mixture formation and combustion phasing contribute to changes in particulate formation and nitrogen-oxide behavior. These pathways can act in opposing directions, so the proposition that any biodiesel mixture always reduces NOx, or always improves efficiency, is scientifically unsustainable. Controlled conclusions should identify the tested fuel and load point.

Low-speed engine and aftertreatment experiments broaden the evidence beyond single pollutant metrics. Work involving biodiesel, filters and SCR treatment shows that particulate species, ultrafine particle behavior and gaseous emissions cannot be summarized adequately by smoke opacity alone. Filtration and exhaust aftertreatment may also change measured results, making engine-out and tailpipe exhaust measurements non-equivalent. Marine dual-fuel studies with biodiesel-diesel ignition blends further illustrate that combustion outcomes depend on interacting fuel streams and engine control. These findings support a holistic emissions protocol: report NOx, particulate mass and number where available, carbon monoxide, total hydrocarbons, operating

load, fuel-energy consumption and the treatment configuration. Without this context, studies that appear to disagree may simply concern different systems [46].

Recent evaluations of marine B24 and modeled HVO-diesel mixtures add relevant but not identical kinds of information. A large-vessel B24 study can inform the potential of an investigated blend in its particular operational setting; a numerical marine HVO study can explore combustion-control sensitivity and define promising test conditions. Neither proves that every B24 blend is identical or that modeled changes will persist across all service histories. A major implication is that fuel type and blending ratio must be recorded precisely, including the identity of any fossil distillate used as the base fuel. This is particularly important when policy discussions simplify all renewable fuel additions into a single nominal percentage.

Road-sector HVO tests identify mechanistic hypotheses rather than direct marine performance guarantees. Single-cylinder and light-duty investigations describe interactions among high cetane quality, injection schedules, partially premixed combustion and exhaust gas recirculation. Such studies provide a useful rationale for exploring engine-setting optimization where an OEM permits it. However, very large marine engines have different cycle characteristics, duty profiles, fuel-handling arrangements and aftertreatment requirements. A marine trial should therefore include engine calibration, continuous engine-condition information, fuel flow measured on a consistent energy basis and reporting of both benefits and operational anomalies. The review treats the appeal of HVO as a reason for structured validation, not a license to transplant road-engine emissions factors into ship inventories [47].

Theme IV — Lifecycle and Sustainability Evidence

Published lifecycle analyses of marine alternatives show that boundaries and assumptions can dominate comparative rankings. Studies comparing renewable fuels, synthetic carriers and petroleum baselines use different electricity and energy sources, co-product allocation procedures, transport assumptions and functional units. Some focus on energy-system greenhouse gases, while others incorporate costs, air pollution or wider environmental criteria. These methodological choices are legitimate when clearly declared, but they can produce superficially contradictory claims if extracted from context. A WTW assessment for palm-derived marine FAME or HVO should therefore declare the exact reference fuel, temporal horizon, fuel energy convention, regional production chain and the service delivered by the vessel. Claims of near-zero or fixed-percentage savings are not credible without these conditions.

Palm-derived fuel assessment faces a particularly important land-carbon challenge. Direct studies of plantation greenhouse-gas budgets and spatial evidence of expansion into carbon-rich forests demonstrate that the emissions consequences of palm production cannot be inferred from biogenic carbon uptake alone. Field evidence, soil carbon processes and modeling of peatland emissions point to material variation over plantation ages, drainage states and management practices. The appropriate inference is neither that every tonne of palm oil has the same adverse emissions factor nor that efficient production eliminates the risk. Results should be reported under explicit direct land-use change assumptions and transparent treatment of indirect market-mediated effects. Verified low-risk cultivation may support a different carbon balance than newly converted forest or drained peatland [48].

Mitigation practices can materially affect results, but the scope of the evidence should be respected. Research on palm-industry mitigation strategies, upstream production hotspots and peatland rewetting provides routes for reducing emissions associated with the wider supply chain. Peatland rewetting can reduce selected soil emissions, but it cannot be assumed to make a converted site equivalent to an undisturbed forest. Likewise, recovering residues may avoid some primary feedstock demand but requires a defensible counterfactual: the residue may have been used for energy, material recovery, soil return or another productive purpose. A serious WTW analysis should model these competing uses and avoid automatically assigning zero burden to any stream labelled "waste." [49,50].

HVO adds an important manufacturing variable because hydrogen generation and consumption influence the carbon intensity of oxygen removal. An HVO refinery using fossil-derived hydrogen and carbon-intensive heat can produce a different WTW outcome from a process using lower-carbon energy and hydrogen. Studies of used cooking oil and green-hydrogen pathways identify the potential value of combining favorable feedstocks with lower-emission conversion inputs; primary-data analyses of commercial refineries demonstrate that real plants and feedstock mixes remain heterogeneous. Work on sludge palm oil highlights a feedstock-processing pathway of regional interest but does not resolve all questions about competing uses, additional demand or verified waste status. These uncertainties should be examined explicitly rather than averaged away [51].

The literature on alternative marine energy also clarifies why comparison classes should be kept visible. Ammonia, hydrogen, methanol, LNG and battery pathways may offer different short-term technical or long-term environmental profiles, but their lifecycle outcomes remain sensitive to production sources and vessel size. A review centered on palm FAME and HVO does not need to rank them against every other alternative; it does need to acknowledge the opportunity cost of allocating scarce sustainably produced lipids to shipping. Analyses of fuel selection, vessel design and costs demonstrate that a technology judged attractive for short-sea operations may be unsuitable for larger or differently equipped ships. Conditional deployment should therefore be situated within a broader energy-transition portfolio rather than equated with a permanent or exclusive decarbonization pathway [52,53].

Discussion and Analysis

FAME Versus HVO: Contrasting Engineering Pathways

The synthesis supports a qualified comparison rather than a universal winner. FAME can leverage existing biodiesel production capacity and may be compatible with specific marine distillate blends under the right fuel grade and engine approval. Its ester functionality, however, makes fuel ageing, water control and composition-dependent cold flow central qualification concerns. HVO offers a paraffinic route with a different oxidation profile and potentially high ignition quality; its density, injection response, lubricity and feedstock-to-hydrogen pathway still need scrutiny. Both families can present acceptable engineering outcomes when the final product is manufactured, supplied and handled correctly. Hence a meaningful comparison evaluates each candidate as a complete fuel-and-vessel configuration rather than asserting that one molecule automatically solves marine decarbonization.

This distinction becomes sharper when sailing pattern is considered. Short-sea ferries may bunker frequently and follow predictable thermal conditions, making sustained fuel surveillance and rapid intervention more practicable. An ocean-going vessel may carry fuel for a substantially longer period, encounter wider temperature changes and depend on reliable purification and injection under sustained loading. Auxiliary power engines differ from main propulsion engines in duty cycles, control systems and the consequences of a failure. Therefore, a positive short-sea trial should not be treated as sufficient qualification for remote routes or dissimilar engine families. The proposed approach assigns each trial a defined operating envelope and requires requalification where fuel composition, tank configuration or operational conditions materially change.

The scarcity of integrated failure-rate evidence is itself a reason for caution. Many papers describe emission characteristics or practical operability without following equipment deterioration, filter plugging frequency, unscheduled maintenance, injector condition and laboratory fuel deterioration in one continuous dataset. Industrial claims of fuel compatibility also vary in specificity, and confidential fleet data may hide failures that would be informative to independent researchers. A stronger knowledge base should distinguish "no reported incident during a trial" from a statistically supported probability of reliable service. It should also record failed trials, tank-cleaning interventions and fuel-conditioning costs rather than reporting only favorable emissions. The resulting evidence would make renewable-fuel qualification more conservative, reproducible and commercially relevant.

Techno-economic assessments can similarly appear more definitive than their data warrant. Oloruntobi et al. (2025) compare FAME and HVO for future marine engines using secondary scenarios and sensitivity analysis, helping identify cost, production and climate questions that deserve explicit treatment. Their illustrative emissions-reduction and cost estimates should not be transferred directly to a palm-derived bunker batch without evidence of its actual feedstock, processing energy, refinery hydrogen and onboard fuel consumption. This distinction between scenario results and auditable vessel-specific observations strengthens the justification for the MPF-QDF approach [54].

Six-Gate Marine Palm-Fuel Qualification and Decarbonization Framework

The original MPF-QDF integrates technical and environmental checks through six linked gates. Gate 1 establishes feedstock and fuel identity, including origin, molecular composition, grade, traceability and whether any feedstock is genuinely waste-derived. Gate 2 verifies product-standard conformity, independent sampling and relevant physical or chemical specifications. Gate 3 confirms the actual engine and equipment configuration is permitted by its OEM and that materials, pumping, conditioning and filtration arrangements are suitable. Gate 4 demonstrates voyage-specific operational performance under relevant storage, load and temperature conditions. Gate 5 evaluates WTW greenhouse-gas outcomes using transparent boundaries and verified inputs. Gate 6 requires continuing monitoring and triggers reapproval after material changes. Figure 2 presents the proposed qualification sequence.

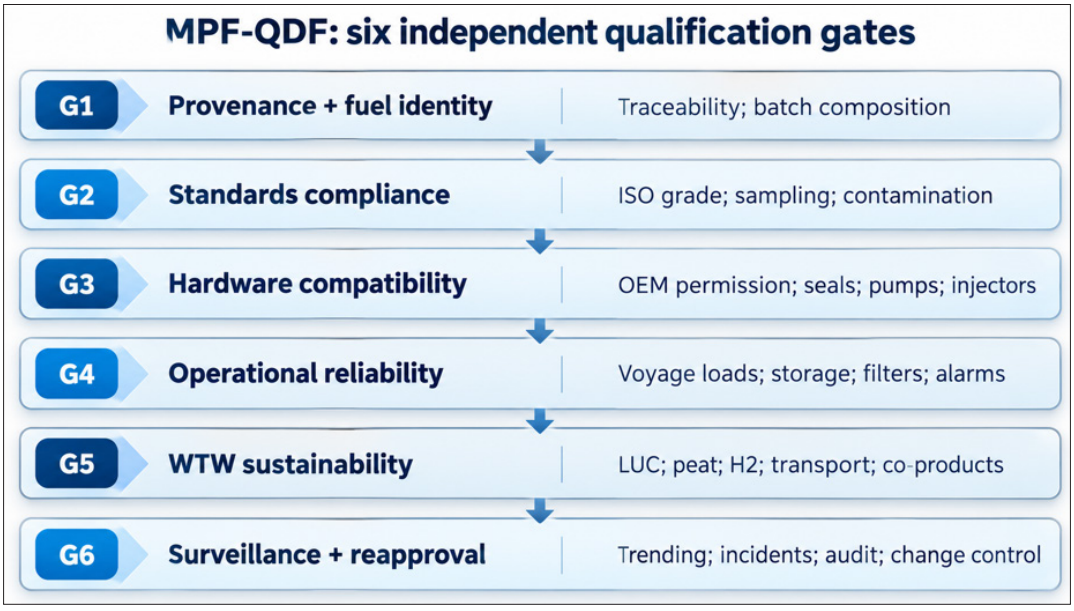


Figure 2: Six Decision Gates in the Marine Palm-Fuel Qualification and Decarbonization Framework (MPF-QDF). Original Conceptual Proposal

Gate sequencing is important because success at an early gate cannot logically cancel a later failure. A fully traceable low-carbon fuel that damages a critical pump should not receive unrestricted operating approval; an engine-compatible fuel with unresolved peatland conversion or unverifiable supply-chain data should not receive an unqualified decarbonization label. The output is therefore conditional: approve within a monitored operating envelope, approve with mitigation and restrictions, request reformulation or further testing, or reject the candidate for that application. Such decisions should capture the exact fuel batch, approved blend, test method, responsible parties, evidence date and review trigger. The framework is a research-derived proposal for structured judgment, not a claim that the six gates already constitute a mandatory international regulatory protocol.

The framework can also organize minimum reporting standards for future experiments. Each paper would state feedstock origin and certification basis, FAME or HVO fraction, petroleum reference grade, full measured property set, engine model and operating schedule, analytical uncertainty, and the maintenance events observed. For a WTW claim, investigators would declare land-use baselines, greenhouse gases included, process-energy and hydrogen inventory, allocation rule, study geography, functional unit and sensitivity cases. Explicit evidence provenance would enable studies that differ in scale to contribute appropriately: oxidation bench tests to Gate 2, mechanical tests to Gate 3, monitored ship trials to Gate 4 and lifecycle inventories to Gate 5. Gate 6 would then connect scientific results to real-world fuel surveillance.

Vessel-Segment Qualification and Implementation

For harbor craft and ferries, a plausible qualification program can begin with a small number of well-instrumented vessels, consistent fueling points and a carefully selected blend. Regular condition-based monitoring should focus on tank condition, filter pressure, fuel quality, injector behavior, specific energy consumption, exhaust species and service interruptions. The controlled environment facilitates comparisons across seasons and maintenance periods, although engine architecture still matters. This segment may be well positioned to test FAME-containing marine distillate blends with rigorous cold-flow and stability safeguards or approved HVO formulations. The evidence should determine any expansion, rather than an assumed fixed percentage drawn from road-diesel mandates.

For high-power and long-distance vessels, qualification would demand a more extensive reliability envelope. Testing should address longer residence times, global temperature exposure, sustained engine load, purification equipment and remote-service limitations. Main-engine and generator combinations may also require separate approvals even when bunkering from a common storage system. Monitoring plans should include fuel compatibility across successive bunker deliveries and contingency arrangements for off-spec fuel. A large-vessel blend study is encouraging evidence for the tested application, but it cannot substitute for a multiyear performance record across multiple engine families and climates. Ship operators need practical decision thresholds tied to specific operational risks, not only aggregate emissions scenarios. The economic implications are broader than cost per metric tonne at the bunker barge. Changes in volumetric fuel consumption, filter replacement, laboratory analysis, storage management, insurance obligations and unplanned downtime can affect total voyage cost. Well-designed assessments should therefore quantify cost per reliable unit of vessel service and link it to WTW carbon performance. Literature on life-cycle cost and alternative-fuel decision frameworks shows that technology selection depends on vessel type and investment horizon. This reinforces the case for segment-specific qualification and for transparent cost reporting during demonstration projects, especially where policy support changes the relationship between reported fuel price and underlying supply-chain cost.

Well-to-Wake Credibility, Land Use and Hydrogen

The most consequential environmental interpretation is that "biogenic" and "low-carbon" are different statements. Biogenic carbon accounting concerns the origin of carbon atoms; a net climate assessment concerns all emissions and carbon-stock changes across the relevant system. Field-measured plantation greenhouse gases and evidence of expansion into carbon-rich land demonstrate why feedstock provenance is material, while peatland studies reveal temporal and hydrological variation. For palm-derived FAME or HVO, an environmental claim should identify origin and land history, direct land-use change, plausible indirect effects, fertilizer-related emissions, processing energy, methane handling, transport and the final vessel duty. A single default palm-oil intensity cannot reflect every regional pathway, yet optimistic scenarios must not be presented as the baseline for all supplies.

Traceability must also be understood as more than collecting a certificate. Audit procedures should link physical or mass-balance claims to documented feedstock volumes, refinery inputs, conversion yields and bunker batches. Where the feedstock is characterized as waste or residue, the assessment must defend its classification and counterfactual. The value of HVO from sludge palm oil or other recoverable streams depends on their treatment requirements and the system they displace, and upstream use of renewable hydrogen can change the outcome. Primary-data refinery research improves confidence but remains contextual, since measured intensities depend on the specific facilities and allocation approach. Using ranges and sensitivity analyses communicates this uncertainty more faithfully than advertising a universal percentage reductio.

The evidentiary threshold also depends on the carbon-accounting claim being made. Certification of feedstock chain of custody, a product certificate of analysis, and a lifecycle carbon-intensity calculation answer different questions and should be independently reproducible. In particular, palm oil mill effluent and other putative waste streams require auditable mass-balance and counterfactual treatment rather than automatic zero upstream burden; primary-data HVO refinery findings cannot by themselves establish the carbon intensity of a different palm supply chain.

Figure 3 depicts the accounting boundary required for the proposed marine framework. The figure distinguishes upstream production and manufacturing from the onboard operation that generates vessel service, and it identifies the WTW aggregate as a calculated result rather than a fuel label. This accounting boundary prevents reductions in fossil carbon emitted at the exhaust from being mistaken for reductions in all climate-relevant gases across land and industrial systems.

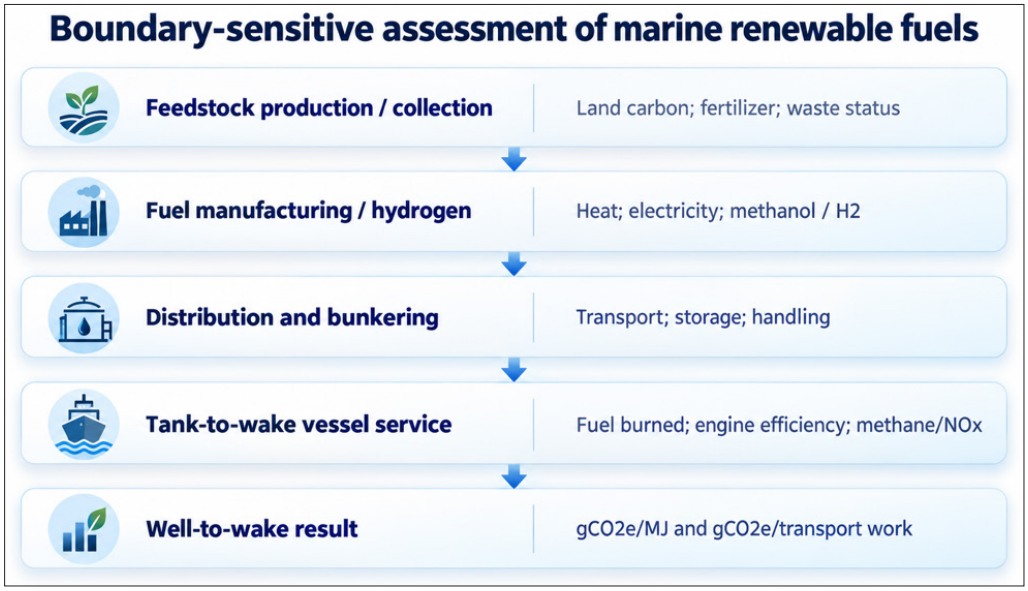


Figure 3: Well-to-Wake Analytical Boundary and Major Sources of Uncertainty for Palm-Derived marine fuels. Original conceptual synthesis

Figure 3 should be read as a map of inventory boundaries rather than a claim that each listed exhaust constituent enters the greenhouse-gas total. In particular, methane (CH_4) is a greenhouse gas where emitted, while nitrogen oxides (NOx) are regulated air pollutants to be reported in parallel rather than simply added to CO_2-equivalent emissions. For conventional FAME- or HVO-fueled diesel engines, measured methane emissions should not be assumed to resemble the methane slip of gas-fueled dual-fuel systems. Consistent treatment of CO_2, CH_4 and N_2O, with explicitly declared characterization factors and biogenic-carbon conventions, is essential when combining well-to-tank and tank-to-wake inventories.

A transparent reporting package should present at least two functional expressions: greenhouse-gas intensity per unit of lower-heating-value energy and emissions per unit of useful shipping service, such as transport work where data permit. The first supports standardized fuel comparison; the second captures changes in energy consumption and vessel operation. Scenarios should isolate renewable hydrogen availability, land-carbon assumptions, residue counterfactuals and shipping-distance changes. Results also need clear treatment of CO2, methane and nitrous oxide using disclosed characterization factors. A study that lacks these details may remain valuable for a specific engineering question, but it should not serve as sufficient verification for a broad WTW decarbonization claim.

For a common energy basis, Equation (1) decomposes well-to-wake carbon intensity into well-to-tank and tank-to-wake components. Both terms must refer to the same fuel, declared lower-heating-value denominator, greenhouse-gas characterization convention and system boundary; upstream land-carbon changes and treatment of biogenic CO_2 must be reported consistently with the selected accounting methodology.

$$CI_{WtW} = CI_{WtT} + CI_{TtW} \quad (1)$$

Where CI is carbon intensity in g CO_2e/MJ, subscripts WtW, WtT and TtW designate well-to-wake, well-to-tank and tank-to-wake respectively. Because vessel service can change with fuel energy content and engine operation, Equation (2) evaluates emissions per unit of transport work. In mixed-fuel operation, the summation prevents the energy contribution of individual fuel streams from being omitted.

$$EI_{transport} = [\Sigma_i (CI_{WtW,i} \times E_i)] / TW \quad (2)$$

In Equation (2), E_i is the lower-heating-value energy consumed from fuel i during the assessed voyage (MJ), and TW is transport work (tonne-nautical miles); the resulting EI_transport is expressed in g CO_2e per tonne-nautical mile. For vessel classes where cargo-based transport work is not meaningful or measurable, the study must declare a different functional unit rather than implying comparability with freight carriers. Equation (2) is an accounting identity, not an empirical finding or a claim that improved nominal fuel carbon intensity necessarily reduces realized voyage emissions.

Implications for Regulation, Investment and Research

Bunker suppliers should move toward batch-specific documentation and traceability that can be reconciled with fuel certificates and downstream carbon claims. Shipowners should require OEM engagement before the first full-scale trial, document tank preparation and specify sampling locations and stop criteria. Classification bodies and regulators can contribute by aligning safety guidance, reporting formats and verification practice without automatically confusing a marine-fuel specification with an equipment approval. Refiners should report the processing route, hydrogen sourcing and product grade rather than promoting FAME and HVO as an undifferentiated biofuel. The combined emphasis on technical and sustainability evidence can reduce the risk of policy incentives rewarding fuels that appear attractive only under incomplete boundaries.

The highest-priority scientific work is a matched comparison of verified palm-FAME and palm-HVO formulations under marine-relevant extended storage, seasonal temperature variation and quantified water contamination. Such studies should use identical petroleum comparators and measure chemical ageing, filterability, microbial markers where relevant, corrosion, elastomer response and pump or injector wear. A second priority is sustained onboard trials with failure and maintenance endpoints, not merely limited-

period fuel-consumption and exhaust measurements. A third priority is integrated LCA calibrated to audited source-specific inventories and updated land-carbon factors. These projects should disclose negative results and confidence ranges. Without such research, deployment may advance faster than evidence about reliability or genuine long-term climate benefits.

Figure-based and conceptual frameworks are useful for communicating trade-offs but should not be mistaken for experiments. The six-gate framework is explicitly proposed as a hypothesis-generating and decision-organizing contribution that needs validation in procurement, onboard trials and audit practice. An important future test is whether it predicts preventable fuel-related incidents more effectively than a simple certificate-based approval process. A parallel environmental test should compare gate-based lifecycle verification against standard emission-factor reporting when feedstock identity or refinery energy sources change. Strong findings would make it possible to specify which gates are binding for each vessel class and which can be monitored dynamically. This would turn a qualitative synthesis into falsifiable operational and sustainability research.

Conclusion

Substantive Conclusions

Palm-derived FAME and HVO are credible subjects for marine-fuel development, but they are technically different fuels rather than interchangeable substitutes for petroleum marine diesel. FAME presents composition-dependent issues involving oxidation, moisture, materials and cold-flow behavior, while HVO has a separate set of considerations involving product density, lubricity, injection response and process hydrogen. Existing trials and experimental studies establish promising pathways under specified conditions, not blanket compatibility with every vessel or blend. The distinction between a compliant delivered fuel and an approved, reliable shipboard fuel system must remain explicit throughout qualification and commercial deployment.

Environmental credibility requires an equally conditional conclusion. Renewable carbon origin does not guarantee lower well-to-wake greenhouse-gas emissions when land-use conversion, peat emissions, refinery energy, hydrogen supply, residue allocation and changes in operational fuel consumption are considered. The most defensible claims are source-specific, quantified, traceable and open to sensitivity analysis. Technical reliability and environmental performance are complementary prerequisites rather than substitutes: favorable results in one domain cannot compensate for material failure in the other. Consequently, a dual demonstration of safe operation and verified lifecycle benefit should be the threshold for labeling a palm-derived marine fuel as a practical decarbonization option.

Recommendations and Future Research

The article recommends implementing the proposed six-gate MPF-QDF through phased marine trials, beginning with fully characterized fuel batches and explicit manufacturer participation. Operators should monitor tank condition, filtration, equipment compatibility, combustion outcomes and service interruptions alongside routine fuel acceptance testing. Producers and auditors should verify feedstock origin, land-use history, manufacturing energy, hydrogen supply and any claimed waste status. Regulators should encourage consistent technical and lifecycle disclosure while avoiding unqualified extensions of road biodiesel mandates to fleets with substantially different risk profiles. Approval should be tied to the vessel, fuel, blend, operating conditions and ongoing evidence, and should be revisited when material circumstances change.

Future work should integrate accelerated fuel-ageing experiments, component-compatibility testing, season-spanning ship trials and primary-data well-to-wake analyses in coordinated study designs. Particular attention is needed for cold-flow behavior of saturated palm esters, real-world fuel deterioration during long voyages, material behavior after repeated FAME-to-HVO switching and the upstream consequences of expanding demand for low-carbon lipids. Open incident reporting and auditable datasets would make conclusions less dependent on brief demonstrations and untested assumptions. The strongest long-term contribution of marine palm-derived fuels will emerge not from labeling them renewable, but from showing transparently when their use is reliable, economically workable and genuinely consistent with climate and broader sustainability goals.

Declarations and Interpretation Notes

This is a critical qualitative literature review and conceptual framework paper. It reports no new experimental trials, field sampling, fleet performance dataset or primary lifecycle inventory. Some cited studies concern road engines, alternative non-palm fuels or maritime decision methods; they are identified as comparative or transferable evidence rather than direct demonstrations of palm-derived fuel performance at sea. The conceptual figures are original explanatory syntheses and should not be interpreted as measured experimental results.

Normative Standards and Guidance (Outside Journal-Article Count)

International Maritime Organization (IMO) (2024) 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels (2024 LCA Guidelines), Resolution MEPC.391(81), adopted 22 March. London: IMO. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391%2881%29.pdf

International Organization for Standardization (ISO) (2024) ISO 8217:2024: Products from petroleum, synthetic and renewable sources — Fuels (class F) — Specifications of marine fuels. Geneva: ISO. https://www.iso.org/standard/80579.html

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