European Maritime Safety Agency

STUDY ON BIODIESEL–BUNKER FUEL BLENDS AS MARINE POLLUTANTS

BLENDS OF BIODIESELS WITH CONVENTIONAL MARINE BUNKER FUELS AS MARINE POLLUTANTS AND THE RESPONSE MEASURES FOR THEIR ACCIDENTAL RELEASES

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Executive summary

This study was commissioned by the European Maritime Safety Agency (EMSA) under the framework contract EMSA/2024/OP/0023 to address critical knowledge gaps concerning alternative fuels as potential marine pollutants and the effectiveness of response measures in the event of accidental releases. As the maritime sector accelerates its transition towards decarbonisation—driven by the IMO Revised Strategy on the Reduction of GHG Emissions from Ships (2023) and the European Green Deal—the uptake of alternative fuels is increasing, while preparedness and response frameworks remain largely designed for conventional petroleum-based fuels.

Among the alternative fuels currently being deployed, biodiesel blends based on Fatty Acid Methyl Esters (FAME) and Hydrotreated Vegetable Oil (HVO) represent a near-term, “drop-in” solution compatible with existing marine engines and infrastructure. Blends such as B20, B30 and B50, used with Marine Gas Oil (MGO) or Very Low Sulphur Fuel Oil (VLSFO), enable emissions reductions without requiring major technical modifications. However, their behaviour as marine pollutants and the suitability of existing response measures in the event of accidental spills are not yet comprehensively documented.

This lack of documentation introduces uncertainty for authorities, operators, and responders, and highlights the need for a structured, evidence-based assessment. Conducted jointly by the World Maritime University (WMU) and Cedre, this study is the first under the EMSA framework contract and aims to support the maritime sector by strengthening spill contingency planning, preparedness, and response as the transition to alternative fuels accelerates.

The study was structured around four main activities (Tasks), covering the full chain from fuel properties and hazards to regulatory frameworks and operational response. Together, these activities provide a comprehensive assessment of biodiesel blends as marine pollutants and identify practical, proportionate adaptations needed within existing response systems.

Task 1 – Current knowledge on alternative marine fuels: properties, hazards, and behaviour

Existing scientific literature and operational experience were reviewed to characterise the chemical and physical properties of biodiesel blends, their environmental fate, and their behaviour following accidental release. Safety and environmental hazards associated with both routine operations and spill scenarios were identified, with particular attention to differences between biodiesel blends and conventional marine fuels.

The analysis confirms that biodiesel blends generally behave in a similar manner to conventional marine fuels when spilled: they float, spread, and form surface slicks. However, several fuel-specific characteristics influence response operations. Biodiesel blends evaporate far less than fossil fuels due to low vapour pressure but exhibit significantly faster biodegradation, with rates up to four times higher under favourable conditions. Acute toxicity to marine organisms is also substantially lower than that of conventional diesel fuels.

Weathering processes can modify buoyancy and detectability. For example, B30 FAME/VLSFO and B30 HVO/VLSFO blends may experience density increases approaching that of seawater, leading to partial submergence in brackish or turbulent conditions. Thin films of B30 FAME/MGO can be visually difficult to detect, while weathered B30 HVO/VLSFO may fragment into emulsified tar-balls. Cold-water conditions can further promote solidification or waxy behaviour, affecting recovery operations.

Hazard Identification (HAZID) exercises were conducted for vessels using or carrying biodiesel blends in both coastal and deep-sea operations, and the results were synthesised into preliminary risk matrices to support prioritisation from a spill response and safety perspective.

Task 2 – Regulatory review and gap analysis

Applicable international, EU, and national regulatory instruments, standards, and guidelines were examined to assess their relevance to accidental releases of biodiesel blends. This included pollution preparedness and response frameworks, fuel specifications, and liability and compensation regimes.

The review identified gaps and ambiguities arising from the fact that most existing instruments were developed primarily for conventional petroleum products. In particular, liability and compensation arrangements may not clearly extend to pure biofuels or higher-percentage blends, potentially resulting in uncertainty following an incident. While MARPOL-related instruments permit the use of certain biodiesel blends, explicit guidance addressing spill preparedness and response for alternative fuels remains limited.

The findings point to the need for targeted updates and clarifications to existing regulatory frameworks to ensure consistent treatment of biodiesel blends across jurisdictions. Improved alignment between international guidance, EU legislation, and technical standards would strengthen legal certainty and operational preparedness.

Task 3 – Response measures, technology, and equipment analysis

Response measures applicable to spills of biodiesel–bunker fuel blends were examined from both vessel-oriented and environment-oriented perspectives. Conventional response techniques—including containment, mechanical recovery using booms and skimmers, sorbents, surface nets, and monitoring—were assessed alongside emerging technologies, with a focus on how biodiesel-specific properties influence detectability, recovery efficiency, and operational decision-making.

Experimental recovery tests conducted by Cedre on fresh and emulsified B30 FAME/VLSFO blends demonstrated that existing recovery equipment remains effective when used appropriately. Weir skimmers achieved high recovery rates but with lower selectivity, highlighting the need for adequate water separation capacity. Oleophilic drum skimmers showed high selectivity when oil contact was maintained, although dynamic operation was required to prevent the formation of a water film that could reduce recovery efficiency.

Overall, mechanical recovery remains the primary response option for biodiesel blend spills. Maintaining oil encounter rates through dynamic skimming and sweep systems is particularly important, as is managing potentially higher water content in recovered mixtures. Onboard response resources, such as sorbents and containment kits included in SOPEP arrangements, continue to be relevant when deployed rapidly. Specialised techniques such as in-situ burning or dispersant use may be considered in specific circumstances but are secondary to straightforward containment and recovery, supported by natural biodegradation once the bulk pollutant has been removed.

Task 4 – Conclusions, best practices, and recommendations

Integrating the technical, regulatory, experimental, and operational findings confirms that biodiesel–bunker fuel blends do not introduce fundamentally new or unmanageable risks in the context of marine pollution response. Existing response infrastructures, strategies, and equipment can be relied upon, with targeted adaptations to address specific fuel behaviours.

Certain characteristics—such as reduced visual detectability of thin films, tar-ball formation in weathered blends, cold-water solidification, and faster biodegradation—require minor adjustments in surveillance methods, response tactics, and preparedness planning. Advanced detection and monitoring technologies are therefore expected to play an increasingly important role.

Best practices emphasise thorough preparedness, rapid response, and the effective use of standard response tools, while leveraging the fuels' biodegradability once the bulk of the pollutant has been removed. Vessels using biodiesel blends should integrate these considerations into emergency response plans, and response organisations should update procedures to address spills involving B20, B30, and similar fuels. Regular training and exercises are essential to ensure effective implementation in real spill scenarios.

Key recommendations include updating contingency plans to explicitly address biodiesel blends, enhancing training and awareness among crews and responders, clarifying regulatory responsibilities and liability frameworks, and pursuing further research on field-scale spill behaviour, shoreline and sediment impacts, fuel fingerprinting, and environmentally acceptable dispersants.

Key findings

Overall, this study provides clear reassurance that the transition towards biodiesel blends as marine fuels can be supported by existing oil spill response frameworks, without the need for fundamentally new response systems. By optimising current technologies, adapting operational practices, and addressing identified regulatory gaps, authorities and operators can manage accidental releases effectively and proportionately.

By integrating scientific evidence, regulatory analysis, stakeholder input, and practical recovery testing, this report delivers a comprehensive and actionable reference for authorities, operators, and responders. It supports informed decision-making at both operational and policy levels and provides a clear pathway for safely managing accidental releases of biodiesel blends while facilitating the maritime sector's transition towards alternative fuels.

1. Introduction

This study on “Blends of Biodiesels with Conventional Marine Bunker Fuels as Marine Pollutants and the Response Measures for their Accidental Releases”, commissioned under the European Maritime Safety Agency’s (EMSA) framework contract EMSA/2024/OP/0023, and conducted jointly by the World Maritime University (WMU, Sweden), and CEDRE (Centre de Documentation, de Recherche et d'Expérimentations sur les Pollutions Accidentelles des Eaux, France), addresses critical knowledge gaps concerning alternative fuels as potential marine pollutants and the effectiveness of the response measures in the event of accidental spills. Its overarching objective is to support the sector and enhance alternative fuel spill contingency planning and management as the maritime sector transitions to alternative energy sources.

1.1 Background

The maritime industry, a critical component of global trade, is under increasing pressure to reduce its environmental impacts. Initiatives from both the International Maritime Organization (IMO) and the European Union (EU) highlight the crucial role of alternative fuels in the strategy to decarbonize maritime transport. The IMO's Revised Strategy on the reduction of greenhouse gas (GHG) emissions from ships adopted in 2023 aims to cut the carbon intensity of international shipping by at least 40% by 2030, increase uptake of zero or near-zero GHG emission fuels and/or energy sources to represent at least 5% of the energy used by international shipping by 2030 and to reach net-zero GHG emissions by or around 2050[2]. Similarly, the European Green Deal seeks to achieve climate neutrality by 2050 and includes specific measures targeting the maritime sector under the FuelEU Maritime initiative[3].

Among the various alternative fuels being explored, biofuels, ammonia, liquefied natural gas (LNG), hydrogen, and synthetic fuels stand out as the most promising. Biofuels, such as Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Esters (FAME), offer a near-term solution due to their compatibility with existing marine diesel engines, providing a "drop-in" alternative to conventional marine fuels[4]. Ammonia and hydrogen present significant long-term potential with their zero-carbon emissions when produced from renewable sources, though they require substantial modifications to existing ship designs and infrastructure[5].

The environmental hazards associated with conventional marine bunker fuels have been extensively documented through numerous marine disasters, such as the Nakhodka (1997), Erika (1999), and Prestige (2002) incidents. These incidents have led to the establishment of comprehensive international conventions, national legislation, and response strategies. However, there is a notable gap in knowledge concerning the environmental implications and appropriate response measures for alternative fuels. Current regulations and contingency plans largely address conventional fuels, leaving a need for a comparable framework for new fuels and their blends to be developed.

Despite their promising potential, the behaviour of alternative fuels as marine pollutants and the appropriate response measures for accidental releases at sea are not well-documented. This lack of documentation poses significant risks to marine ecosystems and highlights the need for focused research to develop effective mitigation measures for these risks. Addressing these gaps necessitate the development of new regulatory frameworks and response strategies to manage the risks associated with the use of alternative fuels in maritime transport.

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[2] International Maritime Organization. (2023). " International Maritime Organization (IMO) adopts revised strategy to reduce greenhouse gas emissions from international shipping." https://www.imo.org/en/mediacentre/pressbriefings/pages/revised-ghg-reduction-strategy-for-global-shipping-adopted-.aspx

[3] European Commission. (2020). "European Green Deal." https://commission.europa.eu/strategy-and- policy/priorities-2019-2024/european-green-deal_en

[4] DNV. (2020). Using biodiesel in marine diesel engines: new fuels, new challenges. https://www.dnv.com/news/using-biodiesel-in-marine-diesel-engines-new-fuels-new-challenges-186705/

[5] Global Marine Forum. (2022). Ammonia as a shipping fuel. https://globalmaritimeforum.org/insight/ammonia- as-a-shipping-fuel/

1.2 Scope and objectives

The current study, the first under this framework contract, intends to examine blends of biodiesels with conventional marine bunker fuels as marine pollutants and response measures for their accidental releases. Blends such as B20, B30, and B50, combined with conventional marine fuels such as Marine Gas Oil (MGO) and Very Low Sulphur Fuel Oil (VLSFO), offer the advantage of immediate compatibility and serve as a transitional step toward lower emissions. However, these blends may present environmental and operational risks in the event of accidental releases, risks that demand targeted research and preparedness.

The main objectives of this project in its first study are as follows:

- compile and analyse existing research and data on the properties, environmental risks, and spill response strategies for biodiesel blends as marine fuel;
- conduct detailed characterizations of the physicochemical properties of biodiesel blends and their environmental behaviour post-release;
- assess the safety and environmental hazards associated with routine operations and accidental spills of biodiesel blends in maritime transport;
- review existing regulatory frameworks to identify gaps in preparedness for accidental marine pollution involving biodiesel blends; and
- provide comprehensive evaluations and recommendations for spill response techniques and technologies that are specific to biodiesel blends.

1.3 Acronym list

The glossary of terms, abbreviations, acronyms, and symbols used in the study can be found in Annex I.

2. Current knowledge on alternative marine fuels: properties, hazards, and response

At the time of drafting this report, considering the lack of scientific literature dedicated to biodiesel blends with marine fuel (only one paper), this literature overview presented hereafter includes biodiesel and biodiesel blends with automotive diesel.

2.1 Review of existing studies and research

■ Materials and methods for the inventory compilation

As a systematic and impartial method of collecting data, a systematic literature review (SLR) was applied to compile the inventory of studies and research using selected keywords and predefined inclusion and exclusion criteria. For each study, data were extracted on fuel type (biodiesel, hydrotreated vegetable oil (HVO), or blended formulations), spill scenario characteristics, documented ecological impacts, employed response techniques, and explicitly reported research limitations. This structured screening and data-extraction protocol ensured a rigorous and reproducible synthesis of the extant literature. A forward-snowballing method was applied to enhance coverage by including additional articles that satisfied the predefined inclusion criteria. The evidence-based systematic review helped apprise policy and method [76], [77].

A comprehensive search strategy was employed using the Boolean string "biodiesel OR renewable diesel OR diesel blend AND response AND spill AND marine AND environment AND accidental release" across multiple academic databases to address the research questions of this study. The research was conducted using four leading bibliographic databases: Google Scholar, ScienceDirect, Web of Science, and Scopus. To ensure an accurate description of the review method, the “Preferred Reporting Items for Systematic reviews and Meta-analyses (PRISMA)” was utilized [55] [36].

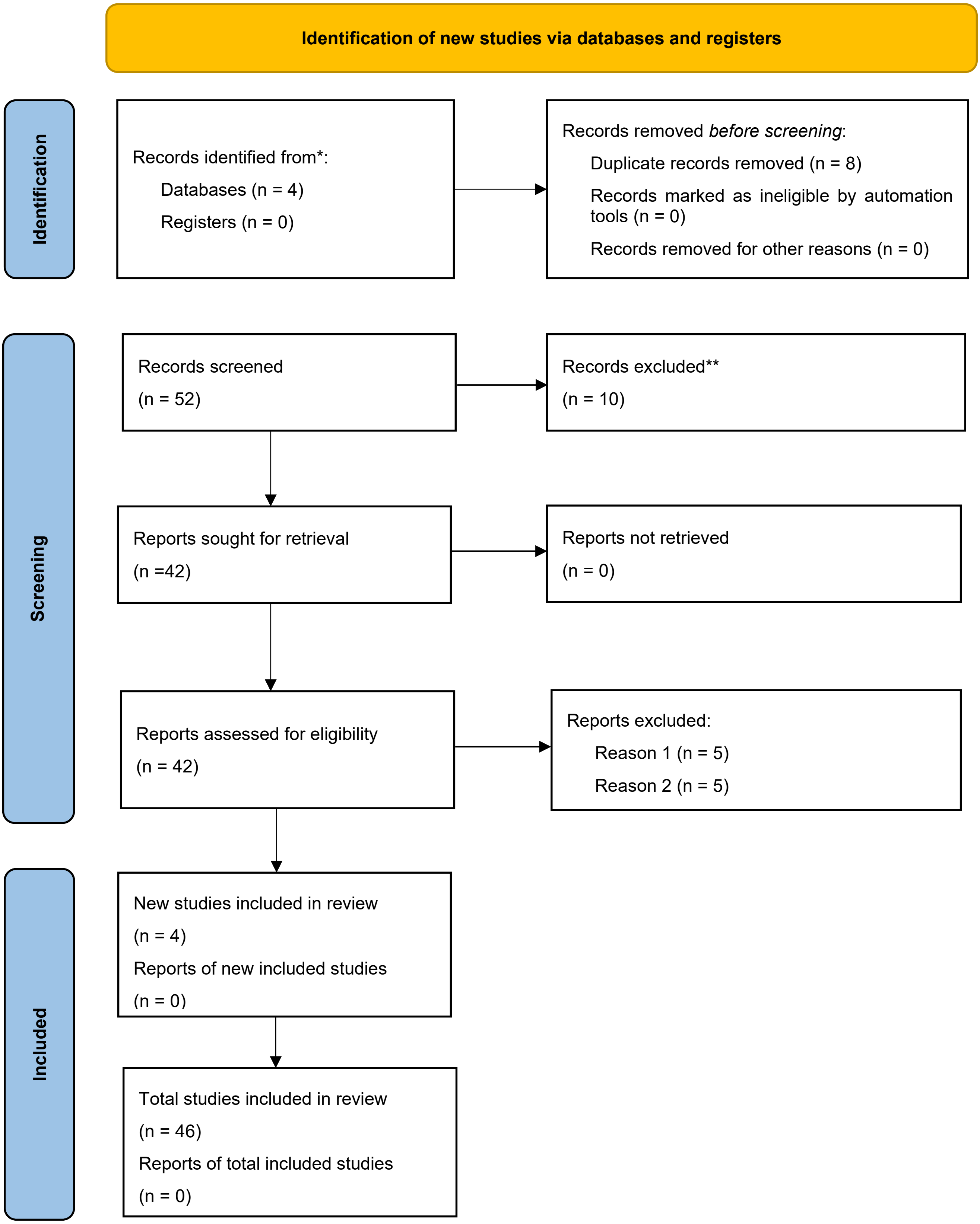
The inclusion criteria for the search encompassed peer-reviewed journal articles and conference papers directly relevant to biodiesel blends as potential marine pollutants and responses in the event of accidental spills. No publication date filters were imposed to capture the entire historical arc of biodiesel-spill scholarship from the earliest record in 1997 to the latest studies published until April 2025. However, duplicates, non-English publications (where translations were unavailable), and studies unrelated to spill impacts or response strategies were excluded from the review.

Systematic searches of Google Scholar (n = 35), ScienceDirect (n = 11), Scopus (n = 5), and Web of Science (n=9) yielded 60 records. Deduplication removed eight articles, leaving 52 for full-text screening. Ten were excluded based on context and research scope, resulting in 42 studies eligible for data extraction. The key variables captured for each study comprised fuel type (biodiesel, hydrotreated vegetable oil [HVO], or blended formulations), spill conditions, documented ecological effects, response techniques, and reported research limitations. A forward-snowballing procedure subsequently identified four additional papers that met the inclusion criteria, bringing the final corpus to 46 studies. This multistage, transparent workflow ensured a rigorous and reproducible synthesis of the current evidence base.

■ PRISMA results

Of the 46 sources that met the inclusion criteria for this systematic review, the majority were peer-reviewed journal articles (n = 41; ≈ 89 %), supplemented by conference papers (n = 5; ≈ 11 %). This distribution confirms that scholarly conversations on biodiesel spill behaviour and response are primarily driven by research publications, with relatively few findings disseminated through conference proceedings.

Figure 1. PRISMA flow chart for the systematic literature review



The annual distribution of articles revealed fluctuating publication trends. Scholar peaked in 2017 with four papers, indicating attention to biodiesel-blend spill issues. Moderate activity with three papers per year appears in 2007, 2009, 2011, 2012, 2019, 2022, and 2024, suggesting sustained but not exceptional engagement. The record shows only one paper in 1997, 2004, 2008, 2010, 2013, and 2021, reflecting a minimal output. Overall, the data revealed episodic bursts rather than a continuous upward trend. This implies that external drivers such as funding initiatives or noteworthy spill events have periodically stimulated scholarly interest in biodiesel-blend spill response and mitigation.

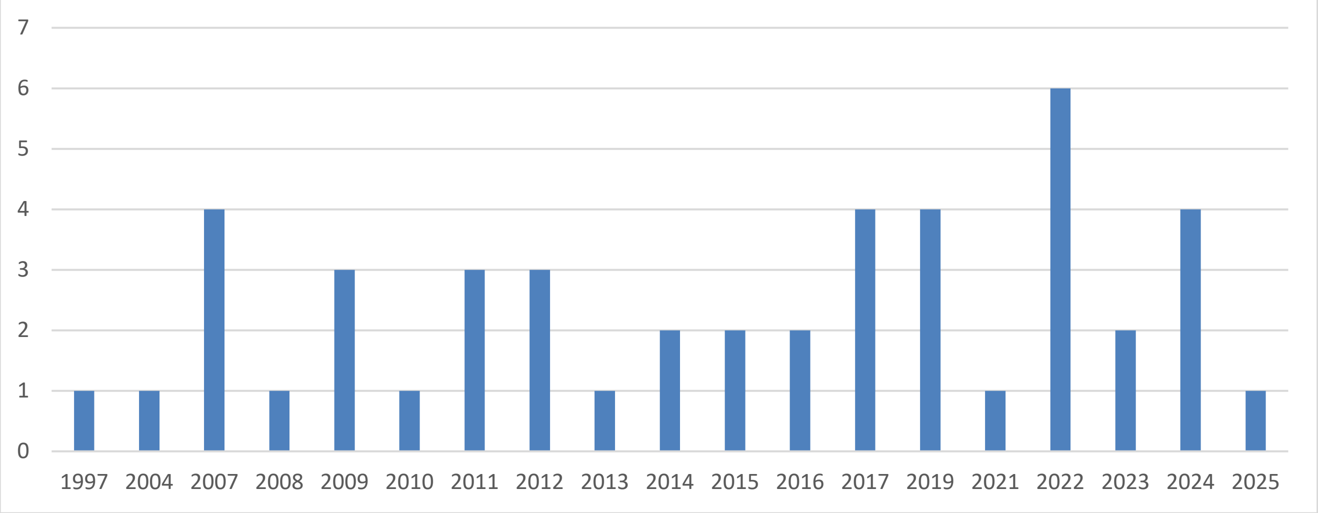


Figure 2. Year wise distribution of articles included in the review (n=46).

2.1.2 Key research projects, studies, and publications related to the response to accidental release of biodiesel blends in the marine environment

Core literature guiding marine preparedness and response to accidental biodiesel-blend releases spans from the first toxicity and fate tests in the mid-2000s to recent evaluations of green-response tools. Foundational work by Khan et al.[55] quantified the acute toxicity of neat and blended biodiesel to representative aquatic taxa. DeMello et al. [36] provided the first seawater weathering/biodegradation data, confirming faster microbial turnover yet persistent surface slick behaviour. The broad review by Hollebone and Yang [34] distilled early fate, effect, and clean-up options, and experimental programs at OHMSETT [49] and Environment Canada's sorbent trials [54], [78] translated those insights into response tactics. Laboratory weathering–dispersant studies by Faksness et al. [59] and comprehensive behaviour-toxicity comparisons for multiple bio-oils [45] update responders on how FAME and HVO blends spread, sink, or disperse relative to petroleum diesel coupled with the U.S. Maritime Administration's spill-behaviour handbook for non-traditional fuels [17], the green-dispersant survey by Giwa et al. [37], and AMOP's field-scale fate assessment [51]. Together, these publications form the current evidence spine: they collectively map toxicity thresholds, physical behaviour, biodegradation rates, and the performance of sorbents, dispersants, in-situ burning, and containment tests, which are critical inputs for forward-leaning contingency plans and decision support models for biodiesel-blend spills at sea. An extended summary of the most relevant literature is provided in Appendix A. A qualitative thematic analysis was conducted on the literature to synthesize the current research themes on biodiesel blends with conventional fuels. The results of the thematic analysis are presented in Annex II.

■ Biodiesel blends addressed in the literature

The compilation presents a rich and diverse overview of 46 studies examining biodiesel and its blends in spill-related contexts, highlighting the increasing complexity and maturity of the research landscape. Early investigations, such as those by Miller & Mudge [79] and Pereira & Mudge [47], relied predominantly on neat biodiesel (B100), especially from rapeseed and soybean oil, to assess weathering and cleanup potential in shoreline environments. As the field evolved, a wider array of feedstocks, including castor, canola, coconut, palm, and even tallow, and blend ratios (B5–B100) were introduced, reflecting a growing recognition of the varying biodegradability and environmental impacts. Several studies have compared multiple blend concentrations, such as Khan et al. [55] and DeMello et al. [36], underscoring the interest in blend-dependent toxicity and degradation behaviour. Yang et al. [28] illustrated a shift towards sophisticated bioremediation strategies, lifecycle assessments, and interactions with other emerging fuels, such as HVO and renewable diesel. A subset of review articles [80] enriches this empirical base by synthesizing the statistical patterns and uncertainties across B20–B100 blends. The table reflects a temporal expansion in feedstock diversity and methodological depth, signalling a maturing interdisciplinary dialogue among environmental science, marine pollution response, and fuel chemistry.

Figure 3 illustrates the distribution of conventional fuels blended with biodiesel in the published literature. Of the studies surveyed, 13% employed low-sulphur or ultra-low-sulphur diesel, 11% used marine gas oil, and 6% utilized fuel oil; the remainder predominantly comprised petroleum diesel. This pronounced focus on automotive diesel underscores a critical gap, as few investigations have addressed biodiesel blends with marine diesel or gas oil in the context of spill response and environmental recovery. To advance this field, this study systematically evaluated the impact of biodiesel-marine diesel formulations under realistic spill-mitigation scenarios.

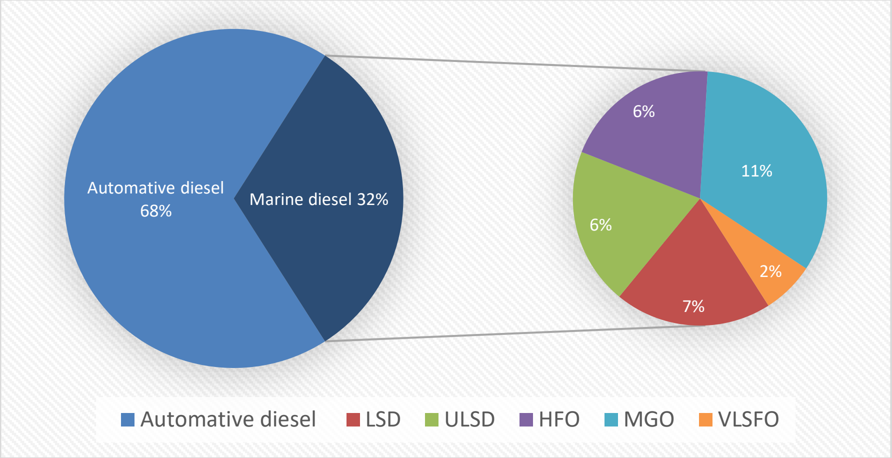


Figure 3. Distribution of literature on biodiesel blends with conventional marine fuel types (n=46).

Various feedstocks are used to produce biodiesel (B100) for blending operations, and they play a crucial role in characterizing the final blend and informing spill-response and mitigation efforts. In the literature, soybeans predominate at 28% of experimental feedstocks, followed by tallow/animal fat at 15%, and rapeseed and used cooking oil, each contributing 10%. Figure 4 illustrates the varied feedstocks employed to generate the primary biodiesel (B100) blends.

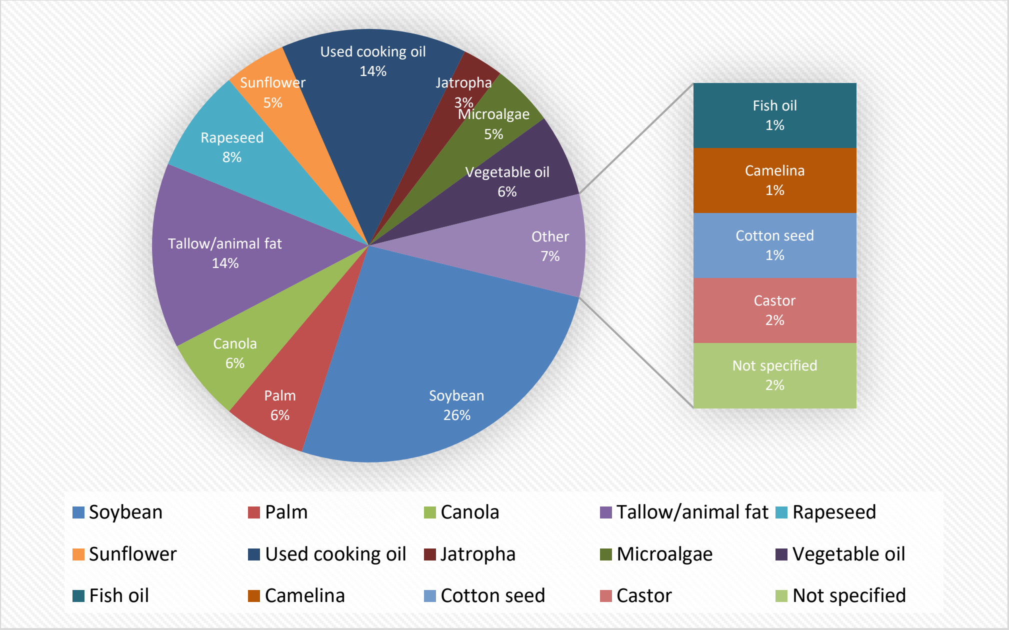


Figure 4. Distribution of literature on feedstock used to produce the biodiesel (B100) (n=46).

The distribution of biodiesel products as a chemical family in the surveyed literature is highly skewed toward FAME, as shown in Figure 5, where cooking oil methyl ester (UCOME) comprises only 10%. While vegetable oil methyl ester (VOME) represents 56%, the mixed feedstock used to create fatty acid methyl ester (FAME) represents 31%. Hydrotreated Vegetable Oil (HVO) makes for 2% of the dataset, even though HVO is increasingly promoted as a drop-in, high-quality marine fuel. This suggests a clear research gap: despite HVO's operational and environmental advantages, it remains under-represented in spill-behaviour, handling, and regulatory studies. Future work should explicitly include HVO to ensure a balanced understanding of all primary alternative marine fuels.

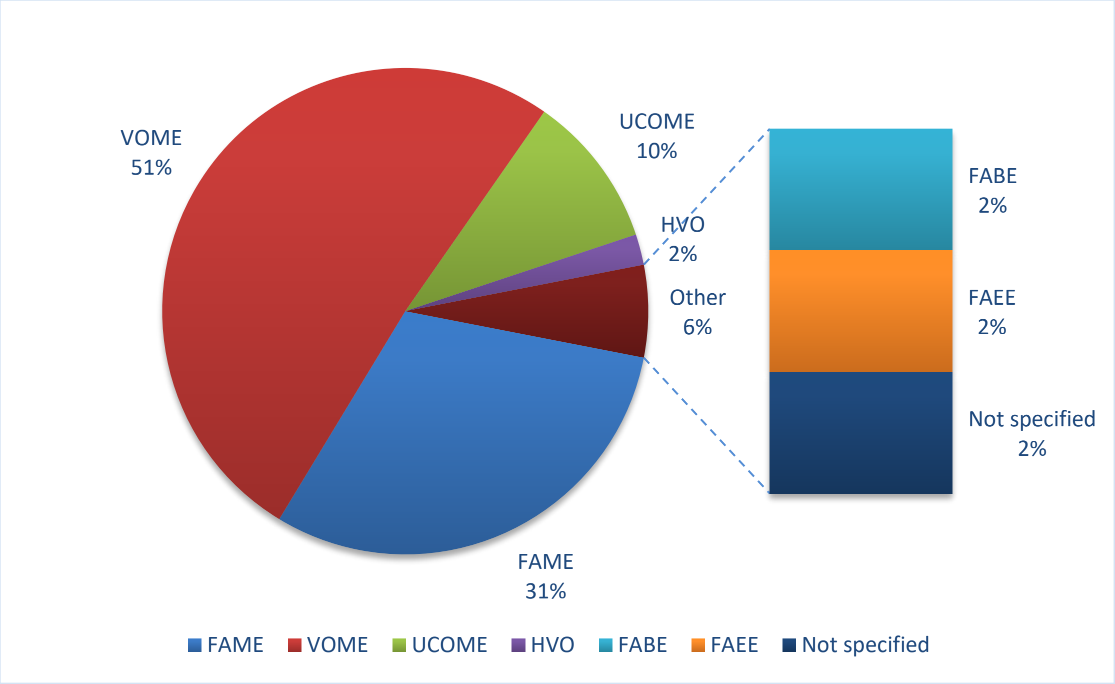


Figure 5. Distribution of literature: FAME, UCOME and HVO (n=46).

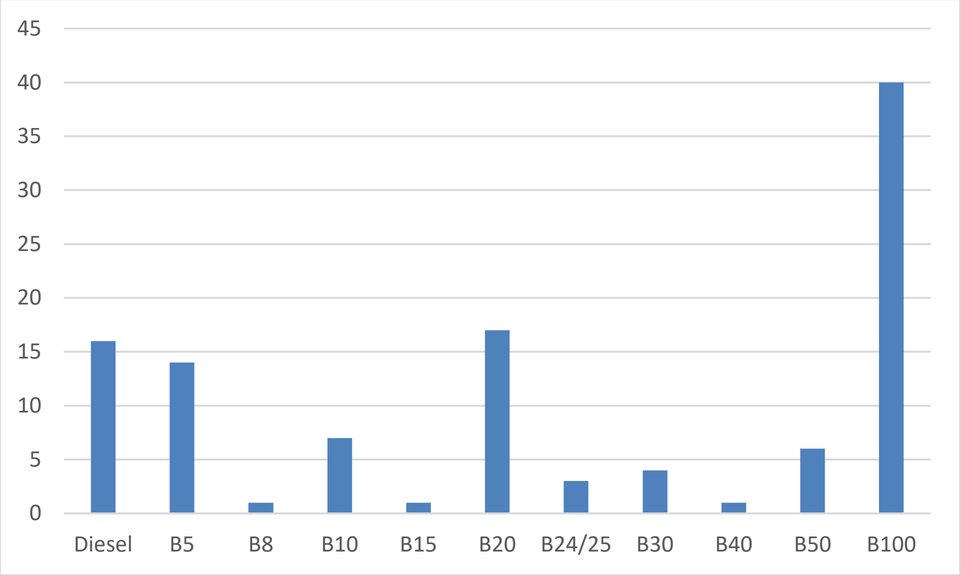


Figure 6. Blends of biodiesel covered in literature,1997-2025 (n=46).

Despite the breadth of biodiesel blend coverage across the 46 reviewed studies (Figure 6), several intermediate and low-percentage blends remain underrepresented, revealing a critical research gap with scientific and operational implications. Notably, blends such as B10 and B15. Meanwhile, B30 to B90 blends are either scarcely investigated or absent from the dataset. This underrepresentation is scientifically significant for several reasons.

Firstly, nonlinear degradation behaviours have been observed in existing studies that compare B0, B20, and B100, indicating that biodegradation rates, toxicity profiles, and weathering characteristics may not follow a simple linear trend across blend percentages. Intermediate blends may exhibit threshold effects or synergistic interactions between biodiesel and petroleum diesel components, especially regarding microbial adaptability, dispersion behaviour, and residue formation [38].

Secondly, real-world fuel usage patterns increasingly involve customized blends optimized for regional emissions regulations, cold flow properties, or supply chain constraints. As such, emergency responders may encounter spills involving non-standard blends that current models and protocols do not fully accommodate. The absence of empirical data for these blends weakens the predictive capacity of environmental risk assessments and limits the calibration of forensic tools such as chemical fingerprinting and remote sensing [17], [80].

Lastly, several blends (e.g., B10-B30) are increasingly used in national mandates (e.g., in Southeast Asia, Brazil, and parts of the EU), yet their environmental fate and spill behaviour remain poorly understood. This gap is essential for aligning bioremediation techniques, regulatory thresholds, and emergency response with ground realities [38], [39].

2.1.3 Institutions, organizations, and individuals that have conducted significant research on biodiesel spill response and environmental impact, and scope of their works

The review of available industry studies and projects revealed that dedicated research focusing specifically on biodiesel blends as marine fuels and their accidental release at sea remains very limited. Many of the studies that were identified[6] addressed biodiesel blends as part of broader research on alternative marine fuels, rather than as a standalone subject.

A list of individuals and organizations that conduct significant research related to biodiesel spill response or contain scientific information could enhance our response to such spill are listed in Annex III.

Most of these studies were designed to assess biofuels' operational, technical, or decarbonisation aspects in shipping, emphasizing bunkering safety, fuel quality, storage conditions, and engine compatibility. Spill-related aspects concerning biodiesel blends have generally been included only indirectly or within broader discussions on the environmental behaviour of biofuels in general.

Among the few studies that explicitly consider the fate and behaviour of biodiesel in the marine environment, the report by ITOPF [62] stands out as the only dedicated analysis on the environmental impacts, behaviour, and response considerations of biodiesel spills at sea.

Other industry reports by EMSA, DNV, ABS, Lloyd's Register, and IEA Bioenergy, while providing valuable technical assessments of biodiesel properties, have primarily focused on operational risks, fuel management practices, and safe bunkering procedures. Their relevance to spill response is mainly in the context of spill prevention (through better fuel handling and operational safeguards) rather than direct spill response strategies or contingency planning.

SINTEF study [59] of FAME (B100) and HVO biofuels guides spill response to show that the fuels form thin slicks that break up easily under wave action, so dispersants can be safely applied in open water. However, natural spreading is slower in sheltered areas, so crews should have booms and skimmers ready for direct recovery. Polypropylene and cotton sorbent booms absorbed more than 80% of both fuels, confirming their value for shoreline defence. Water-accommodated fractions caused far lower acute toxicity to the copepod *Calanus finmarchicus* than marine gas oil, reducing immediate water-column risk. The fuels take up little water and float, making sinking or tar-ball formation on the seabed unlikely. Even after intense laboratory weathering (heated to 250 °C+), their buoyancy and low water uptake changed very little. The three different HVO samples considered in the study behaved alike, so one set of response rules can cover most HVO cargoes. B100 was found to spread slightly faster in calm water than HVO, suggesting that spills rich in FAME demand quicker near-shore containment. Overall, existing booms, skimmers, and dispersants would work well for biodiesel spills, and their lower toxicity means post-cleanup monitoring can be shorter than diesel.

Research at Cedre by Jezequel et al. [51] highlight the biodiesel blends' mechanical-recovery narrow operational

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[6] Refer to Annex III for list of key projects related to response to accidental release of biodiesel blends in the marine environment

window: Cedre's flume-tank trials show that slicks of B0 and B10 persist for only two to three days before turbulence disperses them into a white droplet cloud by day six, compelling responders to deploy booming and skimming assets immediately after release if they are to achieve meaningful oil removal. Throughout a week of controlled weathering, the densities of all biodiesel grades examined remain lower than both fresh and seawater, indicating that the slicks will stay afloat unless they adsorb onto suspended particulates; consequently, under most conditions, the probability of sea-bed smothering is low. Measured viscosities remain ≤200 mPa s for B0 and B10 and approach 400 mPa s only in the FAME sample, values that lie comfortably within the mechanical limits of weir and oleophilic drum or disc skimmers, thereby assuring skimmer operability even after substantial weathering.

Further, adhesion tests revealed slight variation over time, indicating that the interaction between biodiesel slicks and oleophilic recovery materials stays robust across the full response timeline, further validating continued reliance on conventional skimmer technologies. Although all three fuels entrain water rapidly, including FAME up to 50%, the resulting emulsions are unstable and break within about an hour once agitation ceases, enabling operators to decant excess water and thereby minimize secondary waste volumes. After roughly six days, natural dispersion carries fine droplets into the water column; in high-flow or irregular-bed environments, these droplets can reach sediment surfaces, complicating later remediation and highlighting the need for early interception or settling basins [51].

Moreover, persistent, solvent-insoluble surface foams and subsurface white agglomerates develop during weathering, threatening to clog booms and skimmers; therefore, response plans should include provisions for specialized foam collection or controlled sinking techniques. Mass-balance data indicate that approximately 30% of B0 and B10 evaporated while ≥30% biodegraded within four weeks. FAME showed negligible evaporation but nearly complete biodegradation, findings that collectively support a transition to monitored natural attenuation once primary slick removal is complete.

Finally, the authors recommended further testing of higher-blend fuels (e.g., B30 plus HVO) and a detailed characterization of foam and agglomerate formation so that forthcoming contingency plans can more precisely accommodate next-generation biodiesel cargoes [51].

The Oak Ridge National Laboratory report for the US MARAD [17] represents a seminal advancement in spill response science by systematically benchmarking the physicochemical behaviour of emerging nontraditional marine fuels, including FAME biodiesel and hydrotreated vegetable oil (HVO), against conventional marine distillates. Through integrated detection and monitoring protocols, this study established quantitative risk model parameters, such as evaporation rates, spreading coefficients, and emulsification tendencies, specific to biodiesel blends. Crucially, it introduces calibrated spectral and fluorescence-based sensors for the real-time field detection of biodiesel slicks, enabling more rapid containment decisions than those for petroleum alone. By synthesizing toxicity assays with hydrodynamic dispersion models, the project yields a novel framework for tailoring dispersant use to biodiesel's unique weathering profile. This represents the first cohesive dataset linking laboratory-derived weathering kinetics to full-scale spill modelling for non-traditional fuels. Its contribution lies in enhancing predictive accuracy of spill fate simulations, thereby informing both contingency planning and regulatory guidance for biodiesel-blend carriage. However, the study's-controlled experiments undermeasure complex oceanic variables, limiting the translatability of lab-based risk models to dynamic marine environments [17].

SINTEF Ocean's [59] laboratory investigation extends spill-response knowledge by elucidating the weathering behaviour and acute toxicity of FAME and HVO biofuels at Arctic temperatures (-2°C to 4°C). By coupling cold-chamber weathering trials with standardized algal and crustacean bioassays, this project uniquely delineates the temperature-dependent shifts in the viscosity, dissolution rates, and toxicity profiles of biodiesel blends. The research introduces a tailored efficacy assessment of approved chemical dispersants under freezing and near-freezing conditions, filling a critical data gap in polar spill-response protocols. Its novel output lies in the first comparative cold-climate dataset for both weathering kinetics and dispersant performance of biofuels versus marine diesel. This work contributes directly to refining Arctic-specific spill-response plans, ensuring that dispersant selection and application rates reflect the altered behaviour of biodiesel blends in ice-influenced waters. However, reliance on batch-scale laboratory chambers may not capture the full range of in situ Arctic mixing and ice-water interactions affecting biofuel spills [59].

Furthermore, the Canadian ESTS/NRC/DFO cluster delivers chemistry, toxicity, and in-situ countermeasure data regulators used on both sides of the Atlantic. WHOI's early biodegradation experiments supply the reaction-rate constants embedded in most public spill-fate models for biodiesel blends. SINTEF's cold-water test matrix and IOSC outputs translate those constants to real-world Nordic/Arctic conditions. OHMSETT and ORNL/MARAD validate whether existing booms, skimmers, dispersants, and sensors still work when low-viscosity oxygenated biofuels hit the water.

The work of institutions and individuals discussed here may, therefore, be regarded as the core knowledge network that response planners, modelers, and regulators may like to turn to when updating contingency plans or testing new equipment for accidental releases of biodiesel or renewable-diesel blends at sea.

Overall, the industry knowledge base related to biodiesel blends in shipping is growing, but it remains primarily focused on preventing operational issues rather than addressing post-spill environmental response. A notable absence of dedicated international guidance or standardized response protocols tailored explicitly for accidental releases of biodiesel blends into the marine environment prevails.

This highlights a clear gap in current knowledge and provides an important opportunity for future research to focus explicitly on the environmental fate, spill behaviour, response techniques, monitoring challenges, and long-term ecological impacts of biodiesel blends at sea.

2.1.4 Sufficiency of existing knowledge for biodiesel-blend spill contingency planning and response

Collectively, the research portfolio assembled gives contingency planners a baseline; it characterizes acute toxicity, biodegradation kinetics, cold-water weathering, and the performance of mainstream countermeasures (booms, skimmers, sorbents, dispersants) for the most common FAME and renewable-diesel blends. Recent practice-oriented syntheses such as ITOPF's 2024 fate-and-behaviour report, the IMO/PPR draft guidelines on local HNS-spill plans, and EMSA's 2024 bunkering-safety guide show that regulators are already distilling that data into operational advice.

■ Research contribution to biodiesel maritime spill response planning

A robust spill-response architecture spans the full incident lifecycle, blending preventive governance with adaptive field operations.

Preparedness hinges on contingency planning [81], risk appraisal, equipment stockpiles, and recurrent simulations that validate institutional readiness.

Timely detection, via satellite, aerial, and sensor networks, triggers rapid notification protocols linking responders and competent authorities [82].

Early situation analysis evaluates pollutant type, spill magnitude, meteorology, and the vulnerability of adjacent ecosystems and shipping lanes [83].

Strategic option selection then aligns mechanical, chemical, thermal, or biological techniques with fuel characteristics and environmental constraints.

Operational deployment translates plans into action through the coordinated mobilization of vessels, aircraft, containment gear, and shore-protection assets [84]. Specialized cleanup and habitat-protection teams work where coastlines are threatened to minimize ecological injury and expedite recovery [85].

Health-and-safety frameworks safeguard responders and local populations through exposure controls, protective equipment, and real-time monitoring [86].

Systematic waste management ensures recovered residues are segregated, transported, and treated in compliance with regulatory standards [87].

Finally, long-term monitoring, legal accountability, and after-action research feed a cycle of continuous improvement, the distribution of which is mapped in the accompanying table of 46 scholarly contributions.

Accordingly, these factors formed the basis for examining the contribution of literature to marine spill preparedness, planning and response operations, presented in Figure 7.

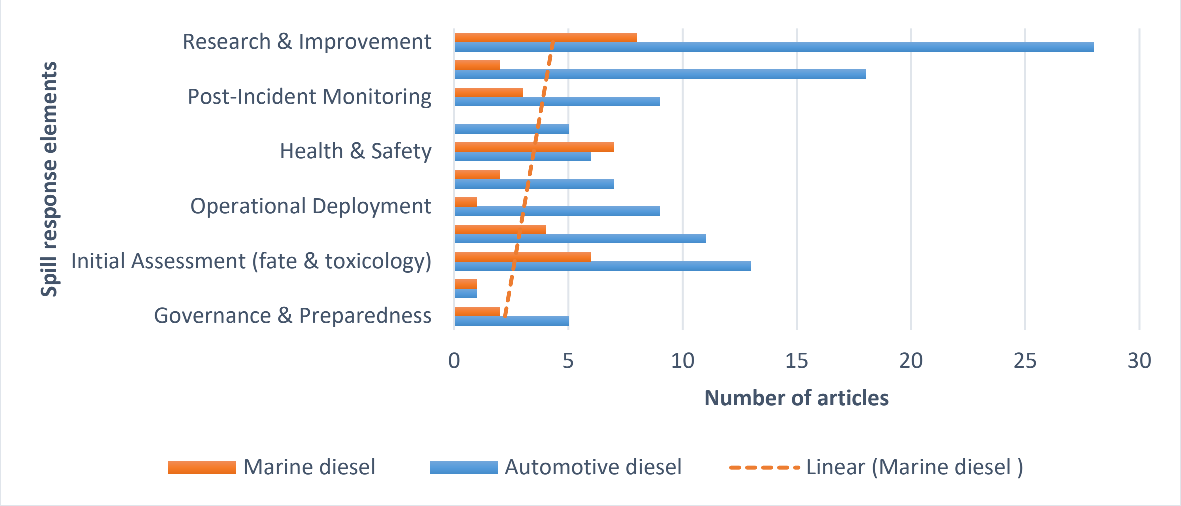


Figure 7. Distribution of literature on spill response planning elements (n=46) for spills of biodiesel blends with marine and automative diesel.

From Figure 7 it is evident that environmental restoration strategies, bioremediation, phytoremediation, and sediment amendment has attracted considerable attention in laboratory and pilot-scale studies for automotive diesel (eighteen articles). Yet only two explicitly evaluate their efficacy on marine diesel blends with biodiesel. This imbalance suggests that the unique physicochemical behaviour of biodiesel-blend slicks in saline environments (emulsification tendencies, altered biodegradation pathways) is not yet understood.

Initial fate and toxicological assessments of diesel spills likewise show a clear marine-diesel gap: while thirteen studies model contaminant distribution or perform ecotoxicity assays on automotive diesel, only six probe the fate or biological impact of marine diesel/biodiesel blends. Those can modify partitioning, bioavailability, and acute toxicity to plankton and benthic organisms. This shortfall represents a significant blind spot in risk assessment.

Concerning, perhaps, is the near-total absence of research on waste management for marine-diesel incidents. Whereas five papers consider handling treatment residuals or spent sorbents in the context of automotive diesel spills, none examine the disposal, recycling, or valorisation of wastes generated by marine-diesel/biodiesel spill responses. Similarly, rapid detection techniques, fluorescence, infrared spectroscopy, or remote sensing tuned to biodiesel-enriched fuel signatures represent only one marine-diesel study versus one diesel-focused paper, pointing to an urgent need for sensor development.

Operational-deployment studies (booms, skimmers, at-sea dispersant trials) and shoreline-clean-up experiments also reveal a marked bias toward laboratory surrogates rather than real-world marine-diesel blends. Nine articles evaluate mechanical or chemical response tools on generic diesel, but only one investigates these approaches on actual marine-diesel–biodiesel mixtures. This disconnect undermines confidence in field applicability and obscures potential interactions between dispersants and biodiesel esters.

In contrast, the health and safety literature show approximate parity, or even a slight predominance of marine, diesel work, reflecting several inhalation and dermal-exposure studies specific to crew and response personnel handling biodiesel blends. Yet without corresponding advances in detection, waste management, and operational trials, responder protection measures cannot be fully optimized for these newer fuels.

■ Literature on weathering process of biodiesel and biodiesel blends with automative diesel

In the environmental fate of biodiesel and biodiesel blends, a range of physicochemical and biochemical processes governs their transformation and ultimate removal from aquatic systems. Adsorption (sedimentation) describes the affinity-driven adherence of biodiesel constituents to particulate surfaces without penetration into their internal matrices. Concurrently, dissolution accounts for the solubilization of biodiesel components into the surrounding water column, while dispersion refers to the mechanical spreading of spilled fuel into the upper water layers under the influence of natural wave action or chemical dispersants [28]. Emulsification further contributes to this heterogeneity by forming stable, finely divided droplets of biodiesel within an immiscible aqueous phase. Volatilization processes, most notably evaporation, facilitate the transition of biodiesel molecules from the liquid phase into the atmosphere, whereas photo-oxidation entails sunlight-promoted reactions between dissolved oxygen and biodiesel constituents, leading to molecular alteration. Finally, biodegradation, mediated by bacteria, fungi, and yeasts, represents the microbial catabolism of biodiesel and its blends, whereby these organisms utilize fuel components as sources of metabolic energy [88].

An analysis of the reviewed literature reveals varying emphases on the weathering processes. Adsorption and dissolution have each been the focus of n=8 studies, representing the most intensively investigated pathways. Biodegradation and dispersion are closely followed, with n=6 investigations apiece. Photo-oxidation has been examined in n=5 instances, whereas evaporation accounts for n=4 studies. Emulsification is the least covered topic, with n=3 publications dedicated to its understanding. Figure 8 shows the weathering process covered by the literature for the period 1997-2024.

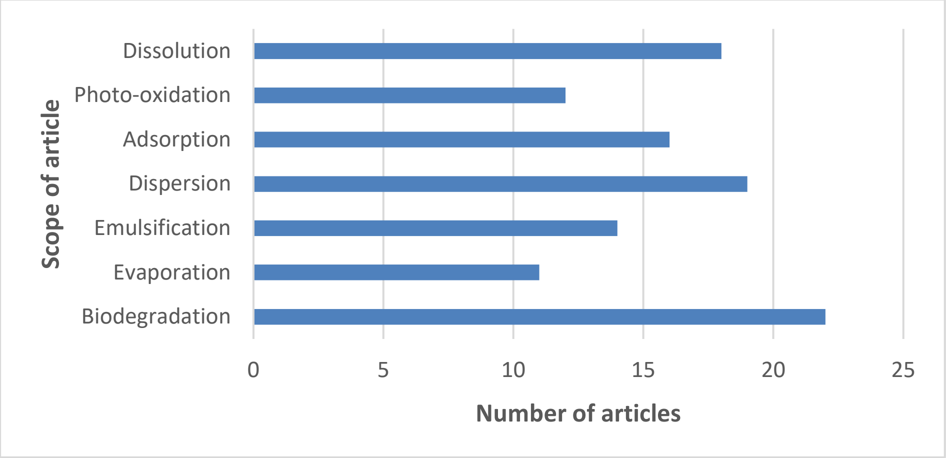


Figure 8. The weathering process covered by literature 1997-2024 (n=46).

■ Knowledge gaps identified across literature

- **Fuel diversity outpaces testing**. Current fate and countermeasure datasets focus on soy, rapeseed, or waste-oil FAMEs and a handful of hydrotreated vegetable oils; emerging algal, tall-oil, and co-processed refinery blends, and the additives they carry remain largely untested, so viscosity, solubility, and toxicity inputs in spill models can be off by an order of magnitude [17].
- **Field validation is thin**. Most biodegradation and countermeasure tests are conducted at laboratory scale or confined to mesocosms, wave-tank trials (OHMSETT), or flume tanks (SINTEF, CEDRE); only a few studies have examined open-water or under-ice releases. Planners therefore rely heavily on extrapolation to predict slick morphology, emulsification, and residue behaviour at scale [38], [89]. It is essential to conduct real-world trials to assess response techniques under realistic conditions.
- **Cold, deep, and mixed-fuel scenarios are under-represented**. SINTEF's Arctic matrices help, but data for sub-zero, high-salinity water columns, deep-sea plumes, and co-mingled spills (biofuel plus conventional diesel or lube oil) are sparse, leaving uncertainties for high-latitude shipping lanes and offshore bunkering hubs [59].
- **Chronic and food-web effects lag**. Acute LC_{50} and micro toxicity endpoints are well covered. However, few long-term or trophic-transfer studies exist for biodiesel oxidation products or burn/dispersant residues, which are important for Natural Resource Damage Assessment (NRDA) and shoreline-closure decisions [32], [30].
- **Detection and modelling tools need tuning**. Remote-sensing algorithms, air-monitor triggers, and fate models were built around petroleum signatures because oxygenated biofuels weather differently and can dissolve rather than float; both detection thresholds and reaction-rate constants still need systematic updating, particularly for rapid response software used by coast guards and port authorities. Clearly, a better experimental understanding of the fate of these products at sea must be pursued [17].

- **Regulatory harmonization is incomplete**. Draft IMO guidance and regional SOPs vary in recommended personal-protection levels, dispersant approvals, and waste-classification criteria; a unified, internationally accepted decision tree for biodiesel-blend spills remains a work in progress [62].

The current literature is strong enough to draft credible, evidence-based contingency plans. However, planners should treat those plans as living documents, build in adaptive monitoring, embed sensitivity analyses for fuel-property variability, and maintain R&D links with the key labs so that new fuel chemistries, toxicity findings, and field trials can be folded into response playbooks as they emerge.

2.1.5 Future research priorities for enhancing the understanding and management of biodiesel blend-related pollution incidents

Future investigations should prioritize the systematic characterization of biodiesel-blend physicochemical behaviour across salinity, temperature, and mixing regimes that are representative of polar, temperate, and tropical waters. While bench-scale data suggest rapid dispersion and variable emulsification, field validation remains limited, particularly for sub-zero and deep-plume scenarios—both of which our literature review identified as critical knowledge gaps.

To improve the accuracy of response efforts, multi-year mesocosm and open-water trials are essential for calibrating fate-and-transport models and remote-sensing algorithms, which are currently optimized for petroleum signatures. These efforts must also account for storage-induced aging effects, such as oxidation and settling, which are known to significantly alter fuel behaviour and toxicity during biodiesel spills.

To advance understanding and response capabilities for biodiesel spill incidents, the following actions should be considered:

■ Toxicity

Parallel toxicological studies should focus more specifically on commercially valuable marine species and move beyond acute LC_{50} endpoints to elucidate chronic, endocrine, and trophic-transfer effects of biodiesel oxidation products and combustion residues [89], [33].

■ Standards and guidelines

Regulatory research should examine implications of emerging fuel compositions on MARPOL Annex VI emission factors and spill liability frameworks, leveraging the evolving EU RED II Directive and Fuel EU Maritime Regulation. Socio-economic analyses are equally essential to quantify ecosystem restoration costs versus preventive quality-assurance measures along the fuel supply chain. While insights from voluntary schemes such as BQ-9000 demonstrate how rigorous testing and traceability mitigate downstream incident risks, converging these strands will generate the holistic evidence base necessary to anticipate the behaviour and impacts of future biodiesel-blend pollution events.

■ Accurate and real time detection and monitoring

Post-incident monitoring protocols should integrate molecular bio-indicators and remote sensing to track ecological recovery over multiple seasons, informing Natural Resource Damage Assessments [62].

Collaboration with quality-assurance schemes will ensure that pre-incident fuel testing data feed directly into spill predictive models, enhancing precision and accountability. Integration of sensor arrays, infra-red, fluorescence, and dissolved-oxygen probes, into autonomous platforms will enhance real-time detection of submerged biodiesel fractions, closing the monitoring gap highlighted by this report. Decision-support algorithms must assimilate these data streams, employing machine-learning techniques to forecast slick trajectories and recommend countermeasure mixes within minutes. However, validating such tools requires cross-disciplinary field exercises that embed scenario-based training for responders, regulators, and harbour masters, as emphasized in contemporary biofuel-safety guidance [17].

In addition, efforts must also focus on satellite remote sensing to effectively detect and track the drift of these products over time. This is particularly critical, as the ULSFO and VLSFO components that may be included in such fuels can exhibit highly atypical behaviours (e.g., slick fragmentation, buoyancy thresholds), making them difficult to detect.

■ Spill response tools

Operational research should optimize and validate response technologies under biodiesel-specific conditions to augment existing petroleum-oriented toolkits. However, large-scale trials at facilities such as CEDRE or OHMSETT reveal performance variability that demands systematic benchmarking across blend ratios and weathering stages.

Controlled wave-tank (flume tank) and HAZID studies report that conventional booms, skimmers, and dispersants are generally effective but require parameter adjustments for low-viscosity, oxygenated fuels [54], [17].

New generations of bio-based herding agents and green dispersants and cleaning agents warrant comparative efficacy and ecotoxicity testing under realistic energy dissipation rates [37], [41].

■ Spill response waste management

Research should also address adaptive waste-management strategies, recognizing that recovered biodiesel emulsions differ in phase behaviour and biodegradability from petroleum residues [48]. While policy-oriented research should propose globally harmonized waste classification and personal protection guidelines, resolving the inconsistencies in current regulatory gap analyses.

■ Degradation and weathering

Interdisciplinary consortia must standardize experimental protocols, ensuring that weathering, toxicity, and biodegradation results are comparable across geographic regions. Such harmonization will facilitate the inclusion of biodiesel-specific modules in international decision-support platforms, closing the detection and modelling gaps flagged by contingency planners.

Coupled laboratory-pilot scale (flume tank)–field datasets should feed open-access repositories to enable meta-analyses and accelerate numerical fate-and-transport and weathering model convergence, which predicts how biodiesel–diesel blends behave after a release [51].

■ Microbial dynamics

Particular attention is warranted for mixed-fuel releases, as co-mingling with lubricants or conventional diesel modifies dissolution kinetics and microbial degradation pathways [36], [29]. While comparative assays on varying feedstock-derived FAMEs and drop-in HVO blends will refine the biodegradation rate constants critical for next-generation spill simulators [59], [80].

■ Analytical methods

High-resolution chemical fingerprinting techniques, such as SPE-GC-MS profiling [90], must be advanced to support forensic source attribution during incident investigations.

It would also be beneficial to promote the establishment of networks of specialized laboratories for this type of analysis and encourage them to conduct inter-laboratory calibrations. This would enable them to test their analytical protocols and data processing methods, ensuring that different laboratories produce consistent results for a given sample.

■ Health impacts

Studies on crew health and safety must update exposure limits for aerosols, aldehydes, and methyl esters released during in-situ burning or high-pressure spraying operations [55], [45].

The previously mentioned operational research priorities will collectively accelerate the development of resilient, evidence-based response frameworks capable of safeguarding marine environments as well as the safety of responders in an era of diversified low-carbon fuels.

2.2 Physicochemical properties of blends of biodiesel with conventional marine bunker fuel

The ISO 8217 norm refers to the specifications of marine fuels. In its 2024 version, blends of conventional bunker fuel (LSFO, ULSFO, HSFO) with biodiesel are now possible up to 100%. Due to this regulatory change, new fuels are entering the marine fuel market. Until now, the fate and impact of biodiesel and marine fuel oil blends in the case of accidental spills have not been the subject of specific studies.

2.2.1 Biodiesel properties

In the 2024 version, ISO 8217 indicates that two biodiesels- FAME and paraffinic diesel - are used in blends with marine fuels. Based on experience from the automotive industry, FAME, HVO, and Fischer Tropsch are believed to have the greatest potential for application in marine diesel engines [1].

- **FAME: Fatty Acid Methyl Ester**

FAMEs are obtained through the transesterification reaction of triglycerides (found in vegetable oils, animal fats, and recycled cooking greases) with methanol. This reaction primarily uses homogeneous or heterogeneous catalysis, involving soluble or insoluble catalysts in the reaction medium. Homogeneous catalysis has been the most industrialized technique in recent years, with production units based on a continuous process.

In comparison, heterogeneous catalysis offers the advantage of eliminating nearly all pollutant emissions and producing higher-purity co-products that can be valorised without prior purification treatment. The transesterification of triglycerides also leads to the co-formation of glycerine (or glycerol), and in the case of fatty acids derived from crushed seeds (e.g., rapeseed, soybean, sunflower), also results in meal. Glycerine is valorised in the cosmetics, pharmaceutical, and food industries, while the meal can be used for animal feed.

In addition to homogeneous and heterogeneous catalysis, other FAME production techniques based on microwave heating [2] or enzymatic catalysis are currently being developed (e.g., at Petrobras in Brazil or by the company Bioenergy Pilot) [3].

The transesterification reaction can also be carried out by replacing methanol with ethanol, producing a fatty acid ethyl ester (FAEE). Compared to methanol, ethanol presents technical production challenges such as lower yields or the need for a second transesterification step, one of which involves homogeneous catalysis. Although FAEEs have fuel properties like FAMEs, this reaction is still under development.

FAME has the general molecular structure $CH_3(CH_2)_nCOOCH_3$ (saturated) and $CH_3(CH_2)_n(CH)COOCH_3$ (unsaturated). Examples of FAME produced from the main vegetable oils used in biodiesel production are summarized in Table 1 [4].

Table 1. Different fatty acids present in FAME biodiesel (GCMD, 2024).

Common name	IUPAC nomenclature	Abbreviation*
Caproic acid	n-Hexanoic acid	C6:0
Caprylic acid	n-Octanoic acid	C8:0
Capric acid	n-Decanoic acid	C10:0
Lauric acid	n-Dodecanoic acid	C12:0
Myristic acid	n-Tetradecanoic acid	C14:0
Palmitic acid	n-Hexadecenoic acid	C16:0

Palmitoleic acid	Hexadec-9-enoic acid	C16:1
Stearic acid	n-Octadecanoic, acid	C18:0
Oleic acid	cis-9-Octadecenoic acid	C18:1-cis
Elaidic acid	trans-9-Octadecenoic acid	C18:1-trans
Linoleic acid	9,12-Octadecadiecoic acid	C18:2
Linolenic acid	9,12,15-Octadecatrienoic acid	C18:3
Arachidic acid	n-Eicosenoic acid	C20:0
Gondoic acid	11-Eicosenoic acid	C20:1
Behenic acid	n-Docosanoic acid	C22:0
Lignoceric acid	Tetracosanoic acid	C24:0

*Referring to Cxx:y, when xx represents the total number of carbon atoms in the fatty acid and y refers to the number of double (unsaturated) bonds in it

■ HVO: Hydrotreated Vegetable Oils

Unlike FAMEs containing oxygen, HVO are free from oxygen-containing molecules. They are produced through the complete hydrogenation of triglycerides (found in vegetable oils, animal fats, or even algae), carried out via an initial catalytic hydrotreatment step under hydrogen pressure and at high temperature. This reaction primarily forms linear paraffins, propane, water, and carbon dioxide.

A second step is then required to ensure that the resulting HVOs meet fuel specifications allowed on the market, particularly regarding the cold filter plugging point and flow properties of the biodiesel produced. This step, called hydro-isomerization, involves using pressurized hydrogen to generate molecules with the same composition but with more branched carbon chains. This transformation improves the cold flow properties of HVOs.

Oil hydrogenation is performed in a dedicated production unit or via co-processing in a diesel refinery. Hydrotreatment systems for lipids are more expensive for an equivalent capacity than FAME production units [3].

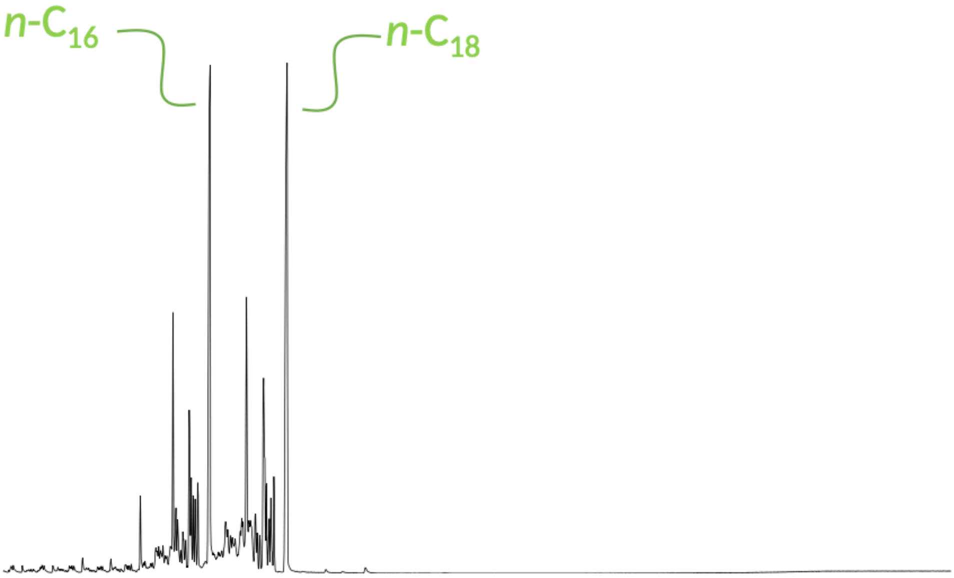


Figure 9. Example of a GC/MS chromatogram (scan mode) of an HVO.

FT: Fisher-Tropsch

Fischer–Tropsch (FT) diesel is a synthetic diesel that results from the FT-synthesis technology pioneered by the Germans in the 1920s. This technology was initially aimed at producing hydrocarbon molecules from coal [5]. The Fischer–Tropsch process converts carbon-containing feedstocks (such as biomass, natural gas, or coal) into liquid hydrocarbons, including a diesel-like fuel. The Fischer–Tropsch synthesis requires a combination of chemical reactions for synthesizing hydrocarbons from a mixture of carbon monoxide and hydrogen. The process, a key component of gas-to-liquid (GTL) technology, produces a petroleum substitute for synthetic lubrication oil and synthetic fuel.

The overall process can be divided into three steps, with each step taking place in the presence of a specific catalyst [6], [7]:

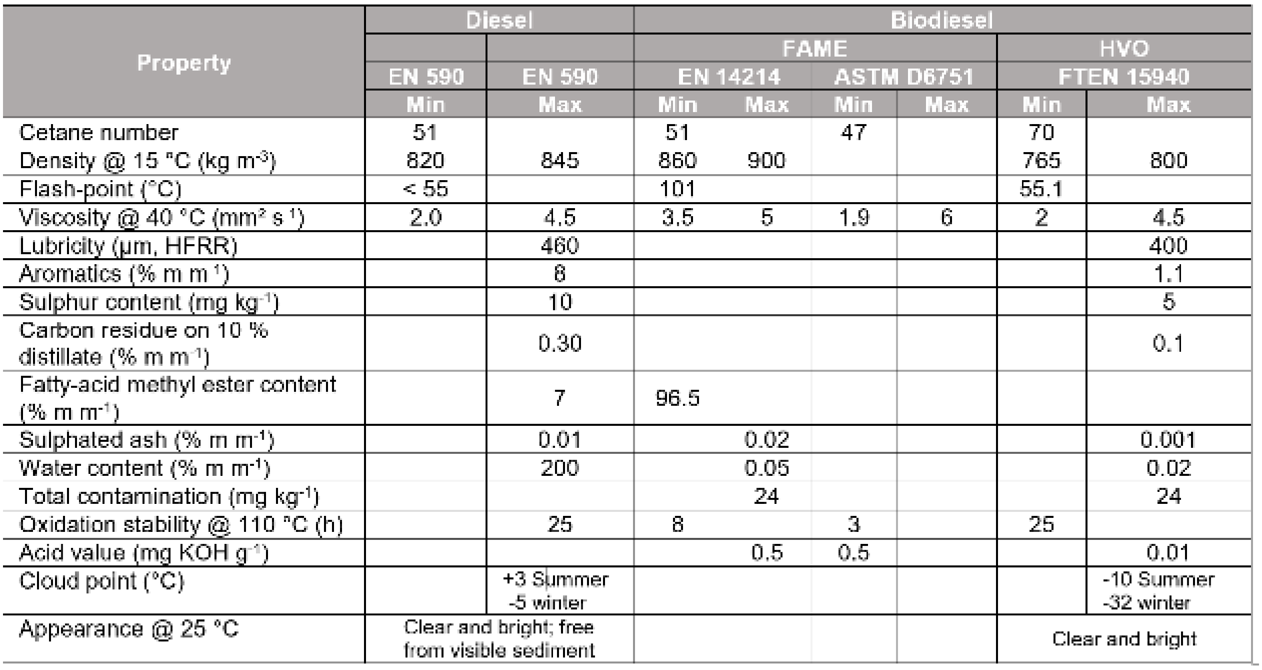
- **Step 1: Syngas formation**: Biomass (wood, agricultural waste, etc.) is gasified to produce syngas (a mix of CO and H_2).
- **Step 2: Fischer–Tropsch reaction**: The syngas is passed over a catalyst (typically iron or cobalt) under high temperature and pressure. This forms long-chain hydrocarbons (paraffins), which can be refined into diesel-range molecules.
- **Step 3: Refining**: The raw FT product is refined to produce a synthetic diesel.

Fischer–Tropsch biodiesel is like fossil diesel regarding its energy content, density, viscosity, and flash point. It is a high-quality, clean transportation fuel with suitable characteristics for diesel engines [8], [9].

Table 2 presents the physicochemical properties of FAME, HVO, and FT biodiesels.

Table 2 Physicochemical properties of diesel and biodiesels (FAME, HVO, and FT) according to international standards (EN 590, EN 14214, ASTM D6751, and EN 15940)

(Note: HVO and FT biodiesels specifications refer to the same standard EN 15490)



Property	Diesel		Biodiesel					
			FAME				HVO	
	EN 590	EN 590	EN 14214		ASTM D6751		FTEN 15940	
	Min	Max	Min	Max	Min	Max	Min	Max
Cetane number	51		51		47		70	
Density @ 15 °C (kg m^{-3})	820	845	860	900			765	800
Flash-point (°C)	< 55		101				55.1	
Viscosity @ 40 °C (mm² s^{-1})	2.0	4.5	3.5	5	1.9	6	2	4.5
Lubricity (μm, HFRR)		460						400
Aromatics (% m m^{-1})		8						1.1
Sulphur content (mg kg^{-1})		10						5
Carbon residue on 10 % distillate (% m m^{-1})		0.30						0.1
Fatty-acid methyl ester content (% m m^{-1})		7	96.5					
Sulphated ash (% m m^{-1})		0.01		0.02				0.001
Water content (% m m^{-1})		200		0.05				0.02
Total contamination (mg kg^{-1})				24				24
Oxidation stability @ 110 °C (h)		25	8		3		25	
Acid value (mg KOH g^{-1})				0.5	0.5			0.01
Cloud point (°C)		+3 Summer -5 winter						-10 Summer -32 winter
Appearance @ 25 °C	Clear and bright; free from visible sediment						Clear and bright	

Figure 10 presents examples of viscosity and density values for different FAMEs (rapeseed, soya, cotton, linen, sunflower, palm, peanut, corn, tallow, lard), HVOs, and FT. This data highlights that FAMEs, FTs, and HVO biodiesels present properties within the same range:

- the density ranges from 0,72 for the FT biodiesel up to 0,87 for the FAMEs; and
- the viscosity value ranges from 2 mm²/s for FT biodiesels up to 4,9 mm²/s for FAMEs.

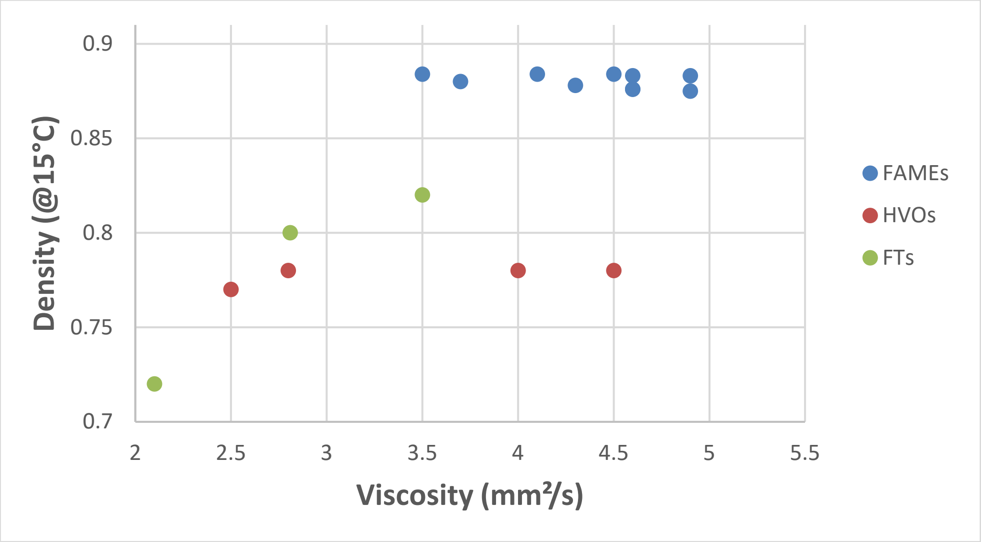


Figure 10. Examples of viscosity and density values for different biodiesels.

2.2.2 Conventional marine fuel properties

■ Marine fuel classification: ISO standards

ISO 8217 is the international standard for marine fuel specifications. It outlines the general requirements, testing methods, and specifications for marine fuels (distillate and residual) used in ships' engines and boilers, for any on-board operations (storage, decanting, centrifuging, filtration, heating) before use. ISO 8217 covers fuel grades and classifications, physicochemical properties, and testing methods. It defines acceptable properties such as density, viscosity, sulphur content, flash point, pour point, and carbon residue. The 2024 edition [10] incorporates biofuels, specifically allowing FAME blends up to 100% (B100). This inclusion supports the maritime industry's transition to renewable energy sources and ensures that biodiesel blends with marine fuel meet stringent performance standards for engine efficiency and reliability.

The fuel grades are classified following ISO 8216-1[11], and include two categories of marine fuel namely, residual marine fuels and distillate marine fuels.

- **Residual marine fuels** (**RM**) (Figure 11): These fuels are more commonly known as Heavy Fuel Oil (HFO). They mainly contain heavy, refined cuts blended with a lighter cutter stock. This blend produces a fuel that meets the specifications required for its intended use, particularly viscosity [12]. Three appellations are generally used to differentiate residual marine fuel according to their sulphur content: **ULSFO** (Ultra Low Sulphur Fuel Oil) with sulphur content below 0.1%, **VLSFO** (Very Low Sulphur Fuel Oil) with sulphur content below 0.5% and **HSFO** (Heavy Sulphur Fuel Oil) with sulphur content over 0.5%. Depending on the physicochemical properties and use of the fuel, different appellations are defined in the ISO 8217: 2024:

    i. **RM** letters are used for fuel without FAME. **RM** is followed by:

      1. a letter “**A** / **E** / **G** / **K**” indicating the maximum carbon residue content (in mass%) ranging respectively from 10%, 15%, 18% up to 20%;
      2. a number indicating the maximum kinematic viscosity at 50°C, ranging from 20 mm²/s to 700 mm²/s; and

      3a. a number referring to the maximum sulphur content (0.1% or 0.5%), or

      3b. the letter **H** for fuel with a sulphur content over 0.5%

    ii. **RF** letters are used exclusively for residual marine fuel blended with FAME at a concentration agreed between the buyer and the seller. **RF** letters are followed by a number indicating the maximum kinematic viscosity at 50°C, ranging from 20 mm²/s to 500 mm²/s.

- **Distillate marine fuel** (**DM**) refers to lighter refined cuts with a sulphur content of 1.5% or less (Figure 12). The DM grades can contain up to 100% paraffinic diesel (HVO or FT). In this class of fuel, distinctions are made between:
    - i. **DMA and DMZ fuels** are in the form of a clear, yellow liquid. The two fuels differ in the minimum viscosity value (2 mm²/s for DMA; 3 mm²/s for DMZ).
    - ii. **DFA** and **DFZ** designate the bio-distillate counterparts of DMA and DMZ, respectively. In these two fuels, FAME biodiesels are present as a "renewable base" at a concentration up to 100%.
    - iii. **DMX** refers to a fuel lighter than **DMA**, with a low cloud point and a minimum flash point of 43°C (instead of 60°C for other DM grades), which requires drum storage. This storage constraint means that the fuel is rarely used.
    - iv. **DMB** grade (and its 'bio' counterpart, DFB) refers to a fuel heavier than other marine distillates.

Even if they do not refer specifically to a standard, two names are commonly used to designate "marine" distillate [12]:

- **Marine gas oil** (**MGO**) class, which includes DMA / DFA / DMZ / DFZ fuels (clear, limpid fuels) that can present various colours depending on their use; and
- **Marine diesel oil** (**MDO**) includes only DMB / DFB fuels heavier than other DM grades.

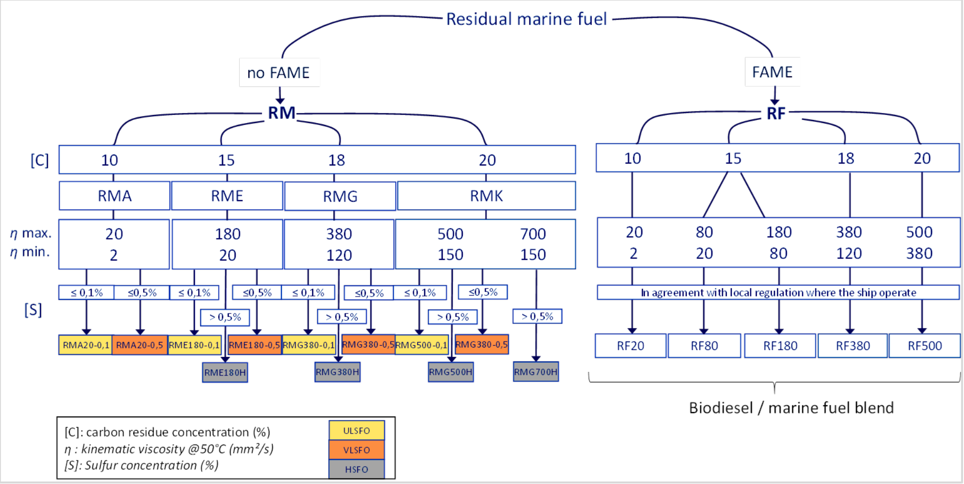


Figure 11. Main physicochemical properties used to differentiate residual marine fuel.

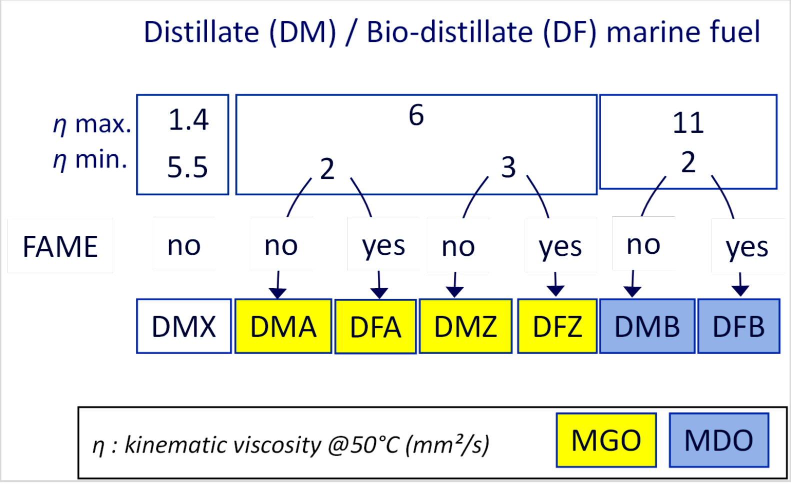


Figure 12. Main physicochemical properties used to differentiate distillate marine fuel.

■ Comments on residual fuel oils' properties

Unlike distillate fuel oils, residual fuel oils display significantly broader physicochemical properties, especially viscosity, density, and pour point value. Consequently, the chemical composition of the two products, although classified under the identical designation, may differ substantially. Figure 13 presents analytical results presented by the Intertek laboratory on residual fuel oil samples collected from various maritime companies. VLSFOs are characterized by a low viscosity but show a wider range of pour points than other residual fuels (ULSFO, HSFO). The variability in pour point measurements constitutes critical information, as all VLSFO present a unique composition: an “average” VLSFO does not exist.

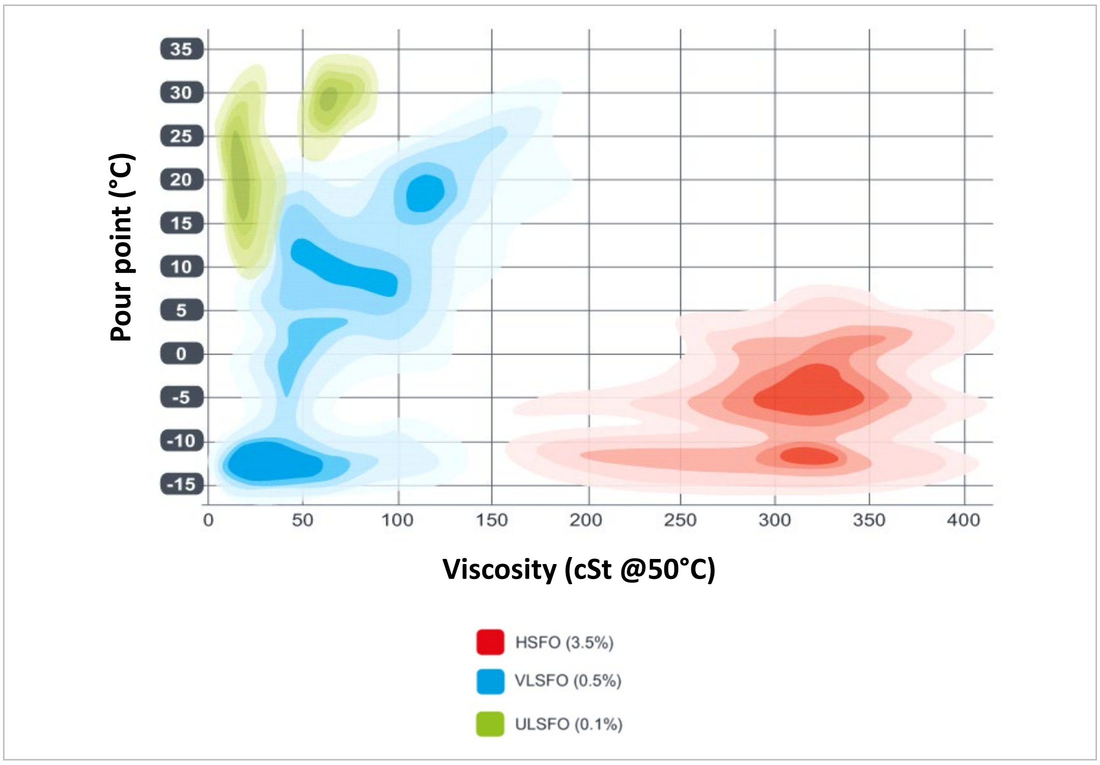


Figure 13. Example of viscosity vs pour point for LFSO (VLSFO and ULSFO) compared to HSFO analyses.

■ Comments on distillate fuel oils’ properties

The physicochemical properties of marine distillates are uniform for each measured parameter. Consequently, similar slick behaviour can be expected for the different distillate fuel oils in the case of an accidental spill. At most, variations in slick colour may be observed during aerial surveillance due to the addition of colour dyes required by national regulations. This is notably the case for fishing gasoil (DMA), which may be blue in France, red in the UK, or green in Ireland, among others.

2.2.3 Properties of biodiesel blends with conventional marine fuel oil

■ Identification of most “popular” biodiesel blends with marine fuel oil

The properties of blends can change depending on the nature and proportion of the biodiesel and the nature of the marine fuel (distillate fuel or residual fuel). A market study of marine fuel bunkering was conducted to select the most widely used fuels. Figure 14 presents residual fuel oil sales for the ports of Rotterdam and Singapore, the two main hubs for marine fuel supply. The port authorities of the two locations published these data [13], [14].

In both Rotterdam and Singapore, VLSFOs had the highest sales volume from 2021 to 2024. The increase in HSFO sales at the Port of Rotterdam reflects the progressive adoption of scrubbers on ships, which are essential for the continued use of this fuel type.

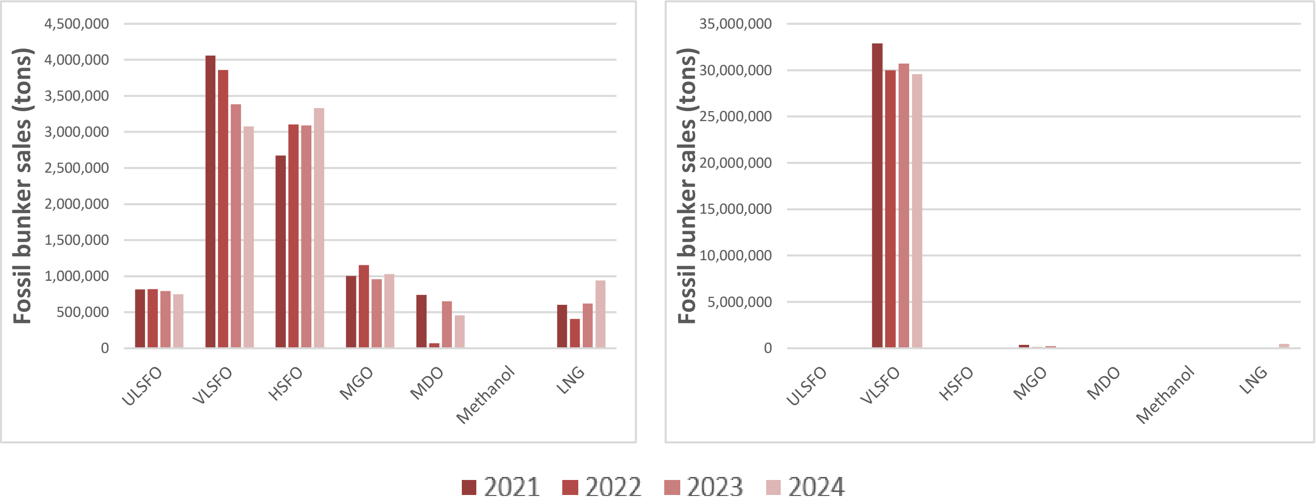


Figure 14. Evolution of residual fuel sales in Rotterdam port (left) and Singapore port (right).

Regarding the nature of the residual fuel oil used to formulate the blends, Figure 15 presents the sales of biodiesel and marine fuel blends for the two ports. This figure highlights that VLSFOs are currently the most used blend production components.

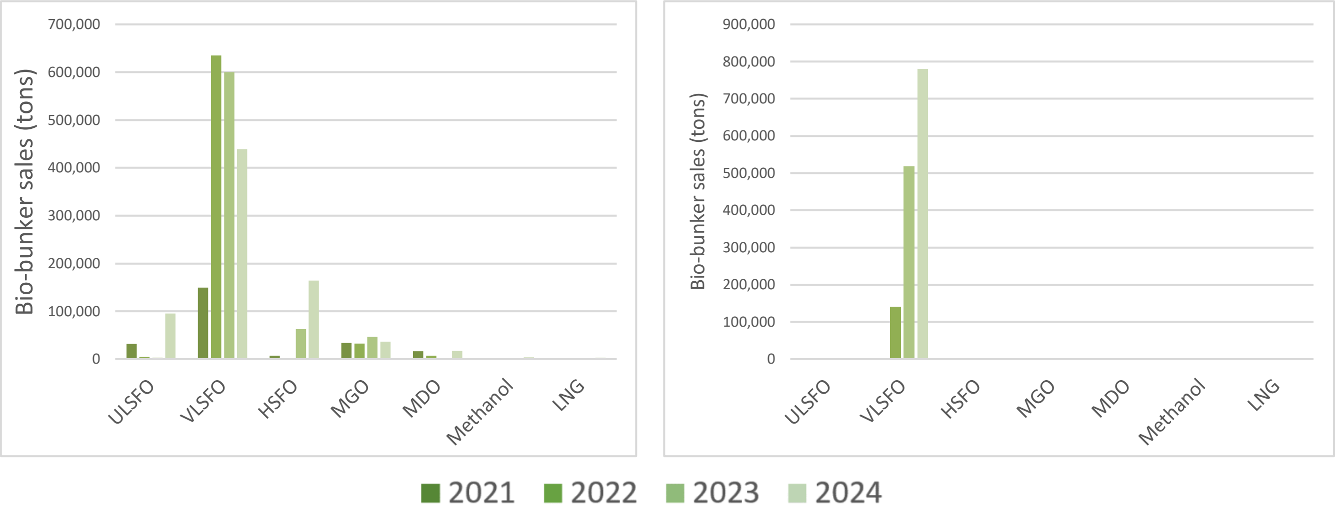
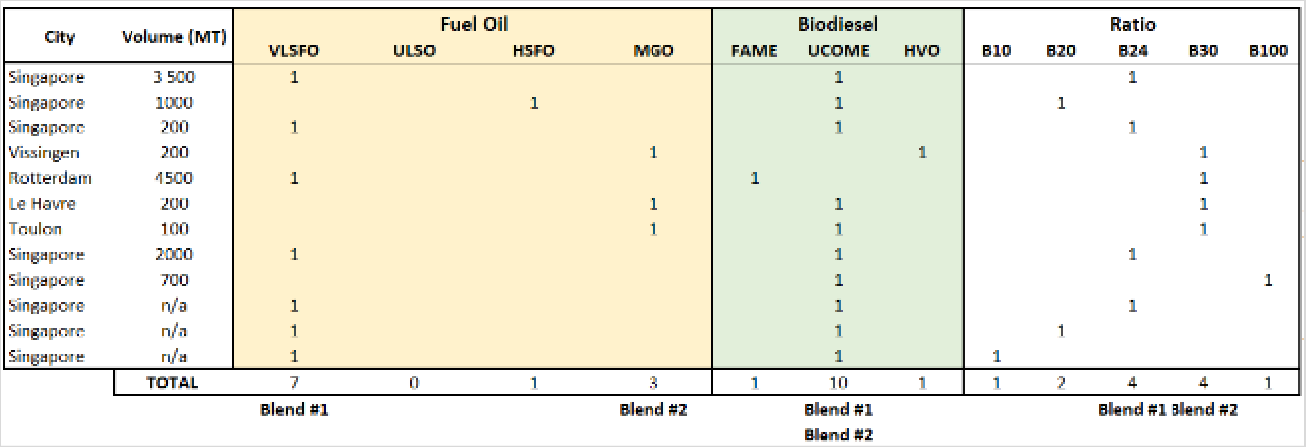


Figure 15. Evolution of biodiesel blend sales with residual fuel in Rotterdam port (left) and Singapore port (right).

Regarding the nature and proportion of biodiesel in the blends, Table 3 summarizes fuel bunkering trials conducted by various oil companies between 2022 and 2024 [15]. This data compilation highlights that the bunkering trials have primarily focused on two types of blends:

- Blend # 1: VLSFO with UCOME at a ratio of 24% biodiesel; and
- Blend # 2: MGO with UCOME at a ratio of 30% biodiesel.

Table 3. Details on biodiesel with marine fuel blends bunkering trials for the 2022 – 2024 period.



City	Volume (MT)	Fuel Oil				Biodiesel			Ratio				
		VLSFO	ULSO	HSFO	MGO	FAME	UCOME	HVO	B10	B20	B24	B30	B100
Singapore	3 500	1					1				1		
Singapore	1000			1			1			1			
Singapore	200	1					1				1		
Vlissingen	200				1			1				1	
Rotterdam	4500	1				1						1	
Le Havre	200				1		1					1	
Toulon	100				1		1					1	
Singapore	2000	1					1				1		
Singapore	700						1						1
Singapore	n/a	1					1				1		
Singapore	n/a	1					1			1			
Singapore	n/a	1					1		1				
	TOTAL	7	0	1	3	1	10	1	1	2	4	4	1
		Blend #1			Blend #2		Blend #1 Blend #2				Blend #1 Blend #2		

Evolution of marine fuel oil properties blended with biodiesel

As many recent projects have focused exclusively on LSFO or biodiesel, there is a lack of scientific studies on biodiesel blends with marine fuel. During the literature review, the study identified only one relevant scientific publication specifically dealing with these blends. Kass et al. [16] investigated the evolution of the physicochemical properties of biodiesel blended with a VLSFO as a function of biodiesel proportion (ranging from 5% to 30%) (Figure 16). The data presented in this study (red plots) have been compiled with data from studies exclusively focused on VLSFOs (blue plots). The raw data are provided in Table 4.

Table 4. Compilation of VLSFO physicochemical properties from literature and Cedre laboratory.

Sample	Pour point	Viscosity		Asph %	Wax %	Density	Flash point (°C)	References
		50 °C	15 °C					
#1	9	283						Cedre (HC-24-69)
#2	9	352						Cedre (HC-24-84)
#3	–12	49.38						Cedre (HC-24-147)
#4	–15	34.58						Cedre (HC-24-148)
#5	–6	217						Cedre (HC-24-150)
#6	–6	86.82						Cedre (HC-24-153)
#7	27	187						Cedre (HC-24-180)
#8	6	303						Cedre (HC-24-181)
#9	12	322						Cedre (HC-24-124)
#10	27	124						Cedre (HC-24-195)
#11	9		4977	0.52	5.4	0.908	84	Daling & Sørheim (2020)
#12	9		5550	0.44	4.5	0.989	109	Daling & Sørheim (2020)

#13	3		19450	4.8	4.9	0.990	100	Daling & Sørheim (2020)
#14	–3	3.4				0.8573		Kim et al. (2023)
#15	2	5.9				0.8969		Kim et al. (2023)
#16	–36	37.1				0.9887		Kim et al. (2023)
#17	25	113.3				0.9923		Kim et al. (2023)
#18	17	118.1				0.9899		Kim et al. (2023)
#19	–15	133.6				0.9318		Kim et al. (2023)
#20	–1	141.7				0.9276		Kim et al. (2023)
#21	–6	157.3				0.9418		Kim et al. (2023)
#22	0	509.2				0.995		Kass et al. (2022)
#23	–6	268.2				0.989		Kass et al. (2022)
#24	–12	157.7				0.983		Kass et al. (2022)
#25	–18	102.7				0.977		Kass et al. (2022)
#26	–24	68.91				0.971		Kass et al. (2022)

This study highlights:

- a decrease of pour point values as the biodiesel percentage increases, initially measured at 0°C for B0, the pour point decreases to -25°C for B30[7]; and
- viscosity significantly decreases with increasing biodiesel content: measured at 510 cSt (at 50°C) for pure VLSFO, it decreases to 70 cSt for B30.

In the context of defining anti-pollution response strategies, the evolution of these two parameters has a significant impact. Indeed, while VLSFO behaves like a semi-solid product that is difficult to recover using conventional skimmers, the B30 blends appear as a liquid with physical properties similar to those of a heavy fuel oil such as RM80, which can be recovered using skimmers and potentially dispersed chemically. These insights are based on the interpretation of literature data [17]. Blends of various VLSFOs with different proportions of FAME were prepared as part of this study to validate them.

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[7] It is important to note that the pour point of pure biodiesel (i.e., B100) is approximately -3°C. Therefore, it is somewhat surprising that blending this biodiesel with a VLSFO, with a pour point measured at 0°C, results in mixtures exhibiting pour points lower than those of the pure components. The author of the original study was contacted by Cedre and acknowledged the unusual nature of these results, although no clear explanation could be provided. The present study offers an opportunity to further investigate this observation.

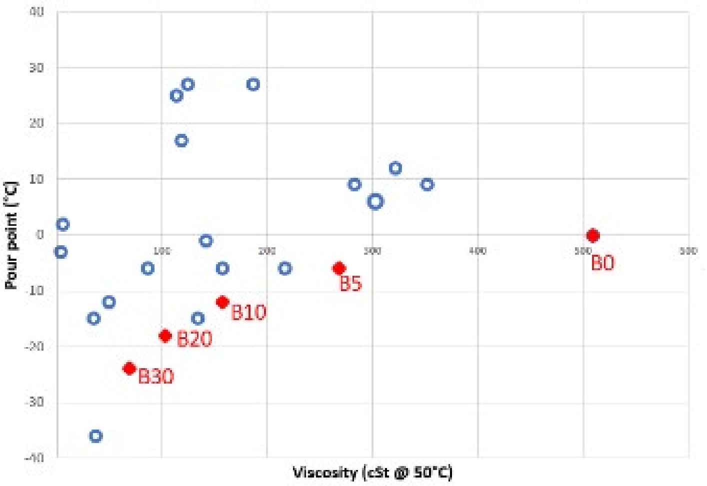


Figure 16. Examples of viscosity values (cSt @50°C) and pour point (°C) for VLSFOs (blue plots) and for VLSFO blends with biodiesel (red plots — the number indicates the biodiesel percentage).

2.2.4 Behaviour of biodiesel blends with conventional bunker fuels in case of accidental spill

The weathering of petroleum products (crude oil, gasoline, heavy fuel oil) is complex, as different processes (evaporation, dispersion, emulsification, photo-oxidation, …) take place simultaneously, mainly governed by environmental conditions. In addition, each product has its own chemical composition, and the extent of the various processes depends on its initial physicochemical characteristics.

To assess the fate and behaviour of dedicated oil in case of accidental release, the following approaches can be considered, from the simplest to the most complicated ones:

- The initial physicochemical characteristics can be used to get a general idea of its fate (density is representative of the buoyancy), its distillation curve provides a reliable estimation of the maximum evaporation rate, the viscosity informs on the spreading and potential use of response techniques. This set of data can also be implemented in modelling software such as ADIOS 2 which only deals with initial properties.
- Laboratory protocols can be applied to assess more realistically the oil weathering, and to get additional information such as the time-window of opportunity for dispersant use. Evaporation can be simulated by a simple distillation at various temperatures while the Mackay method using rotary funnels is used to create water-in-oil emulsions. However, no laboratory method considers all the parameters simultaneously, which are affected by the interactions between various phenomena: evaporation is limited by the formation of emulsions; the emulsification process can be balanced with natural dispersion. These results, in addition to initial characteristics, can also be implemented modelling software.
- Finally, pilot scale experiments can be conducted to simulate these various processes realistically and simultaneously. Cedre has equipped its facilities with a hydraulic canal in which different marine (as well as inland) water conditions can be recreated: wind, current, waves, and solar radiations. With this equipment, it is possible to weather dedicated oil in similar climatic conditions as the ones that can be encountered in the oil field from which it is extracted (or the area of shipment). Samples are regularly taken to monitor the evolution of the physicochemical properties.

■ Physicochemical characterisation

In terms of oil spill response, viscosity, density, and pour point are key parameters for predicting oil slick behaviours and defining response strategies. Four VLSFOs were selected from several VLSFO samples to cover a range of viscosities (from 10,000 cSt up to 50,000 cSt @15°C).

Figures 17 and 18 present the viscosity, density, and pour point measures of biodiesel blends with marine fuel for different biodiesel proportions (5%, 10%, 20%, 24%, 30%, and 50%). These results highlight:

- a slight decrease in density while VLSFO is blended with FAME;
- a significant decrease in viscosity for each VLSFO blended with FAME; and
- a decrease in the pour point value while the biodiesel part increases. This decrease is observed from 30% of biodiesel in the blend.

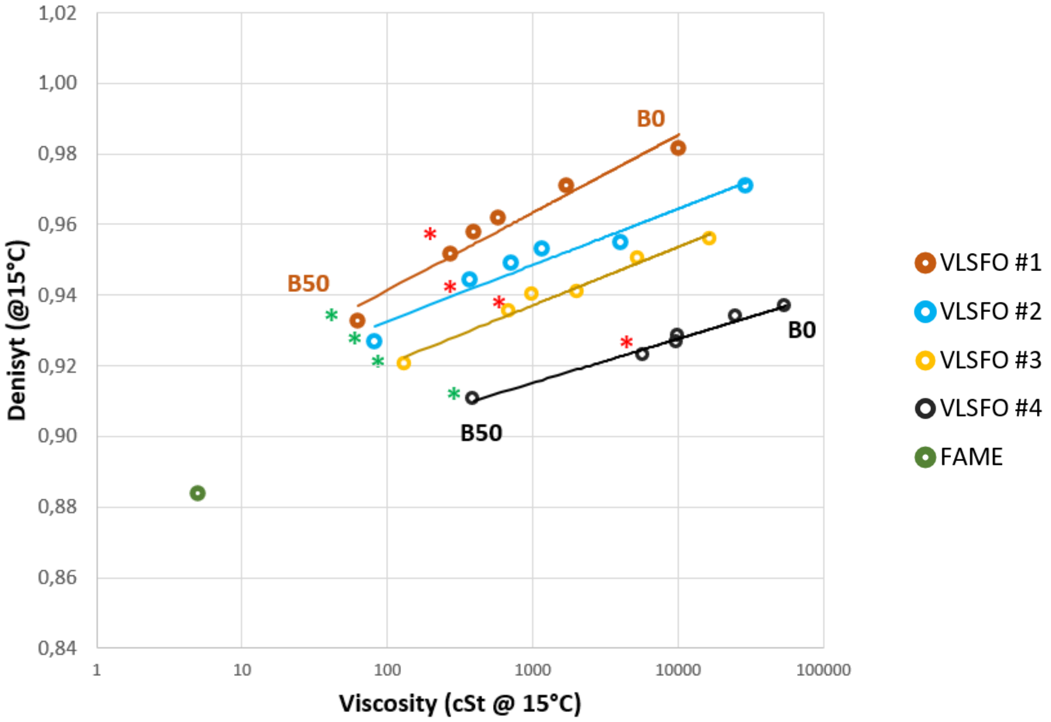


Figure 17. Variation of viscosity and density measures of 4VLSFO blended with FAME at a ratio of 0%, 10%, 20%, 24%, 30%, and 50%.

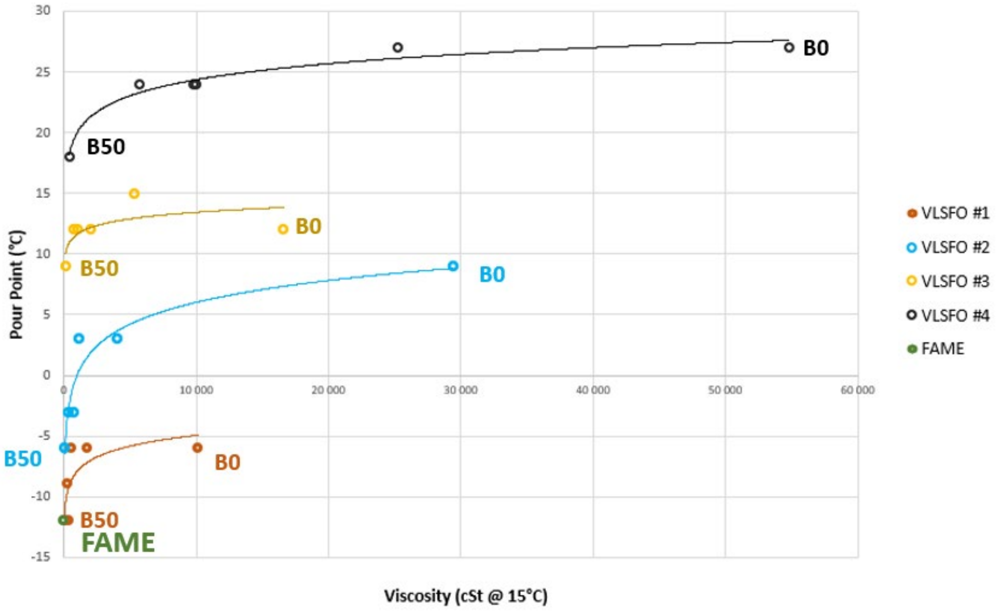


Figure 18. Variation of viscosity and pour point measures of 4VLSFO blended with FAME at a ratio of 0%, 10%, 20%, 24%, 30%, and 50%.

Based on these preliminary results, we can expect that the addition of FAME to a VLSFO (whatever the VLSFO properties):

- has no consequences on oil slick buoyancy; and
- increases oil spreading due to the decrease in viscosity and pour point.

These evolutions of physicochemical properties suggest that adding biodiesel to a VLSFO will impact the definition of oil spill response strategies, such as mechanical recovery efficiency or chemical dispersion windows of opportunity. These preliminary observations will be studied during weathering studies performed at a pilot scale in Cedre's flume tank.

Regarding the evolution of biodegradability according to biodiesel proportions in the blends, Figure 19 presents the results obtained after 28 days of blends' exposure to marine bacteria consortium in optimized conditions. The degradation rates presented in this figure correspond to the influence of the biodegradation process as well as the evaporation process, two weathering processes that occur simultaneously.

Figure 19 reflects the influence of FAME addition on the global degradation of blends. FAME is known to be refractory to the evaporation process but highly sensitive to the biodegradation process (Jézéquel et al., 2024; Cedre, 2024). Consequently, while FAME proportion increases in the blend, its natural degradation rate increases at the same time. This is clearly observed in Figure 19, especially for the VLSFO #1 and #2. For the two other VLSFO, the influence of FAME addition on the degradation rate is not so clear for FAME proportions below 30%. This effect can be related to the semi-solid state of these two products - due to their high pour point value – which affects the oil bioavailability to the bacterial activities. For a FAME proportion from 30%, it seems that the bioavailability increases due to a more significant spread of the oil compared to the other blends (0, 10, 20, and 24%).

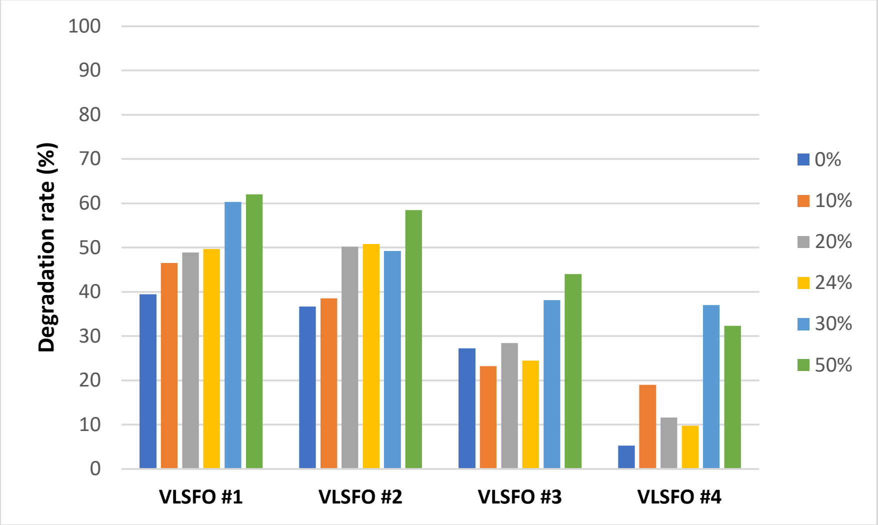


Figure 19. Evolution of degradation rate of blends of FAME with 4 VLSFO.

■ Fate and behaviour of alternative fuels in the marine environment under different weather conditions: Oil weathering study at pilot scale

The oil weathering is evaluated using Cedre's hydraulic canal, the Polludrome®, which simulates open sea conditions (Figure 20). Pilot-scale tests offer the advantage of being conducted under conditions that closely resemble the real environment. They are carried out over a minimum duration of 7 days, during which the monitoring of physicochemical parameters helps to better understand the kinetics of product weathering in the first hours after their release. In the case of an accidental spill, this time window is particularly important to monitor, as it corresponds to the period during which the spilled product can change very rapidly, which will influence the response strategies to be implemented. Description of the weathering test protocol is presented at Annex IV.

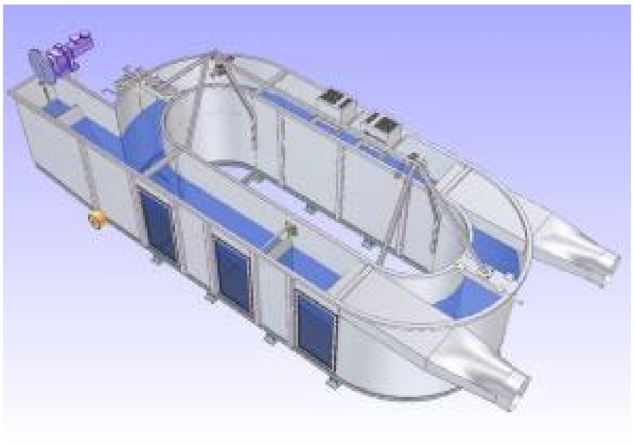
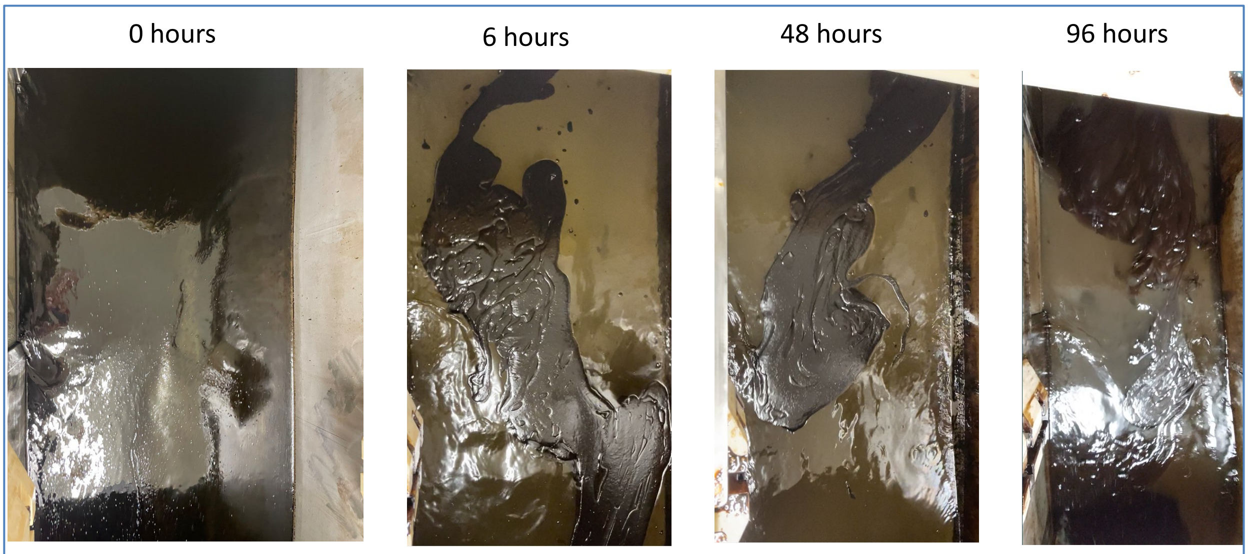


Figure 20. The Polludrome

The following section describes the evolution of the physicochemical properties of blends under various environmental conditions and test protocols. The different parameters were plotted against the weathering time, and where possible, regression models were applied based on statistical analysis using Sigmaplot 16.0 software.

- **Evolution of the physicochemical properties of the B30 FAME/ VLSFO**

Figure 21 presents the evolution of the B30 FAME/VLSFO slick during the weathering test at pilot scale. Initially, the blend is a liquid black product which spread rapidly to cover the surface of the Polludrome®. After a few hours of weathering, the oil slick is fragmented into large lumps/ patches distributed over the surface of the tank surface. The water column gradually becomes turbid and takes on a yellowish tint. After 2 days of weathering, viscous brown patches of oil are observed at the water surface of the tank. During agitation period, a submersion of small patches of oil is observed in the water column.



0 hours

6 hours

48 hours

96 hours

Black and liquid oil slick covering the entire surface of the tank.

Black / brown slick fragmented into large lumps. Water column color turn yellow / brown due to dispersion.

Brown lumps distributed over the water surface.

Figure 21. Evolution of the B30 FAME/VLSFO appearance according to the weathering duration.

○ *Viscosity*

Figure 22 presents the evolution of B30 FAME/VLSFO blend viscosity during the weathering experiment. The viscosity increases rapidly as soon as the oil is released. Initially measures at 156 mPa.s, the viscosity reached 3830 mPa.s after 24 hours of weathering. Between 24 hours and 7 days of weathering the viscosity increase is more progressive. After 7 days of weathering the viscosity was measured at 6360 mPa.s.

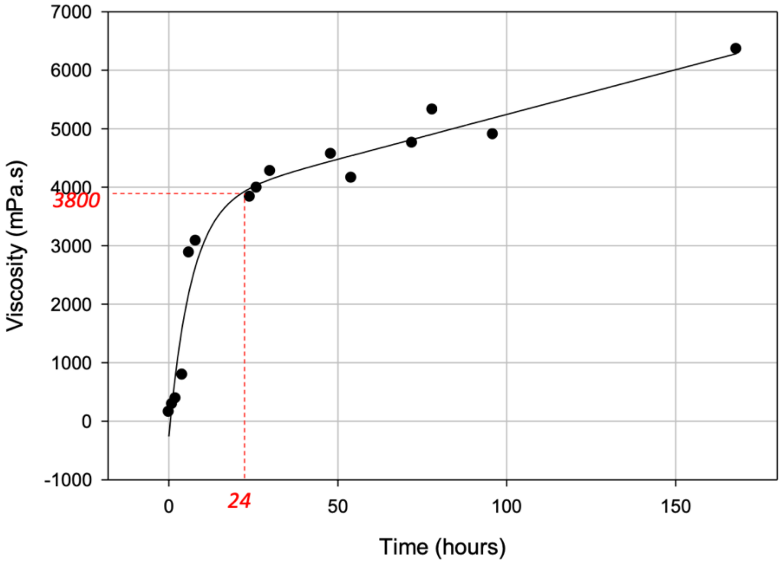


Figure 22. Evolution of the viscosity (mPa.s) of the B30 FAME / VLSFO.

○ *Emulsification*

At 20°C, the water content increased rapidly during the first hours, reaching a maximum close to 85% (Figure 23). The emulsification process was very quick, with 85% or more of the maximum water content achieved after just 6 hours of weathering.

During the emulsification process, the progressive incorporation of water droplets in the oil explains the progressive increase of viscosity.

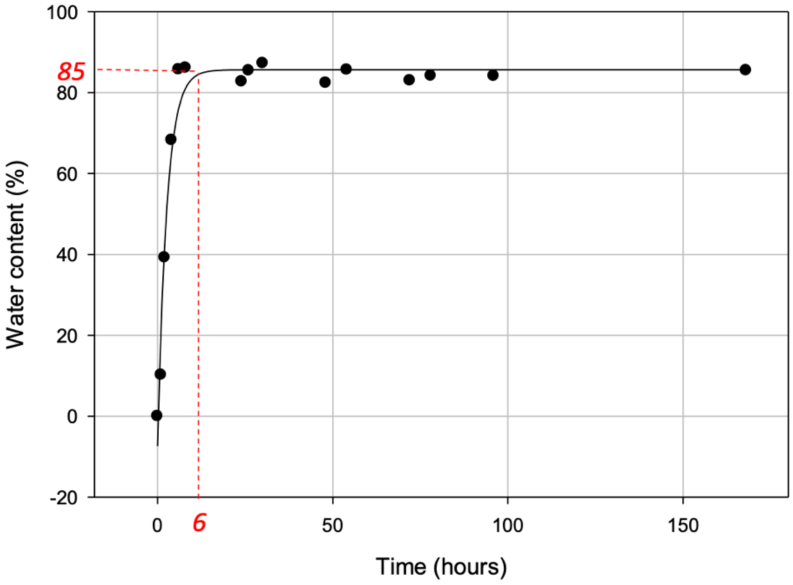


Figure 23. Evolution of the water content (%) of the B30 FAME / VLSFO.

- *Stability of the emulsions*

The stability ratio was calculated by comparing the water content of the emulsion sample after the addition of a chemical demulsifier to its initial water content. Emulsions with a stability ratio of 0.8 or higher can be considered relatively stable, which corresponds to the settling of approximately half the water in an emulsion with an 80% water content.

The stability of the emulsions was monitored throughout the weathering experiments. Figure 24 depicts the evolution of the stability of the B30 FAME/VLSFO emulsion and highlights that as soon as the emulsification process occurs, the emulsion can be considered very stable.

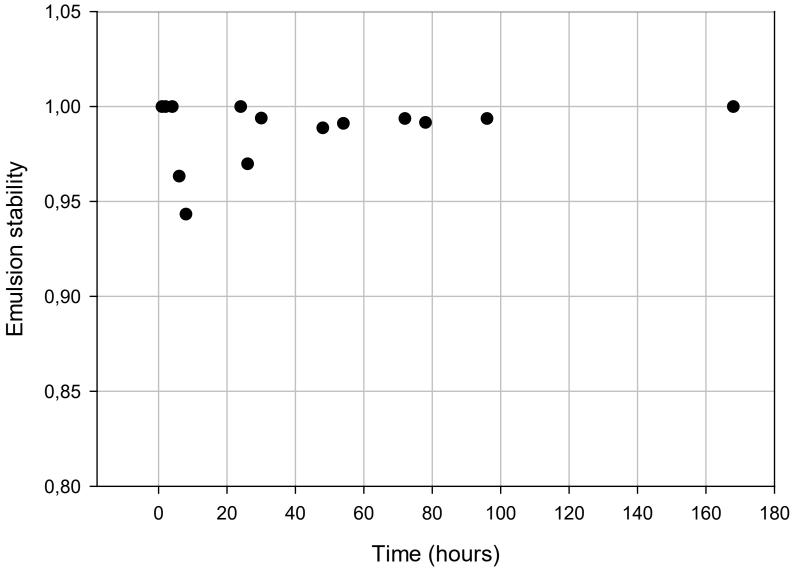


Figure 24. Evolution of the stability of the B30 FAME/ VLSFO emulsion.

- *Density*

The density of the oil increased rapidly during the first 6 hours of weathering and then stabilized around 1.001 at 20°C (Figure 25). This increase in density is related to the emulsification process and the incorporation of water droplets in the oil. This increase in density will influence the buoyancy of the emulsion: with a density of 1.001, we can expect that, according to water surface, the slick can submerge below the water surface for agitated conditions.

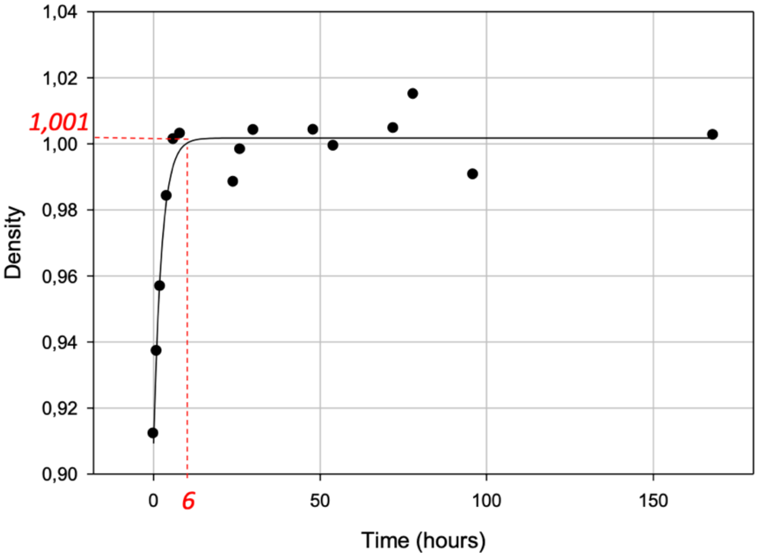


Figure 25. Evolution of the density of the B30 FAME/ VLSFO.

o *Flash point*

The flash point of the B30 FAME/ VLSFO exceeds 100°C for the fresh oil (maximal temperature tested). This value is high, well above the 60°C threshold value. According to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), several categories are defined for flammable products, but these only apply to flash points up to 60°C. Therefore, once the flash point exceeds 60°C, the risk of flammability in oil slicks can be considered negligible.

Consequently, in situ burning technique cannot be considered as a potential response measure for B30 FAME/VLSFO blend.

o *Evaporation*

Regarding the evaporation process, B30 FAME/VLSFO did not evaporate during the weathering test as well as in the laboratory, during the distillation test at 150°C, 200°C, and 250°C. This is related to the composition of both products and the abundance of chemical compounds not sensitive to this weathering process.

o *Natural dispersion*

During the weathering experiment, the water column coloration turned progressively yellowish rapidly after the oil release. Water samples were collected and analysed to evaluate if any natural dispersion occurred. The oil concentration in the water column reached 370 mg/L after 6 hours and stabilized at 190 mg/L (Figure 26). These concentration values explain the water coloration and reflect a natural dispersion of the oil. This natural dispersion is not complete, as it only concerns 190 mg/L out of the highest concentration - 2500 mg/L - that can be obtained theoretically in the case of a complete dispersion of 20L of blend in the 7m^3 – Polludrome.

To assess the composition of the dispersed oil (FAME only, VLSFO only, or both), water samples were collected, and the oil extract was identified by using a GCMS. An example of a chromatogram is presented in the Figure 27. This chromatogram clearly highlights the presence of chemical compounds coming from both FAME and VLSFO.

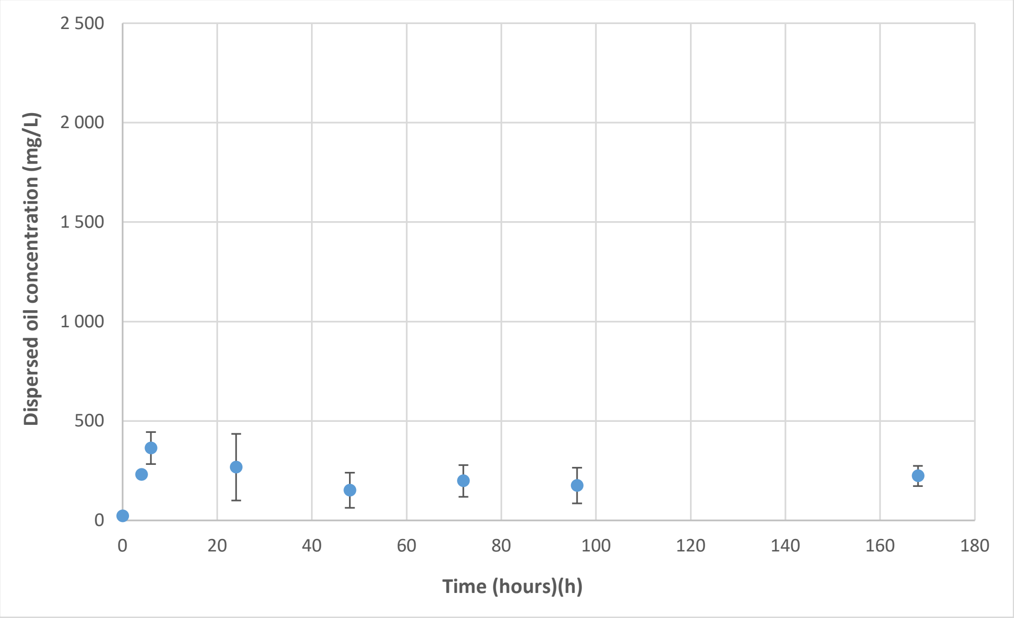


Figure 26. Evolution of B30 FAME / VLSFO concentrations (mg/L) in the water column.

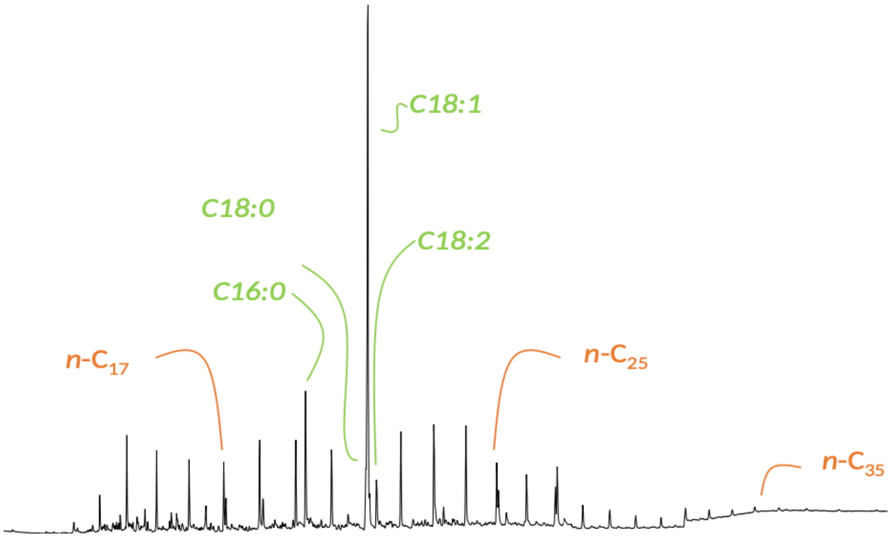


Figure 27. GC/MS Chromatograms (scan mode) of dispersed oil highlighting the presence of FAME (green compounds: C16:0, C18:0, C18:1, C18:2) and VLSFO (brown compounds: n-Cx refers to petroleum n-alkanes (x from 10 up to 35).

- *Chemical dispersibility*

Windows of dispersibility have been established by Cedre[8] based on IFP results. Oils are considered "dispersible" when IFP efficiency exceeds 50%. They are deemed "poorly dispersible" if efficiency is below 20%. Dispersibility is considered "reduced" for values in between these limits.

Figure 28 presents the values for the IFP tests conducted at 20°C on fresh oil sample and samples collected after 6, 24, 48, and 72 hours of weathering.

Based on the IFP tests, the oil is considered dispersible for viscosities up to 3000 mPa.s. For higher viscosities, dispersibility is reduced, but the oil remains "possibly dispersible" up to 48 hours. The corresponding time-windows of opportunity for dispersant use are estimated at 8 hours based on the viscosity evolution over time. After 2 days of weathering, the B30 FAME/VLSFO is considered as not dispersible.

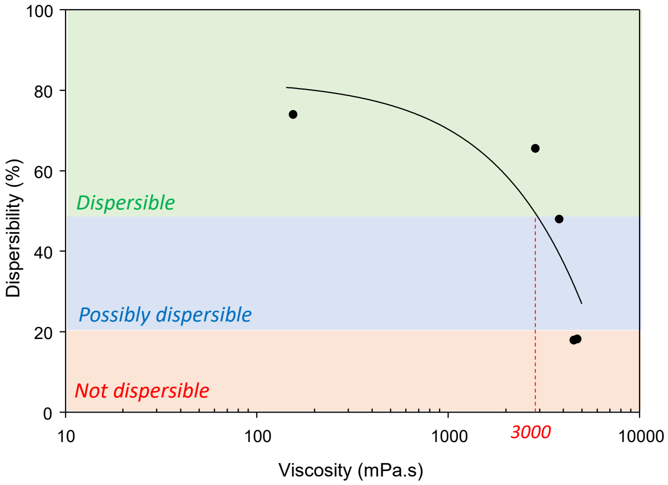


Figure 28. Evolution of the B30 FAME/ VLSFO dispersibility (%) according to viscosity (mPa.s).

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[8] Guyomarch, Julien, Stephane Le Floch, and Ronan Jezequel. "Oil weathering, impact assessment and response options studies at the pilot scale: improved methodology and design of a new dedicated flume test." In *Proceedings of the 35th Arctic and Marine Oil Spill Program Technical Seminar on Environmental Contamination and Response*, pp. 1001-1017. 2012.

o *Recovery by using oleophilic skimmers*

The use of floating booms to contain and thicken the slick represents the initial phase of recovery operations. However, due to the low viscosity and fast spreading rates, the booming operations may have limited effectiveness since they will be dealing with a spread-out area and a very thin film. That combined with very shallow depths in the area may limit mechanical recovery to the areas of natural accumulation of oil (e.g. convergence zones) or shorelines. When oil is collected into thicker slicks, the information about its adhesion to skimmers is more relevant. Oil adhesion to an oleophilic plate is considered a reliable parameter for evaluating the feasibility of using oleophilic skimmers to recover the oil.

Figure 29 presents the evolution of B30 FAME/VLSFO adhesion to an oleophilic surface according to the weathering duration. Adhesion increased rapidly as soon as the oil was released. From 830 g/m² for the fresh oil, the adhesion reached a value of 2875 g/m² only after 6 hours of weathering. Between 6 hours and 7 days of weathering, the oil adhesion continued to increase. This increase can be related to the increasing viscosity of the emulsion: a linear relationship was observed between adhesion and viscosity (Figure 30).

Based on these observations, the use of oleophilic skimmers appears viable. However, a more specific study would be necessary to assess the actual efficiency of this response option under real-world conditions.

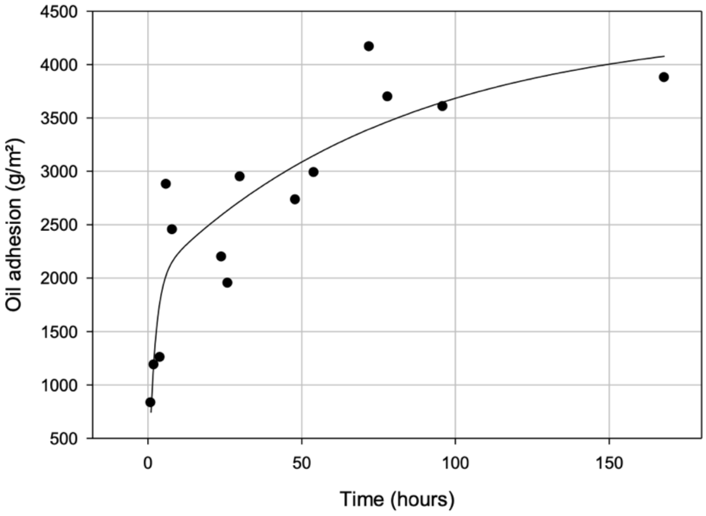


Figure 29. Evolution of the B30 FAME/ VLSFO adhesion (g/m²) to an oleophilic surface according to weathering time (hours).

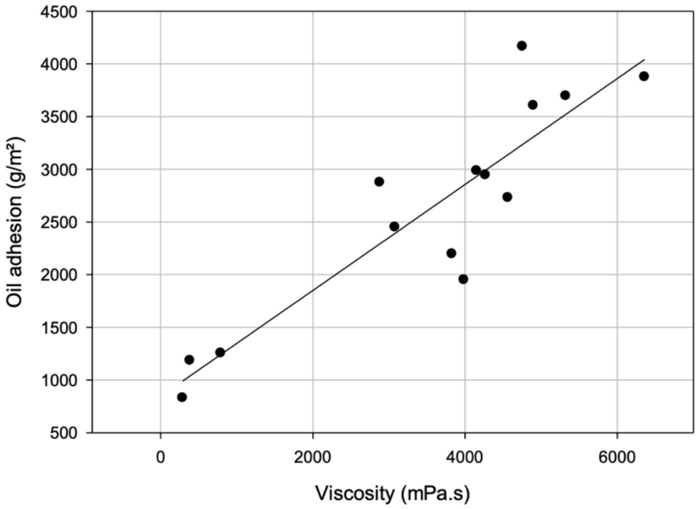


Figure 30. Evolution of the B30 FAME/ VLSFO adhesion (g/m²) to an oleophilic surface according to viscosity (mPa.s).

o *Biodegradability*

Biodegradability is assessed through a laboratory experiment which consists of a 28-day exposure of blend to a bacteria consortium in optimized conditions for biodegradation (nutrients, oxygen, temperature, low oil concentration).

Figure 31 illustrates the relative extent of the weathering processes (evaporation and biodegradation) for the B30 FAME/VLSFO. The contribution of the biodegradation process was calculated relatively to the fresh oil. Considering the evaporation and biodegradation processes separately, it appears that 36% in weight of the B30 FAME/VLSFO is biodegraded and 1% is evaporated. The results mean that, after natural degradation, 63% of the B30 FAME/VLSFO will persist in the environment. These results are consistent with the blend composition:

- 30% of FAME, a biodiesel for which the biodegradability can reach 100% in optimized conditions (Cedre, 2023); and
- 70% of a VLSFO, a refined product that can be less sensitive to the biodegradation process. For VLSFO#4 used in the blend, biodegradability reached a maximum of 5% in optimized conditions.

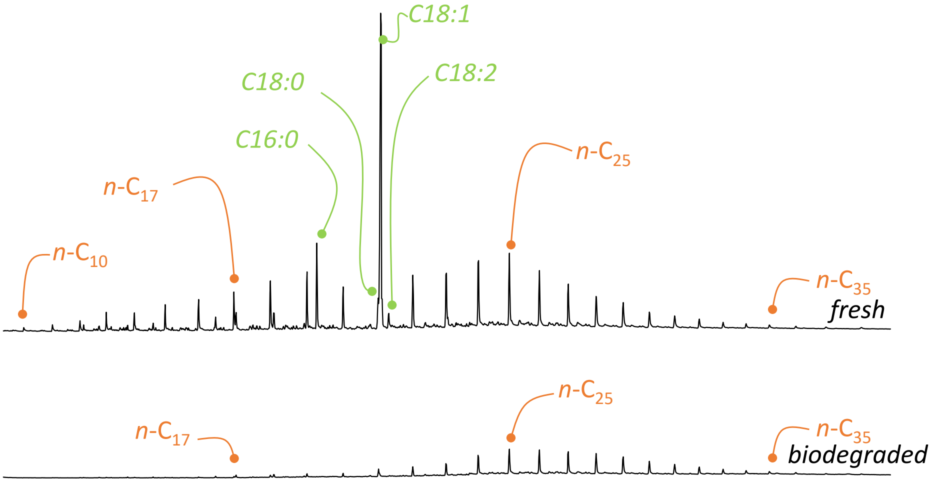


Figure 31. GC/MS Chromatograms (scan mode) of fresh B30 FAME/VLSFO (top) and biodegraded B30 FAME/VLSFO (bottom). n-C_x (brown) refers to petroleum n-alkanes (x from 10 up to 35). C16:0, C18:0, C18:1, C18:2 (green) refers to FAME compounds.

o *Ecotoxicity*

<u>*Marine bacteria: Aliivibrio fisheri*</u>

The luminescence of *Aliivibrio fisheri* are presented for 3 conditions: Seawater alone, B30 FAME/VLSFO, and Biocide (as a control). The bioluminescence is directly linked to the bacterial activity, which is related to the ecotoxicity of the environment in which the bacteria grow: lower luminescence levels are indicative of higher environmental toxicity.

The results of the Microtox test presented in Figure 32 highlight that the luminescence of *Aliivibrio fisheri* is affected when exposed to the soluble fraction of B30 FAME/VLSFO. However, this decrease in luminescence appears low compared to the results obtained with a toxic compound.

After integration of the areas under the curves, the ecotoxicity values were estimated using the following formula:

$$\% \text{ inhibition} = (100-(A_{toxic}*100))/A_{control}$$

Two percentages of inhibition were calculated: one with seawater (43%) and the other with the (doped) culture medium (49%) to verify the purity of the seawater. The results show that the B30 FAME/VLSFO exhibited low ecotoxicity in its undiluted form, compared to the reference biocide, with robust repeatability and statistical significance. For information, the Figure 33 presents the quantification of PAHs compounds in the water samples used for the Microtox tests.

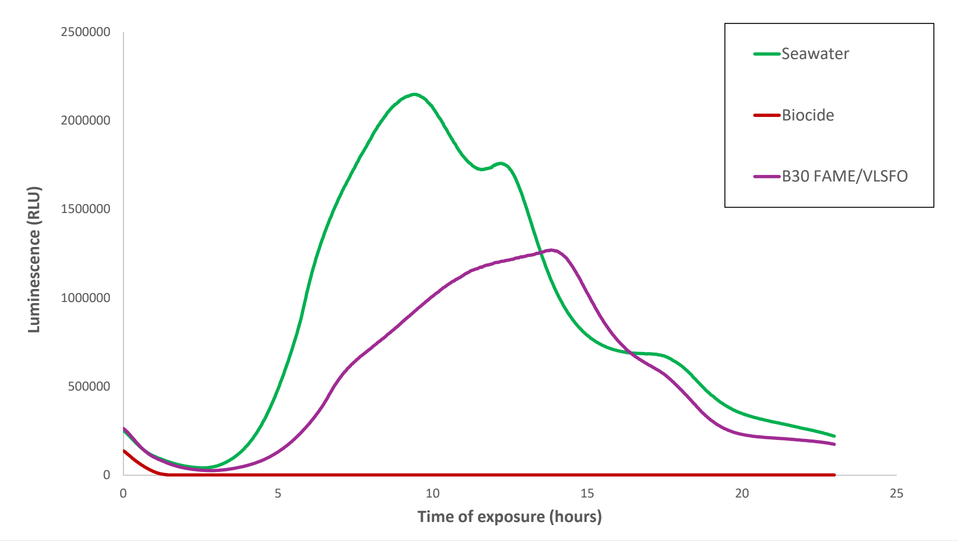


Figure 32. Bioluminescence evolution (Relative Luminescence Unit) during 23h for the different conditions tested.

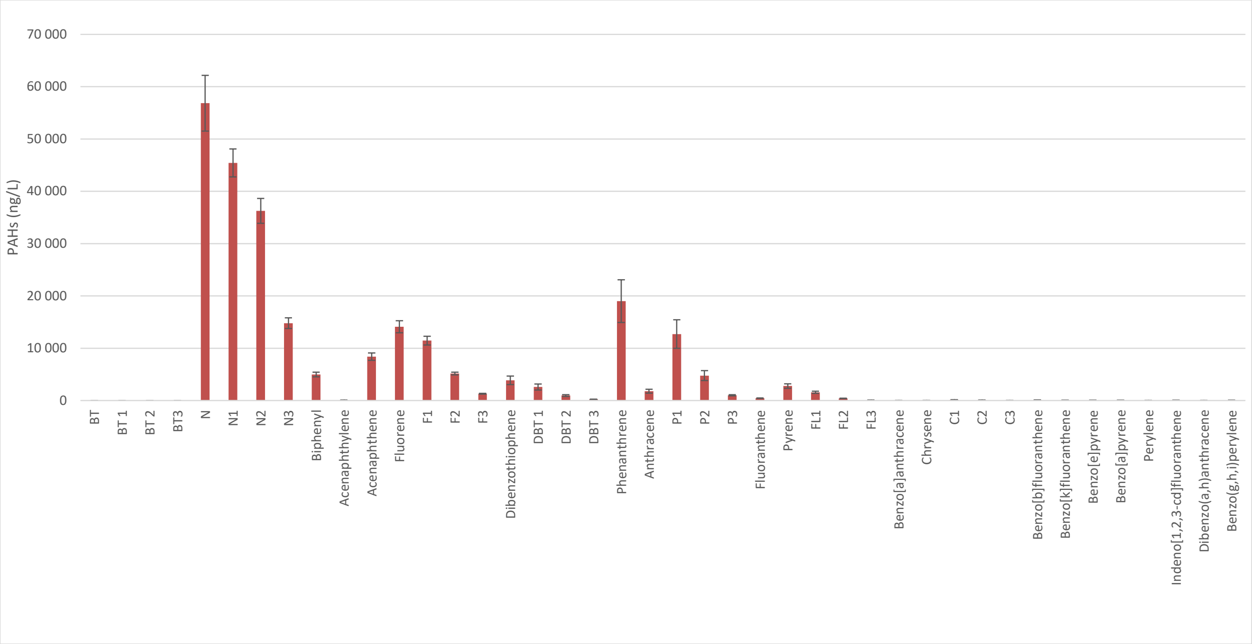


Figure 33. PAHs concentrations in WAF sample of B30 FAME/VLSFO.

○ *Overview of weathering effect on B30 FAME/ VLSFO properties*

Table 5 summarizes the physiochemical properties of B30 FAME/VLSFO for the fresh and the 7-days weathered oil.

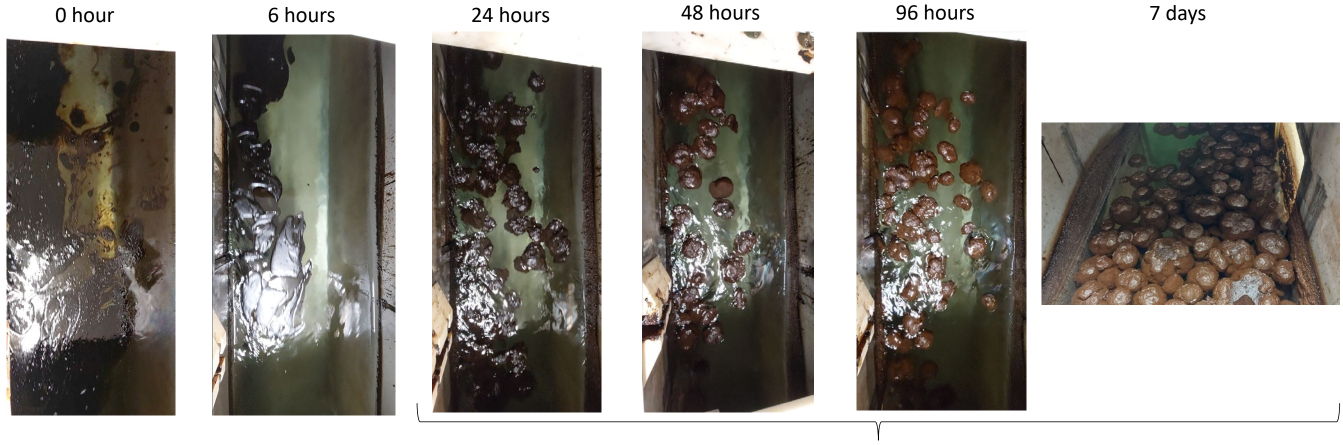
Table 5. Physicochemical properties of fresh and weathered B30 FAME/ VLSFO.

	Fresh	7-days weathered
Viscosity (mPa.s)	156	6 360
Pour point	24	
Density	0.912	1.001

API gravity	23.7	9.9
Water content (%)	0	85.4
Adhesion (g/m²)	830	3 875
Evaporation max (%)	0	1
Distillation (%)		
< 150°C	0	-
150 - 200°C	0	-
200 - 250°C	0	-
Flash point (°C)	> 100	> 100
Biodegradability (%)	43 %	-
Chemical dispersibility (IFP tests) (%)	70 %	Not dispersible
Natural dispersion	low (7%)	
Ecotoxicity	Marine bacteria: low	

Evolution of the physicochemical properties of the B30 HVO/ VLSFO

Figure 34 presents the evolution of the B30 HVO/ VLSFO slick during the weathering test at pilot scale. Initially, the blend is a liquid black product which spreads to cover the surface of the Polludrome®. After 6 hours of weathering, the slick thickness increases and forms large lumps / patches of oil distributed over the surface of the Polludrome®. After 24 hours, the lumps break to form black balls that progressively turn brown. After one week of weathering, the B30 HVO/VLSFO slick is observed as an accumulation of floating brown balls (5 to 10 diameters). Due to agitation, these balls can submerge at a maximum of 20 cm depth, but they resurface rapidly.



Black and liquid oil slick covering the surface of the flume tank.

Viscous black slick slick fragmented into large viscous lumps.

Brown lumps fragmented progressively into brown balls (5 to 10 cm diameter) distributed over the water surface.

Figure 34. Evolution of the B30 HVO/ VLSFO appearance according to the weathering duration.

o Viscosity

Figure 35 presents the evolution of B30 HVO/ VLSFO blend viscosity during the weathering experiment. The viscosity increases rapidly as soon as the oil is released. Initially measuring at 200 mPa.s, the viscosity reached 19000 mPa.s after 24 hours of weathering. The evolution of viscosity appears linear during the 7-days experiment, and it reaches 80000 mPa.s. Even if this evolution is linear, we can expect that the viscosity value will not increase significantly beyond 7 days, as no evolution of the other physicochemical properties was highlighted.

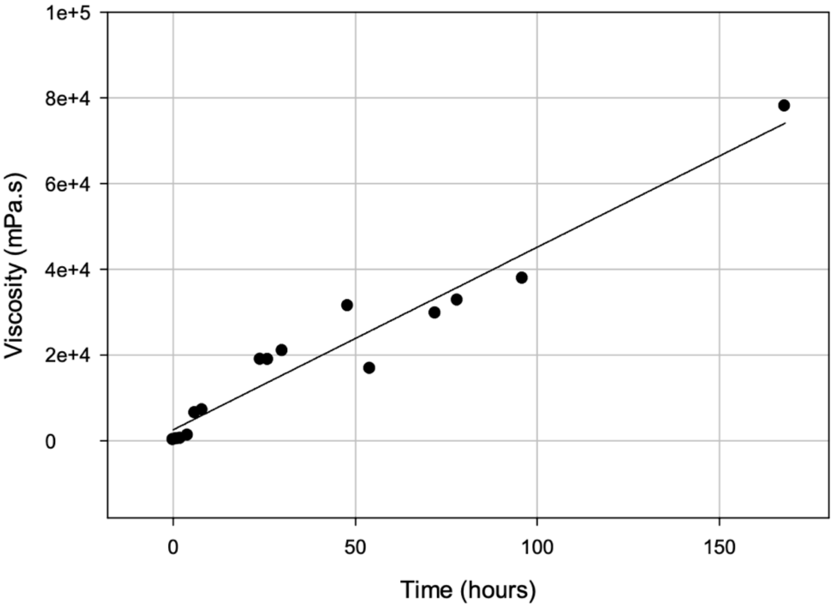


Figure 35. Evolution of the viscosity (mPa.s) of the B30 HVO/ VLSFO.

o Emulsification

As observed for B30 FAME/VLSFO, the water content increased immediately after the oil release, reaching a maximum close to 90% (Figure 36). The emulsification process was very quick, with 87% of water content achieved after just 6 hours of weathering. During the emulsification process, the progressive incorporation of water droplets in the oil explains the progressive increase in viscosity.

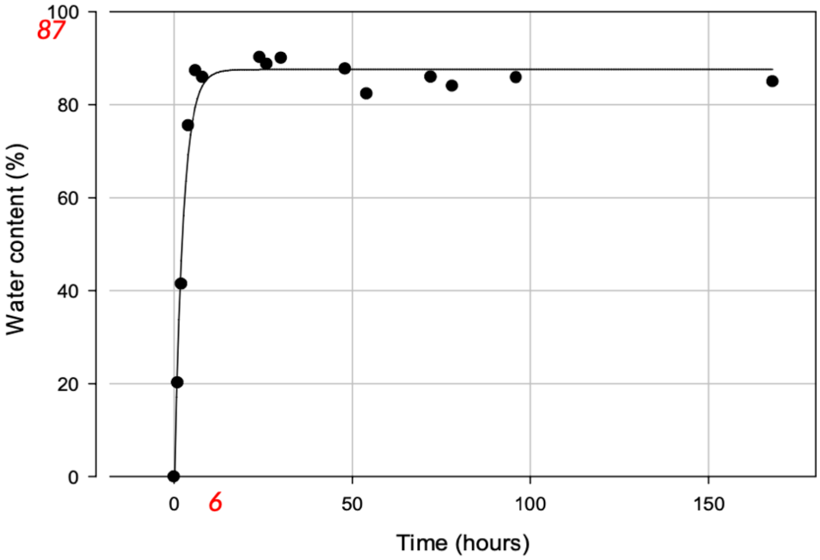


Figure 36. Evolution of the water content (%) of the B30 HVO/ VLSFO.

○ *Stability of the emulsions*

The stability ratio was calculated by comparing the water content of the emulsion sample after the addition of a chemical demulsifier to its initial water content. Emulsions with a stability ratio of 0.8 or higher can be considered relatively stable, which corresponds to the settling of approximately half the water in an emulsion with an 80% water content.

The stability of the emulsions was monitored throughout the weathering experiments (Figure 37). This figure highlights that the B30 HVO/VLSFO emulsion can be considered as very stable.

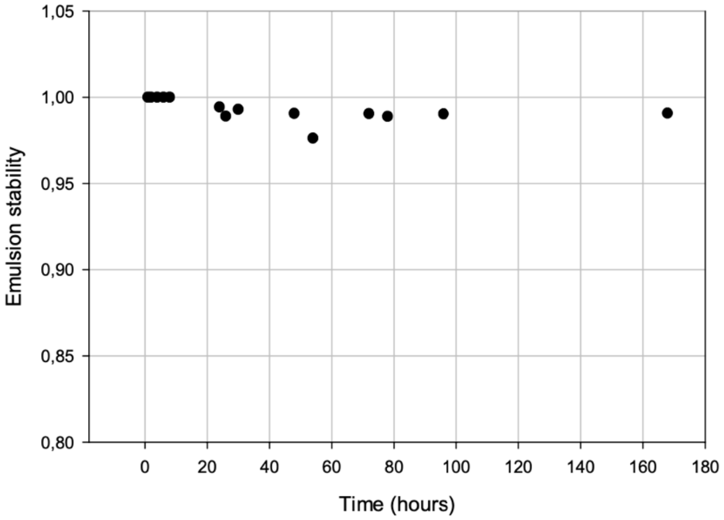


Figure 37. Evolution of the stability of the B30 HVO/ VLSFO emulsion.

○ *Density*

As noticed for the B30 FAME/VLSFO blend, the density of the oil increased rapidly during the first 6 hours of weathering and then stabilized around 1.003 after 12 hours of weathering (Figure 38). This increase in density is related to the incorporation of water droplets in the oil (emulsification process). This higher density influences the buoyancy of the emulsion: with a density of 1.003, we can expect that, according to water surface agitation, the slick can submerge below the water surface for agitated condition. During the test, submersions of balls were observed at a maximum of 20 cm depth.

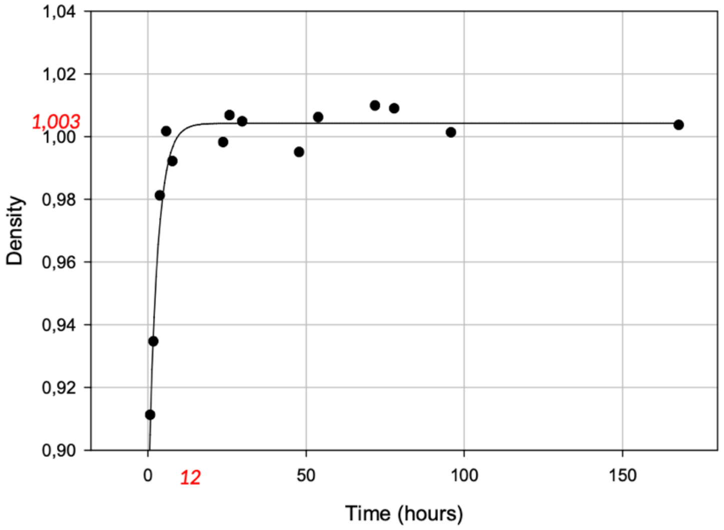


Figure 38. Evolution of the density of the B30 HVO/ VLSFO.

Flash point

As observed for the B30 FAME/VLSFO, the flash point of the B30 HVO/VLSFO exceeds 100°C for the fresh oil (maximal temperature tested). This value is high, well above the 60°C threshold value. According to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), several categories are defined for flammable products, but these only apply to flash points up to 60°C. Therefore, once the flash point exceeds 60°C, the risk of flammability in oil slicks can be considered negligible.

Therefore, in situ burning technique cannot be considered as a potential response measure for B30 HVO/VLSFO blend.

Evaporation

Regarding the evaporation process, B30 HVO/VLSFO does not evaporate during the weathering test. This was also noticed at lab scale during the distillation at 150°C, 200°C and 250°C. This is due to the composition of the two products (HVO and VLSFO), both characterized by an abundance of chemical compounds not sensitive to this weathering process.

Chemical dispersibility

Windows of dispersibility have been established by Cedre[9] based on IFP results. Oils are considered "dispersible" when IFP efficiency exceeds 50%. They are deemed "poorly dispersible" if efficiency is below 20%. Dispersibility is considered "reduced" for values in between these limits.

Figure 39 presents the values for the IFP tests conducted at 20°C on fresh oil sample and samples collected after 6 and 24 hours of weathering.

Based on the IFP tests, the B30 HVO/VLSFO cannot be considered as chemically dispersible.

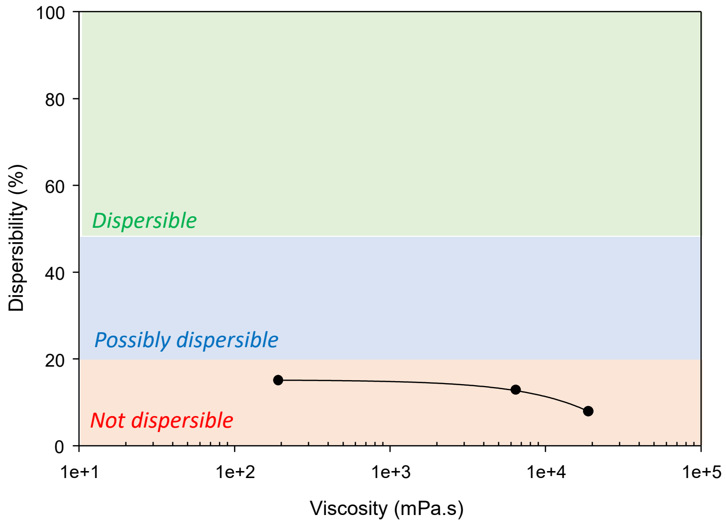


Figure 39. Evolution of the B30 HVO/ VLSFO dispersibility (%) according to viscosity (mPa.s).

Recovery by using oleophilic skimmers

Figure 40 presents the evolution of B30 HVO/VLSFO adhesion to an oleophilic surface according to the weathering duration. Adhesion increased rapidly as soon as the oil was released. From 1245 g/m² for the fresh oil, the adhesion reached a plateau at 13000 g/m² after 24 hours of weathering.

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[9] See footnote 7 ante

Based on these measures, the use of oleophilic skimmers appears viable. However, ball formations observed during the weathering experiment suggest that deployment of nets can be an interesting response measure to recover the B30 HVO/VLSFO blend (Figure 41).

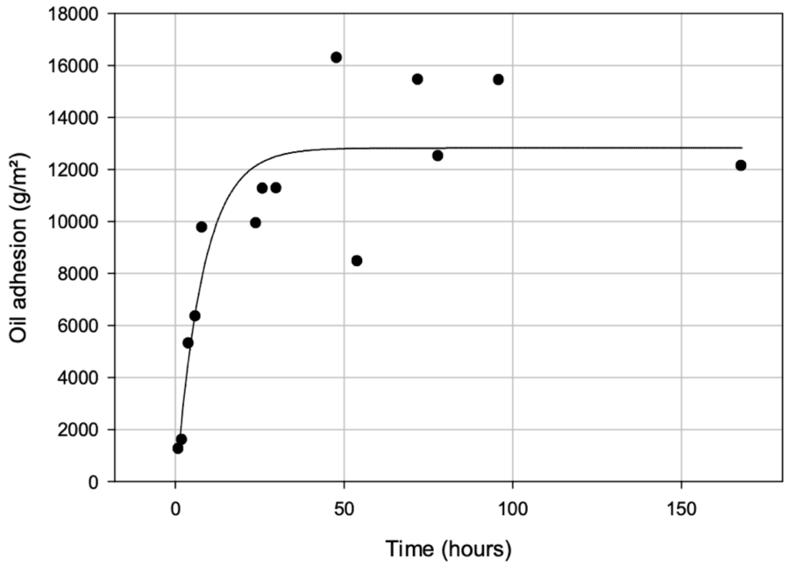


Figure 40. Evolution of the B30 HV / VLSFO adhesion (g/m²) to an oleophilic surface according to weathering time (hours).

Figure 41. Balls of weathered B30 HVO/VLSFO observed after 7 days of weathering.

- *Biodegradability*

Figure 42 presents the relative extent of the weathering processes (evaporation and biodegradation) for the B30 HVO/VLSFO. The contribution of the weathering processes was calculated relative to the fresh oil. Considering the evaporation and biodegradation processes separately, it appears that a maximum of 32% of the B30 HVO/VLSFO blend is biodegraded and 1% is evaporated. Those results mean that, after natural degradation, 67% of this blend will persist in the environment. These results are consistent with the blend composition:

- 30% of HVO, a biodiesel for which the biodegradability can reach 100% in optimized conditions (Cedre, 2023);
- 70% of a VLSFO, a refined product that can be less sensitive to the biodegradation process. For VLSFO#4 used in the blend, biodegradability reached a maximum of 5% in optimized conditions.

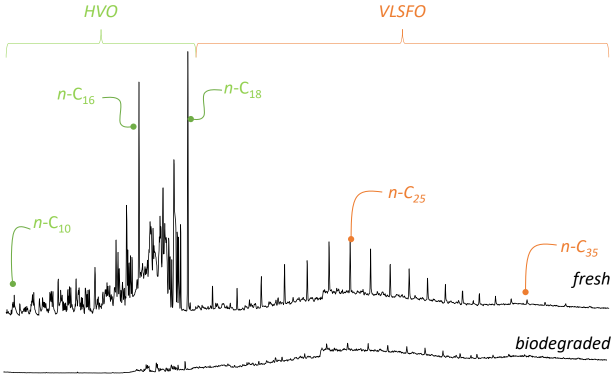


Figure 42. GC/MS Chromatograms (scan mode) of fresh B30 HVO/VLSFO (top) and biodegraded B30 HVO/VLSFO (bottom). n-C_x (brown) refers to petroleum n-alkanes (x from 10 up to 35).

- ### *Natural dispersion*

No plume of micro-droplets or changes in water colour was observed during the weathering test in Polludrome®. To confirm that no natural dispersion occurred, water samples were collected and analysed. The results highlight that B30 HVO/VLSFO did not disperse naturally in the conditions of the weathering test.

- ### *Ecotoxicity*

Marine bacteria: Aliivibrio fisheri

The luminescence of *Aliivibrio fisheri* are presented for 3 conditions: Seawater alone, B30 HVO/VLSFO and Biocide (as a control). The bioluminescence is directly linked to the bacterial activity which is related to the ecotoxicity of the environment in which the bacteria grow: lower luminescence levels are indicative of higher environmental toxicity.

The results of the Microtox test presented in Figure 43 highlight that the luminescence of *Aliivibrio fisheri* is affected when exposed to the soluble fraction of B30 HVO/VLSFO. However, this decrease of luminescence appears low compared to the results obtained with a toxic compound.

After integration of the areas under the curves, the ecotoxicity values were estimated using the following formula:

$$\% \text{ inhibition} = (100-(A_{\text{toxic}}*100))/A_{\text{control}}$$

Two percentages of inhibition were calculated: one with seawater (43%) and the other with the (doped) culture medium (54%) to verify the purity of the seawater. The results show that the B30 HVO/VLSFO exhibited low ecotoxicity in its undiluted form, compared to the reference biocide, with robust repeatability and statistical significance.

Figure 44 presents the quantification of PAHs compounds in the water samples used for the Microtox tests.

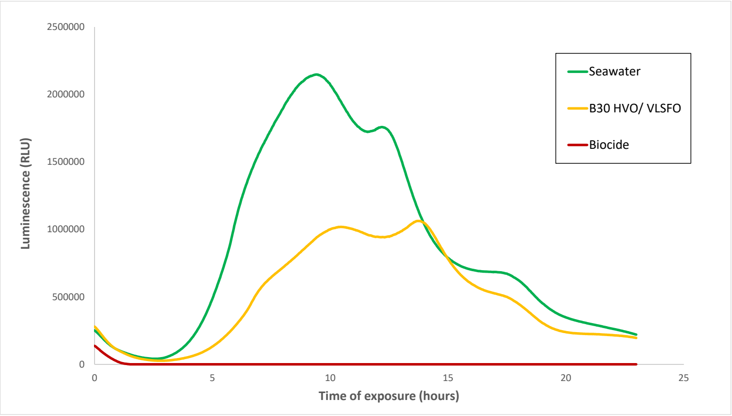


Figure 43. Bioluminescence evolution (Relative Luminescence Unit) during 23h for the different conditions tested.

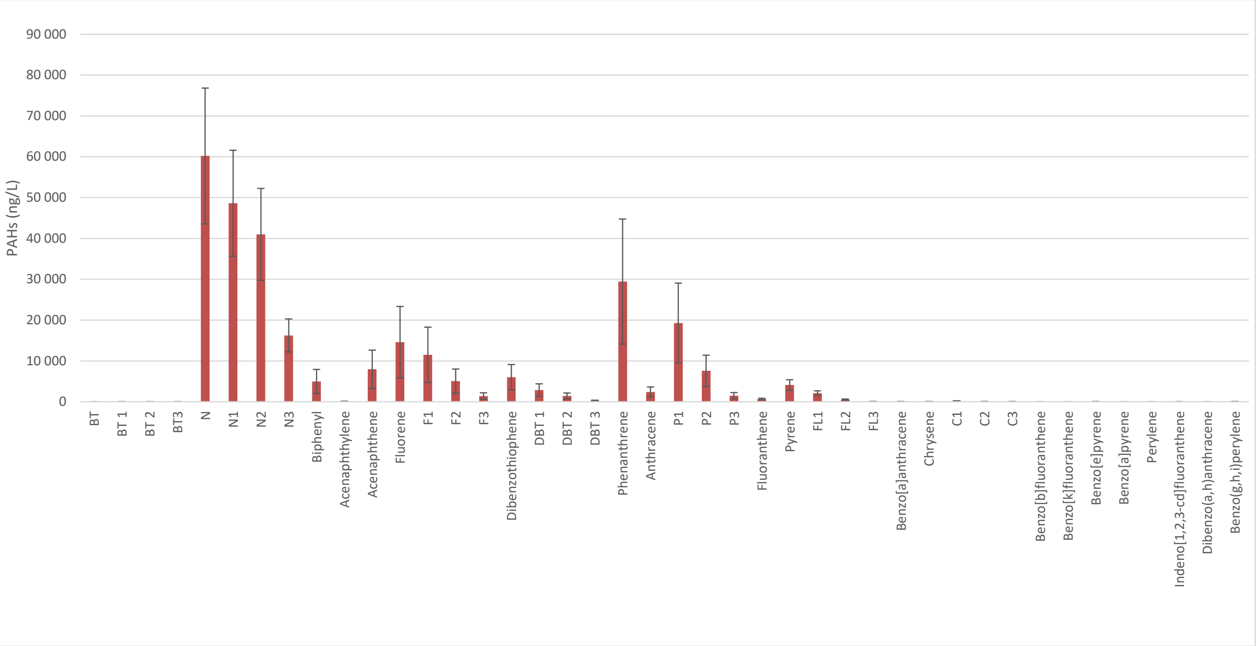


Figure 44. PAHs concentrations in WAF sample of B30 HVO/ VLSFO.

- *Overview of weathering effect on B30 HVO/ VLSFO properties*

The Table 6 summarizes the evolution of the main physicochemical properties of the B30 HVO/VLSFO for the fresh and 7-days weathered oil.

Table 6. Physicochemical properties of fresh and weathered B30 HVO/ VLSFO.

	Fresh	7-days weathered
Viscosity (mPa.s)	200	80 000
Pour point (°C)	18	
Density	0.884	1.003
API gravity	28.5	9.44
Water content (%)	-	85
Adhesion (g/m²)	1 245	13 000
Evaporation max (%)		0
Distillation (%)		
< 150°C	0	
150 - 200°C	0	
200 - 250°C	0	
Flash point (°C)	93.5	> 100

Biodegradability (%)		
Chemical dispersibility (IFP tests) (%)	15	0
Natural dispersion	no	No
Ecotoxicity	Marine bacteria: low	

■ Evolution of the physicochemical properties of the B30 FAME/ MGO

MGO used to produce the B30 FAME/ MGO presents a blue colour. This colour is due to the presence of 1-4 di-*n*-aminoanthraquinone, a chemical compound used as a tracer to differentiate non-road diesel to road-taxed diesel. This colour might change according to State regulations (red, yellow, green, or black).

The main evolution of B30 FAME/MGO slick observed during the weathering test are presented in Figure 45. The pictures were taken under agitated conditions, and 15 minutes after agitation had stopped for the sampling phase.

Observations made during Polludrome tests show that the B30 FAME/ MGO spreads rapidly now of oil release. After 4 hours of agitation, a natural dispersion was observed as a whitish plume in the water column. As soon as the agitation was stopped, a phenomenon of recoalescence of the dispersed microdroplets occurred and a blue slick formation was observed on the water surface. From 1 day to 3 days, the same observations were made:

- a complete natural dispersion during agitation phase; and
- a recoalescence of oil droplets and formation of a yellow slick at the water surface. The colour change was due to an oxidation of the blue tracer when exposed to solar radiation.

After 78 hours of weathering, due to the complete natural dispersion, it was not possible to collect sufficient oil samples at water surface even after a settling time. Consequently, no results are presented beyond this period of weathering.

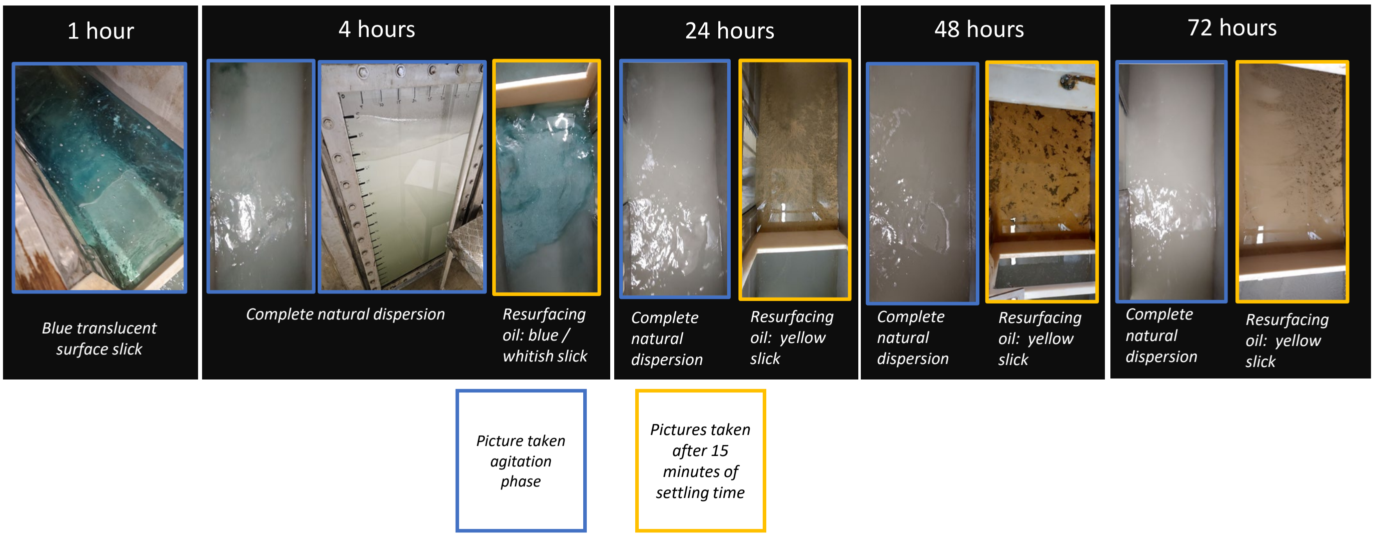


Figure 45. Evolution of the B30 FAME/ MGO appearance according to the weathering duration.

This evolution of the B30 FAME/MGO blend is very similar to the evolution of MGO studied earlier at Cedre (Cedre, 2024). The main difference lies in the time before the natural dispersion is observed, namely:

- after 48 hours of weathering, for the MGO alone; and
- few hours after the oil release, for the blend of MGO with 30% of FAME.

This difference suggests an effect of FAME addition on the natural dispersion of an oil.

- ### *Viscosity*

Figure 46 presents the results of viscosity measurements carried out on oil samples. The values tend to increase very slightly from 3 to 9 mPa.s.

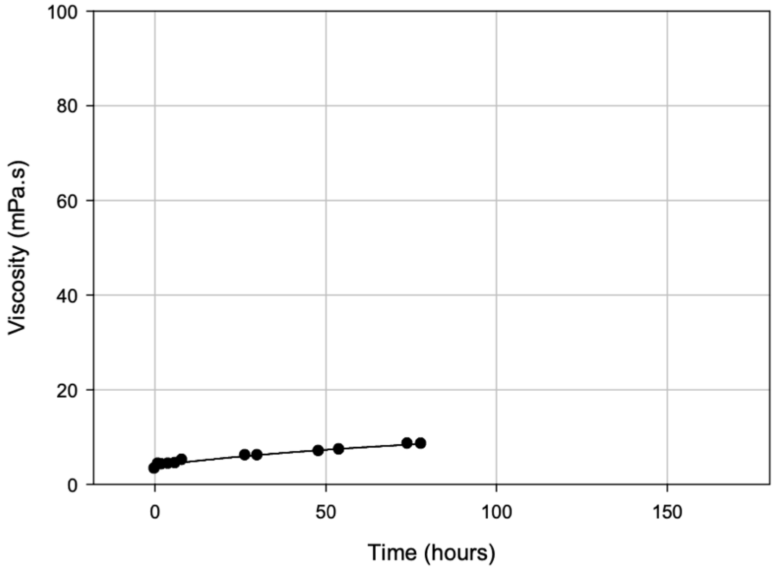


Figure 46. Evolution of the viscosity (mPa.s) of the B30 FAME/ MGO.

- ### *Emulsification*

An emulsification of the B30 FAME/MGO blend was observed at the water surface through a change in slick colour (from blue to whitish colour). However, the measure of water content in oil samples (Figure 47) did not highlight that the B30 FAME/MGO tends to emulsify. This is due to non-stability of the emulsion which breaks down immediately after the oil sampling. Consequently, even if an emulsion is observed at the water surface (whitish foam), the weathering process does not influence the volume of B30 FAME/MGO to be recovered.

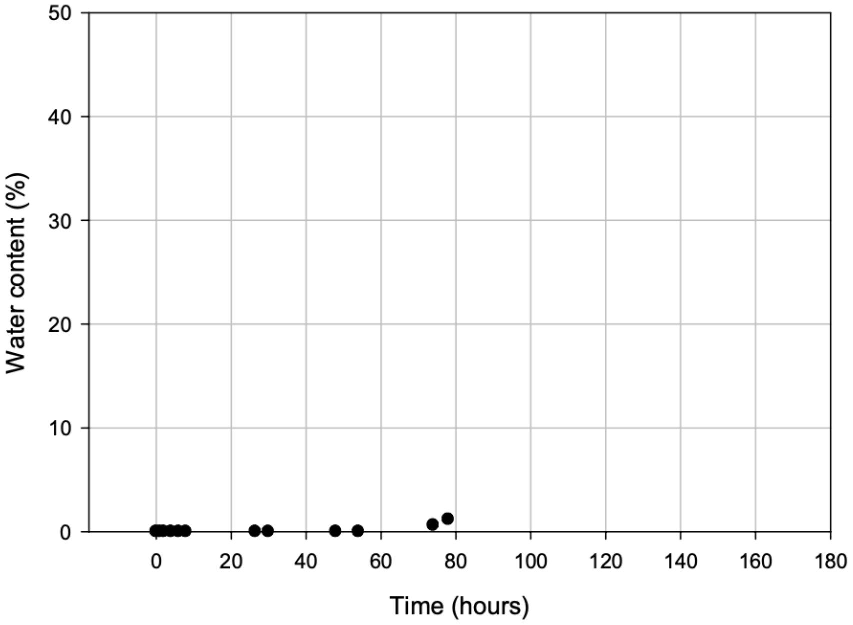


Figure 47. Evolution of the water content (%) of the B30 FAME/ MGO.

- ### *Density*

Figure 48 shows a limited increase in B30 FAME/MGO density during the experiment. Initially measured at 0.846, it reached a density of around 0.871 after 78 hours. The increase in density can be linked to evaporation of the lightest compounds. The density value remains low and well below the density of seawater (1.025). Consequently, a sinking or a submersion of a B30 FAME/MGO slick is not expected.

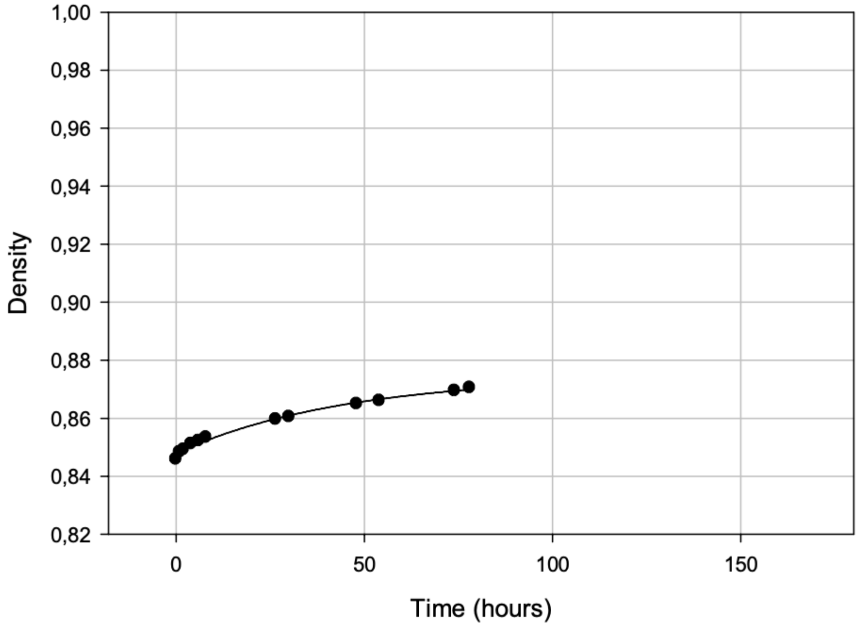


Figure 48. Evolution of the density of the B30 FAME/ MGO.

- *Flash point*

The evolution of flash point measure is presented in the Figure 49. The initial measure (70°C) is above the 60°C threshold value beyond which the risk of flammability of oil slicks can be considered negligible.

Therefore, in situ burning technique cannot be considered as a potential response measure for B30 FAME/MGO blend.

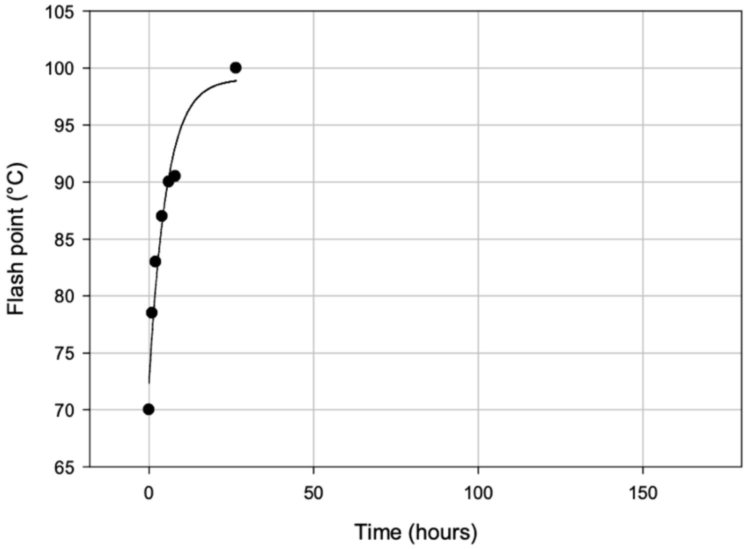


Figure 49. Evolution of the flash point valuer (°C) of the B30 FAME/ MGO.

- *Evaporation*

Regarding the evaporation process, the evolution of the evaporation rate is presented in Figure 50. The evaporation rate increased rapidly during the first 8 hours, reaching a maximum of approximately 18%.

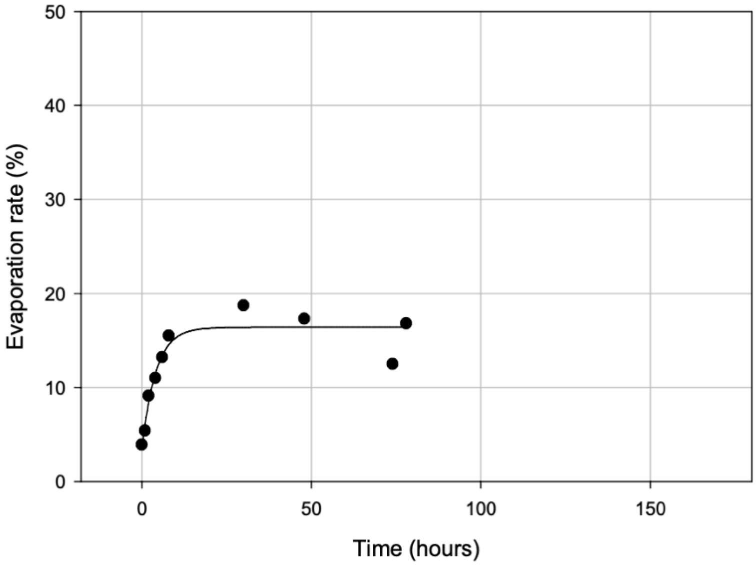


Figure 50. Evolution of the evaporation rate for the B30 FAME/ MGO.

- *Natural dispersion*

During the weathering experiment, the water column coloration turned progressively whitish rapidly after the oil release. Water samples were collected and analysed to evaluate if any natural dispersion occurred. The oil concentration in the water column reached 1500 mg/L after 24 hours, dropped to 1100 mg/L between 55 and 80 hours before reducing to 750 mg/L at 170 hours. These concentration values explain the water coloration and reflect a natural dispersion of the oil.

To assess the composition of the dispersed oil (FAME only, MGO only or both), water samples were collected and the oil extract was identified by using a GCMS. An example of chromatogram is presented in the Figure 52. This chromatogram clearly highlights the presence of chemical compounds coming from both FAME and MGO. Consequently, it can be stated that the natural dispersion observed during the weathering experiment was not due to a “separation” of FAME (dispersed part) and MGO (floating part) but to a real dispersion of the blend itself.

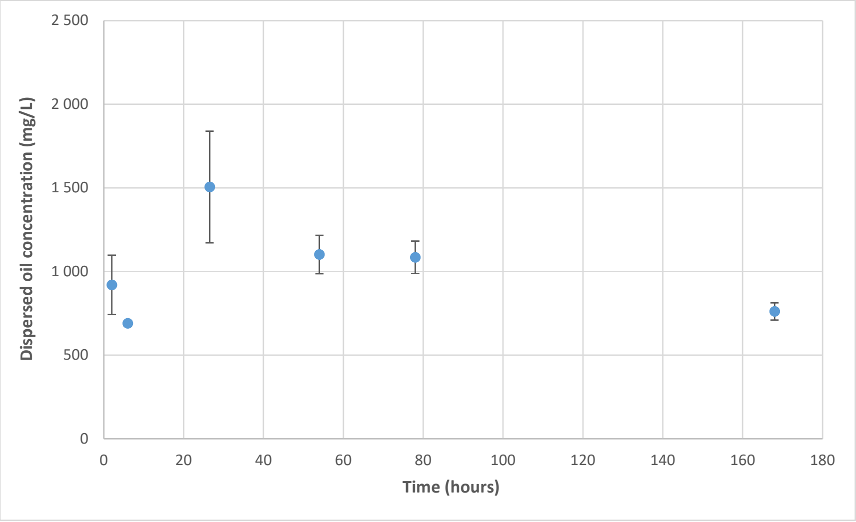


Figure 51. Evolution of B30 FAME/ MGO concentration (mg/L) in the water column.

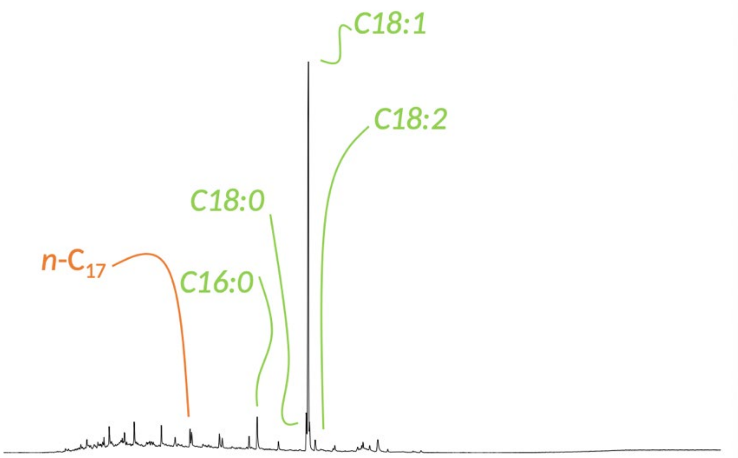


Figure 52. GC/MS Chromatograms (scan mode) of dispersed oil highlighting the presence of FAME (green compounds: C16:0, C18:0, C18:1, C18:2) and MGO (brown compounds: n-C_x refers to petroleum n-alkanes).

- *Chemical dispersibility*

Regarding the chemical dispersibility of the B30 FAME/MGO blend, this measurement was carried out on the fresh oil. The dispersion reached a value of 87%: the blend can be considered as a dispersible oil.

During the weathering experiment, as a natural dispersion was rapidly observed and measured, the assessment chemical dispersibility was not necessary.

- *Recovery by using oleophilic skimmers*

Figure 53 presents the evolution of B30 FAME/MGO adhesion to an oleophilic surface according to the weathering duration. Adhesion decreases from 150 g/m² up to75 g/m² after 78 hours of weathering. The adhesion of B30 FAME/MGO is low compared to the 2 other blends tested during this study. The main property which influences the adhesion value is the viscosity of the product. In the present case, the difference of viscosity between a marine distillate (like gasoil) and a marine bunker fuel (heavy fuel oil) explains the difference of adhesion.

Regarding the adhesion evolution with weathering time, as a rule, adhesion values increase in proportion to viscosity values. In practice, the presence of water droplets in an emulsified product can lower the oil's adhesion to oleophilic materials such as discs and drums. In the present case, as the adhesion measurement was conducted on the emulsified oil before its sampling, this effect was observed event if the emulsification process was not demonstrated.

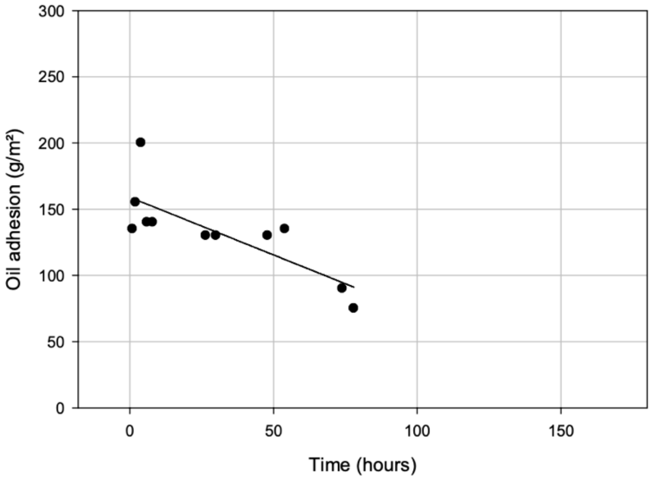


Figure 53. Evolution of the B30 FAME/ MGO adhesion (g/m²) to an oleophilic surface according to weathering time (hours).

- *Biodegradability*

Figure 54 presents the relative extent of the weathering processes (evaporation and biodegradation) for the B30 FAME/MGO. The contribution of the weathering processes was calculated to the fresh oil. Considering the evaporation and biodegradation processes separately, it appears that a maximum of 68% of the B30 FAME/MGO blend are biodegraded and 22% are evaporated. Those results mean that, after natural degradation, 10% of this blend will persist in the environment.

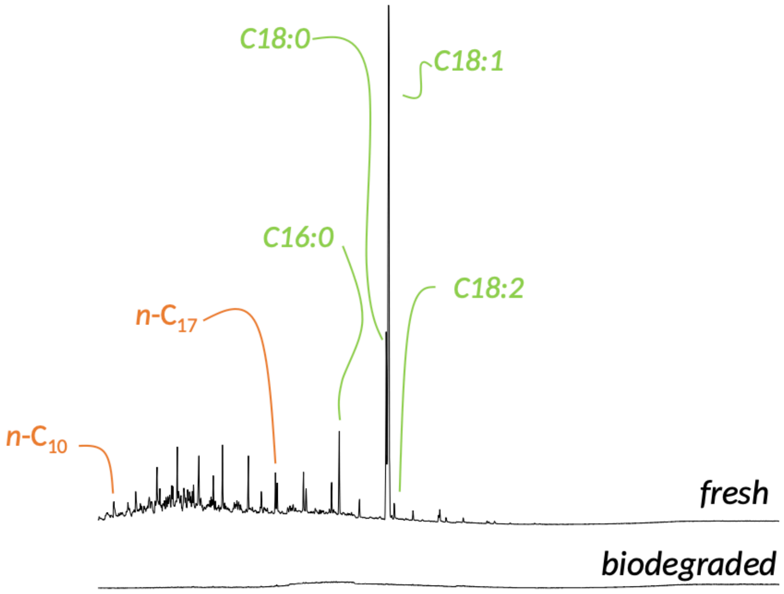


Figure 54. GC/MS Chromatograms (scan mode) of fresh B30 FAME/ MGO (top) and biodegraded B30 FAME/MGO (bottom).

- *Ecotoxicity*

<u>Marine bacteria: *Aliivibrio fisheri*</u>

The luminescence of *Aliivibrio fisheri* are presented for 3 conditions: Seawater alone, B30 FAME/MGO and Biocide (as a control). The bioluminescence is directly linked to the bacterial activity which is related to the ecotoxicity of the environment in which the bacteria grow: lower luminescence levels are indicative of higher environmental toxicity.

The results of the Microtox test presented in Figure 55 highlight that the luminescence of *Aliivibrio fisheri* is affected when exposed to the soluble fraction of B30 FAME/MGO. However, this decrease of luminescence appears low compared to the results obtained with a toxic compound.

After integration of the areas under the curves, the ecotoxicity values were estimated using the following formula:

$$\%\ \text{inhibition} = (100-(A_{\text{toxic}}*100))/A_{\text{control}}$$

Two percentages of inhibition were calculated: one with seawater (43%) and the other with the (doped) culture medium (54%) to verify the purity of the seawater. The results show that the B30 FAME/MGO exhibited low ecotoxicity in its undiluted form, compared to the reference biocide, with robust repeatability and statistical significance.

Figure 56 presents the quantification of PAHs compounds in the water samples used for the Microtox tests.

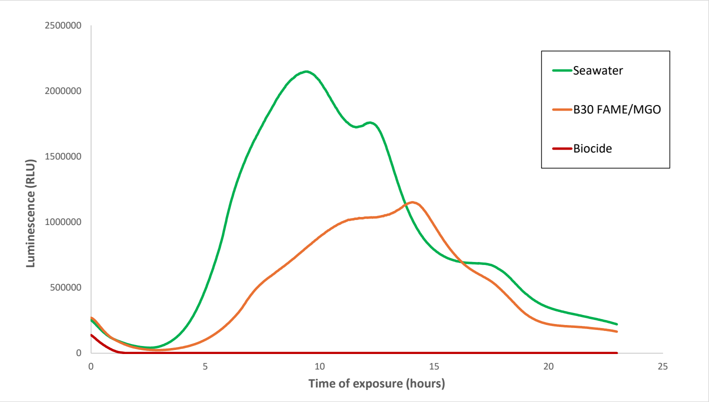


Figure 55. Bioluminescence evolution (Relative Luminescence Unit) during 23h for the different conditions tested.

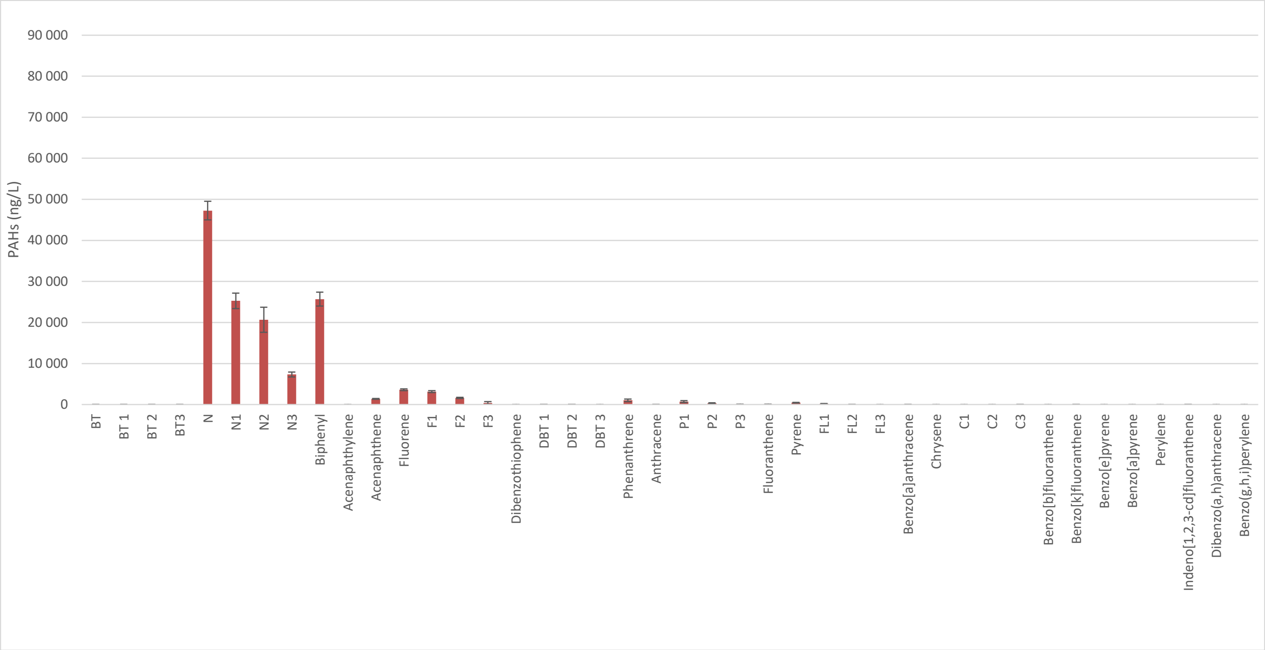


Figure 56. PAHs concentrations in WAF sample of B30 FAME/ MGO.

- *Overview of weathering effect on B30 FAME/ MGO properties*

The Table 7 summarizes the evolution of the main physicochemical properties of the B30 FAME/ MGO for the fresh and 7-days weathered oil.

Table 7. Physicochemical properties of fresh and weathered B30 FAME/ MGO.

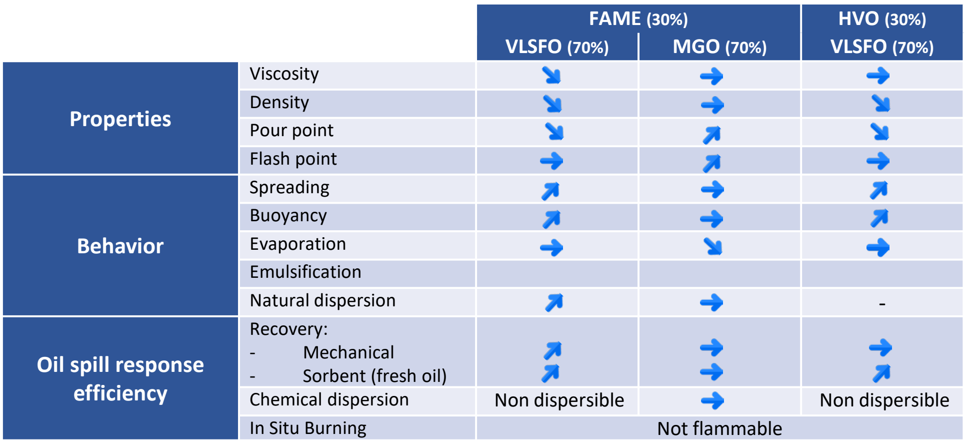
	Fresh	7-days weathered
Viscosity (mPa.s)	3	9
Pour point (°C)	- 18	
Density	0.846	0.871
API gravity	35.8	30.9
Water content (%)	-	1.2

Adhesion (g/m²)	135	75
Evaporation max (%)		18
Distillation (%)		
▪ **< 150°C**		
▪ **150 - 200°C**		
▪ **200 - 250°C**	22	
Flash point (°C)	70	> 100
Biodegradability (%)		
Chemical dispersibility (IFP tests) (%)	82.2	
Natural dispersion	0	Total
Ecotoxicity	Marine bacteria: low	

2.2.5 Overview of characterisation of physicochemical properties and weathering of blends of biodiesel with conventional marine bunker fuel

- Regarding the physicochemical properties of blends of biodiesel with conventional marine fuel, laboratory analyses and weathering experiments were conducted to characterize these new fuels and to assess at pilot scale their behaviour in case of accidental spill. The main results are summarized in Table 8.

Table 8. Effect of biodiesel blending on marine fuel properties, behaviour, and oil spill response efficiency.



		FAME (30%)		**HVO** (30%)
		VLSFO (70%)	**MGO** (70%)	**VLSFO** (70%)
Properties	Viscosity	↘	→	→
	Density	↘	→	↘
	Pour point	↘	↗	↘
	Flash point	→	↗	→
Behavior	Spreading	↗	→	↗
	Buoyancy	↗	→	↗
	Evaporation	→	↘	→
	Emulsification			
	Natural dispersion	↗	→	-
Oil spill response efficiency	Recovery: - Mechanical - Sorbent (fresh oil)	 ↗ ↗	 → →	 → ↗
	Chemical dispersion	Non dispersible	→	Non dispersible
	In Situ Burning	Not flammable		

- Regarding the oil spill response technique, it can be stated that the addition of FAME to a marine gasoil will not influence the OSR strategies. In case of a spill in agitated conditions, a natural dispersion will occur few hours after the spill. Consequently, it is highly probable that the response time will be too long for successful OSR deployment. In case of an oil spill in calm conditions (harbour area), the natural dispersion will occur, but this phenomenon will be more progressive. For these conditions, and depending on the oil volume, a mechanical recovery (skimmer) or use of sorbent (boom, pad) can be considered as an effective strategy before the natural dispersion occur.

- Concerning the VLSFO, the oil selected for the present project was considered as the most problematic VLSFO during IMAROS 2 project. These conclusions were based on its high viscosity, pour point values and semi-solid state which affect the efficiency of mechanical recovery.
- When blended with HVO, the viscosity of the VLSFO is lower than the VLSO alone. After 7 days of weathering, the blend viscosity was in the same range than the 7-days weathered VLSFO tested during IMAROS 2 project. Consequently, it can be stated that HVO blending has no effect on viscosity of the weathered VLSFO and on mechanical recovery efficiency;
- When blended with FAME, the VLSFO become easier to recover by using skimmer due to a significant decrease in both viscosity and pour point values. This effect of FAME addition to a viscous oil to increase the efficiency of the mechanical recovery technique has already been considered in previous oil spills. Indeed, during the Erika spill (France, 1999), a product called Diester (FAME produced from rapeseed oil) was injected in the wreck to facilitate the pumping operations of the heavy fuel oil.

3. Regulatory review and gap analysis

A structured and thorough review of the regulatory frameworks governing the use of biodiesel blends in maritime fuel applications has been initiated at the international, regional (EU), and national levels. This review aims to identify the current regulatory enablers and limitations associated with the operational use of these alternative fuels, spill response, and environmental management.

Key provisions under MARPOL Annex VI and related Unified Interpretations were reviewed. Regulation 18.3 and MEPC.1/Circ.795/Rev.6 were examined, facilitating the acceptance of biodiesel blends up to B100 under specific compliance conditions. These regulations clarify that vessels using biodiesel blends up to B30 do not require additional NO_x emissions testing, and ships using B30–B100 blends may forgo retesting, provided there are no modifications to engine components that affect NO_x emissions. This development effectively removes a key barrier to the broader adoption of biodiesel in existing marine engines and aligns with the IMO's greenhouse gas (GHG) reduction goals.

At the EU level, developments under the Renewable Energy Directive (RED II), Fuel EU Maritime Regulation, and the revised EU MRV Regulation were reviewed, particularly concerning how well-to-wake emissions and CO_2 factor adjustments apply to certified sustainable biofuels. These initiatives support the transition to alternative fuels, ensuring that biodiesel blends comply with emission reduction targets set for the maritime sector.

On the national level, countries like Singapore and the United Kingdom have made significant progress in accommodating biodiesel blends up to B30 in their regulatory frameworks. These developments include updates to fuel quality assurance practices, supply chain documentation, and operational protocols that facilitate using biodiesel blends in shipping. Notably, Singapore's Maritime and Port Authority (MPA) raised the permissible limit for biodiesel blends in conventional bunker tankers from B25 to B30, eliminating the need for separate approvals.

3.1 Main instruments governing the response to marine pollution by biodiesel and biodiesel blends, and the scope of their application

3.1.1 IMO instruments

Under MARPOL Annex VI (Regulation 18.3 and the NO_x Technical Code), biodiesel blends containing up to 30 percent biodiesel (B30) automatically comply with existing NO_x limits and even blends from B30 up to pure biodiesel (B100) may be used without additional NO_x re-certification provided that no engine modifications affecting emissions have been made (MEPC 1/Circ.795/Rev.8).

Carriage and handling requirements for biodiesel blends fall under MARPOL Annex I when bio-content does not exceed 25 percent, classifying them as oil cargoes; blends above 25 percent are regulated as chemical cargoes under Annex II and must meet IBC Code standards.

However, interim guidance adopted by the PPR 12 Sub-Committee and approved at MEPC 83 (MEPC.1/Circ.917) raises the permissible bio-content on conventional bunker ships to B30, allowing these vessels to carry such blends without chemical-tanker reclassification.

Safety provisions under SOLAS Chapter II-2 now enforce a minimum fuel flashpoint of 60 °C, through amendments effective 1 January 2026, and require enhanced documentation and verification to prevent inadvertent use of lower-flashpoint fuels.

Complementing SOLAS, the ISM Code obliges ship operators to embed biodiesel-specific risk assessments, emergency procedures, and crew training within their Safety Management Systems, as guided by the April 2024 Maritime Technologies Forum recommendations.

Although primarily designed for gaseous fuels, the IGF Code's low-flashpoint fuel provisions are increasingly applied to liquid biofuels, informing system design and operational safeguards.

Other IMO guidance documents include MEPC 1/Circ.879 (2018) and MSC-MEPC.2/Circ. 17 (2019), clarify annex applicability by blend ratio, while Resolution MEPC.362(79) (December 2022) mandates the inclusion of fuel flashpoint information in the Bunker Delivery Note (effective 1 May 2024). Finally, MEPC 1/Circ.905 (2023) introduces interim guidance allowing a reduced CO_2 Emission Conversion Factor for biofuels that achieve at least a 65 percent well-to-wake GHG emissions reduction, pending final LCA methodology.

3.1.2 Industry standards

Since 2013, CIMAC Working Group 7 has issued guidance on managing marine distillate fuels containing FAME, initially focusing on blends up to B7. Following the 2024 revision of ISO 8217, these principles now extend to higher FAME concentrations. CIMAC's guidelines address fuel testing, using methods such as EN 14078 or ASTM D7371 for FAME content and EN 15751 for oxidation stability, along with storage and handling best practices, cold-flow property management, material compatibility, and maintenance to prevent microbial growth, sediment release, and filter blockage.

ISO 8217:2024 introduces new "DF" categories that allow up to 100 percent FAME, and mandates reporting of FAME content, net heat of combustion, cloud point, cold filter plugging point (CFPP), and flashpoint in line with SOLAS requirements. The standard also expands tables for residual fuels with low and high sulphur content, plus bio-residual fuels, all subject to general Clauses 5–10 to promote consistency and reduce interpretation ambiguity.

Complementary fuel-quality standards EN 14214 in Europe and ASTM D6751 in the United States define the compositional (ester content, free glycerine, acidity) and performance (oxidation stability, cold-flow) requirements for neat biodiesel (B100) before blending. Associated blended-fuel specifications (ASTM D975, D7467, D396) ensure that finished marine-diesel grades containing up to 20 percent biodiesel meet operational criteria.

At the regional level, CEN/TC 19 harmonizes sampling, analytical, and classification methods for biofuels, producing standards such as EN 16709 for B20-B30 diesel and EN 16734 for B10, which facilitate uniform testing and trade across EU member states.

3.1.3 Classification societies and IACS

IACS unified interpretations further refine IMO fuel rules. MEPC 1/Circ.795/Rev.9 (2024) clarifies that blends containing up to 30 percent bio or synthetic fuel satisfy MARPOL VI Regulation 18.3.1, while higher blends fall under Regulation 18.3.2 but may be used without reassessment if onboard NO_x testing confirms compliance with Technical Code limits. IACS Unified Requirements M71 and M51 guide engine type-approval based on distillate-grade testing and recommend shipboard trials for higher-blend fuels to verify engine performance and reliability.

In December 2023, the Indian Register of Shipping published "Use of Biofuels on Ships," offering comprehensive guidance on fuel specifications (FAME, HVO, BTL), tank arrangements, material compatibility, trial procedures, and NO_x measurement and verification, thereby supporting safe biodiesel integration into vessel operations.

3.1.4 EU "Fit for 55" Package

The EU's Renewable Energy Directive II (RED II) mandates that at least 14 percent of transport energy derive from renewables by 2030, rising to 40 percent under the proposed RED III. Sustainable biofuels like FAME and HVO qualify if they meet stringent GHG savings and sustainability criteria. The Fuel EU Maritime Regulation, effective from 2025, requires progressively reduced GHG intensity of fuels used on board ships above 5000GT, offering certified biofuels a key compliance pathway.

The EU Emissions Trading System (ETS) includes maritime activities, obliging operators to surrender allowances for CO_2 emissions; however, emissions from compliant biofuels carry a zero-emission factor, exempting them from surrender. The Fuel Quality Directive and Energy Taxation Directive further drive lifecycle GHG reductions and restructure tax rates to favour low-carbon fuels, creating robust economic incentives for biodiesel adoption.

3.1.5 National practices

Singapore's Maritime and Port Authority increased the permissible biodiesel blend limit from B25 to B30 in 2022, standardizing quality requirements, certification, and documentation to facilitate cleaner bunkering.

The United Kingdom's Renewable Transport Fuel Obligation sets a 12.4% renewable-energy target by 2032, with tradable certificates (RTFCs) incentivizing biodiesel supply.

In the United States, the EPA enforces MARPOL Annex VI through 40 CFR 1043 under the Act to Prevent Pollution from Ships, while the Renewable Fuel Standard mandates biofuel blending across transport fuels.

Canada aligns its Pollution from Ships Regulations with MARPOL VI and imposes renewable-content mandates for diesel.

In China, Domestic Emission Control Areas incentivize low-sulphur biodiesel to meet DECA limits.

Japan's 2020 Roadmap to Zero Emission foresees biofuels supplying 40 percent of international-shipping energy by 2050.

South Korea's ECAs enforce a 0.10 percent sulphur cap in port areas, allowing biodiesel blends as a compliance strategy.

The Panama Canal Authority accepts compliant biofuel blends for transit under Notice N-1-2020.

India's Merchant Shipping Notice of November 2023 prescribes EN 14214 or ASTM D6751 compliance, Proof of Sustainability certification, and adherence to manufacturer limits on fuel properties.

Australia limits diesel to B5 blends, though future carbon-reduction targets may expand maritime biodiesel use.

Annex VI presents a comprehensive summary of the regulatory review and offers detailed insights into the current state of biodiesel-related regulations.

3.2 The regulatory gap analysis identified several areas requiring further attention

3.2.1 Gaps in existing IMO regulations (MARPOL Annex I and II)

Although MARPOL Annexes I and II comprehensively regulate oil and noxious liquid substance spills, biodiesel blends beyond B30 fall into a regulatory grey area. It is unclear whether such blends should invoke oil-spill response protocols under Annex I or chemical-spill procedures under Annex II, creating uncertainty for responders regarding appropriate equipment, dispersants, and procedures during accidental releases.

3.2.2 Behaviour of biodiesel blends in marine spills

Current international frameworks lack standardized datasets or models for predicting how biodiesel blends behave when released into the marine environment. Unlike petroleum, biodiesel's higher biodegradability, altered spreading, emulsification, microbial degradation dynamics, and its potential to deplete oxygen in confined waters are not captured by existing fate-and-transport tools, hindering accurate impact assessments and response planning.

3.2.3 Spill response techniques: lack of testing for biodiesel

Conventional containment and recovery techniques, booms, skimmers, dispersants, and sorbents, were developed for petroleum oils and have not been systematically evaluated for biodiesel blends. Lower viscosity and higher solubility may undermine boom and skimmer performance, while dispersants and sorbents optimized for hydrocarbons may be ineffective against polar biodiesel components. This underscores the need for dedicated testing and development of tailored response materials.

3.2.4 Gaps in international spill preparedness frameworks

Key preparedness conventions and regional contingency plans under the IMO OPRC Convention focus exclusively on petroleum hydrocarbons and provide no biodiesel-specific operational guidance. Without protocols addressing biodiesel's rapid biodegradation, water solubility, and distinct emulsification behaviour, responders risk deploying inappropriate or ineffective strategies during a biodiesel incident.

3.2.5 Gaps in technical standards (ISO and ASTM)

Although ISO 8217 and ASTM biodiesel standards set rigorous fuel-quality parameters, they do not encompass spill-response considerations. No internationally recognized methodologies for monitoring biodiesel spills, guiding containment and recovery, measuring environmental impacts, assessing biodegradation rates, or modelling oxygen demand, leaving a technical void in regulatory guidance.

3.2.6 Operational preparedness gaps (OSROs and national plans)

Oil Spill Response Organizations and national contingency plans remain structured around petroleum scenarios, lacking biodiesel-specific equipment, sorbents, monitoring tools, or operational plans. This gap exposes ports and coastal authorities to vulnerabilities when confronting biodiesel incidents, as existing assets may prove ill-suited to address biofuel-related challenges.

3.2.7 Training and awareness deficiencies

Current IMO model courses, regional workshops, and industry training programs do not include biodiesel-specific spill-response content. Consequently, response personnel, ship operators, and regulators may be unprepared for biodiesel spills' unique hazards and operational requirements, delaying effective action and potentially exacerbating environmental impacts.

Annex VII outlines the identified regulatory governance gaps and areas requiring further work to facilitate the safe and efficient use of biodiesel blends in maritime transport.

3.3 Developing and updating biodiesel/blends regulatory frameworks and data needed

3.3.1 Regulations and guidelines to clarify fuel classification

MARPOL Annexes I and II should be amended to explicitly classify biodiesel blends by bio-content, e.g., up to B30 under Annex I oil-spill provisions and above B30 under Annex II chemical-spill provisions, with clear criteria for transitional blends. Similarly, the IMO should issue a dedicated circular or guideline defining this threshold and outlining the requisite response protocols and approved dispersants. This will eliminate the current ambiguity over whether a biodiesel spill is treated as an oil or chemical incident, ensuring that responders know which annex procedures to follow immediately.

■ Dedicated IMO Guidelines for biodiesel spill response

Building on the gaps identified in existing OPRC frameworks, the IMO should develop a stand-alone “Biodiesel Spill Response Guide” under the OPRC Convention. This guide would cover detection, containment, recovery, and biodegradation management tailored to FAME/HVO blends, and specify monitoring metrics (e.g., oxygen demand, emulsification rates). Incorporating biodiesel scenarios into SOPEP/SMPEP templates will ensure that ships and ports proactively plan for such incidents rather than defaulting to petroleum-focused strategies.

3.3.2 ISO and ASTM standards expansion

International fuel-quality standards – ISO 8217, ASTM D6751, D7467 – must be extended to include spill-response protocols. New annexes should specify test methods for sorbent capacity, dispersant efficacy against biodiesel, and rapid field assays for blend identification in water. Embedding these requirements into ISO and ASTM will drive uniformity in equipment certification and force suppliers to provide spill-response data alongside fuel-quality certificates.

3.3.3 Operational manuals and training updates

Oil Spill Response Organizations' operational manuals and national contingency plans should be revised to include biodiesel-specific equipment lists (e.g., polar sorbents), oxygenation tools, and microbial containment measures. IMO Model Courses and regional training programs must add modules on biodiesel spill characteristics, response tactics, and use of updated guidelines, closing current awareness and preparedness gaps among responders, ship crews, and port authorities.

3.3.4 Environmental fate and behaviour research

Comprehensive studies should be commissioned to generate standardized datasets on biodiesel blend fate in seawater, covering spreading coefficients, emulsification kinetics, weathering rates, oxygen depletion dynamics, and microbial degradation pathways. These data will inform predictive modelling tools and improve impact assessments, addressing the lack of unified international standards for spill-behaviour prediction.

3.3.5 Response technique validation studies

Systematic laboratory and field trials should be undertaken to evaluate the performance of existing booms, skimmers, dispersants, and sorbents against biodiesel blends. Comparative efficacy data will guide the development of adapted or novel containment materials and dispersant formulations, filling the current void where petroleum-optimized tools may underperform or fail when exposed to polar biofuel components.

3.4 Overview of regulatory review and gap analysis

Existing frameworks like MARPOL Annexes I, II, and VI partially regulate biodiesel use and carriage, particularly up to B30 blends. ISO 8217:2024 provides detailed specifications for biodiesel quality, including flashpoint and FAME content. Interim IMO circulars allow B30 carriage on oil tankers and clarify NOx compliance without retesting. However, pollution response frameworks like OPRC and OSROs are still petroleum focused. Some national regimes (e.g., Singapore, India) provide operational guidelines, but few address spill-specific response measures.

Significant gaps exist in spill classification, response planning, and training for biodiesel blends. MARPOL lacks clear categorization for B30+ blends during accidental releases, complicating emergency responses. OPRC, IMO model courses, and national contingency plans do not yet account for biodiesel's unique behaviour. ISO and ASTM standards cover fuel quality but omit spill monitoring or biodegradation protocols. No validated equipment, sorbents, or procedures are available for biodiesel-specific spill response.

Dedicated IMO guidelines should be developed for biodiesel spill classification, response, and equipment use. OPRC conventions and model training courses need revision to include biodiesel-specific risks and techniques. ISO and ASTM standards should introduce modules for biodiesel spill behaviour, monitoring, and biodegradation. Updates to SOPEP and SMPEP should reflect onboard procedures for biodiesel blends. Regional response agreements and OSRO protocols must incorporate biofuel capabilities and tools.

Missing elements include predictive models for biodiesel spill fate, weathering, and biodegradation under real-world conditions. Comparative data on equipment performance (booms, skimmers, dispersants) with biodiesel is scarce. No standardized monitoring methods exist for biodiesel in spill scenarios (e.g., oxygen demand or solubility). Gaps also include toxicity data for biodiesel components and chronic environmental effects. Field validation studies and scenario-based training are urgently needed to inform new standards.

4. Response measures, technology, and equipment analysis

4.1 Response measures analysis

4.1.1 Aerial surveillance

■ Overview

Pollution detection and reconnaissance missions aim to fulfil two distinct purposes [18]:

- firstly, they can be carried out routinely to detect and collect evidence for the repression of operational discharge by ships; and
- secondly, aerial observation is used in the event of a spill to support response operations at sea.

Aerial detection can be realized by observation platforms (aircraft, unmanned aerial vehicles (drones), tethered aerostats, satellites, etc.). Detection can be performed visually or using remote sensing equipment (range of techniques used to detect and identify phenomena from a certain distance, either through human capacities or special sensors). In the case of aerial observation of oil pollution, remote sensing relies on the use of detection systems, including SLAR (Side-Looking Airborne Radar), FLIR (Forward-Looking Infrared Radiometer), infrared, and ultraviolet scanners, as well as microwave radiometers [18].

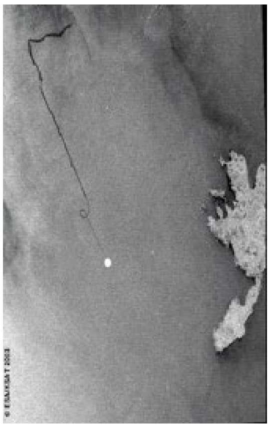


Figure 57. Aerial detection of an ongoing discharge. The polluting vessel is represented by a white dot. Envisat ASAR wide ©ESA/KSAT 2003

Figure 58. Oil spill observed by French Customs ©French custom/Polmar2

■ Equipment for aerial detection

Table 9 presents the main types of existing detectors and their key characteristics.

Table 9. Main types of existing detectors and key characteristics [19].

DETECTOR NAME	**Synthetic Aperture Radar (SAR)**	**Side-Looking Airborne Radar (SLAR)**	**Microwave Radiometer (MWR)**	**Laser Fluorosensor (LFS)**	**Sonar, single or multibeam**	**(Visible + infrared)**	**Multispectral optical and thermal (Visible and infrared)**	**Raman spectroscopy**	**Ultraviolet (UV)**	**Video and photography**	**Human observer**
	USAGE CHARACTERISTICS										
Detection method	Backscatter	Backscatter	Microwave emission	UV-induced fluorescence	Echo sounder	-	Reflectance	-	Reflectance	Reflectance	Reflectance
Sensor type	Active	Active	Passive	Active	Active	-	Passive	Active	Passive	Passive	Passive
Satellite/Aircraft/ RPAS/vessel	Satellite	Aircraft	Aircraft/RPAS	Aircraft/RPAS	Vessel/ROV	-	Aircraft/RPAS/ vessel	RPAS	Aircraft/RPAS	Satellite/Aircraft/ RPAS	Aircraft
	ENVIRONMENTAL CONDITIONS										
Time of day	All	All	All	All	All	IR: 24h	Vis: Daylight only TIR: 24h	All	Daylight only	Daylight only	Daylight only
Atmospheric limitations	None	None	Clear skies only	Clear skies only	None	-	Clear skies only	Clear skies only	None	Clear skies only	Clear skies only
Sea surface (in Beaufort - Bft)	1 < Bft < 6	1 < Bbt< 6	1 < Bft < 6	0-3 Bft <	-	-	0-3 Bft <	-	0-3 Bft <	0-3 Bft <	0-3 Bft <
	DETECTABLITY										
Location of detected HNS	Sea surface	Sea surface	Sea surface	Sea surface	Sea bottom	-	Atmosphere (IR: 5-12 μm), sea surface (if in the visible spectrum)	Sea surface	Sea surface	Sea surface (if in the visible spectrum)	Atmosphere, sea surface (if in the visible spectrum)
Examples	Xylene	Vegetable oil	-	Benzene	-	-	-	-	Styrene, xylene		
	LIMITATIONS										
Operational	False positives, look-alikes	False positives, look-alikes	Need comparison of spectra recorded in a database. In some cases, only substance transmission databases may be required	A database of spectra associated with the types of substances being investigated. In some cases, only substance transmission databases may be required	Long delay of screening for uncertain position	In some cases, only substance transmission databases may be required	False positives, look-alikes A database of spectra associated with the types of substances being investigated. In some cases, only substance transmission databases may be required	A database of spectra associated with the types of substances being investigated. In some cases, only substance transmission databases may be required	-	False positives, look-alikes	HSE limits, fatigue, difference in interpretation, false positives
Determining thickness	No certified method for determining thickness	No certified method for determining thickness	No measurement if thickness < 50 μm	Identification possible If 0.1 < thickness < 10 μm	-	Detection only for lowest thickness values	~ 10 μm	-	~ 0.1 μm	No certified method for determining thickness	No certified method for determining thickness

- **Oil spill characteristics**

Many parameters should be considered before using aerial detection in oil spill response (environmental conditions, type of oil, etc.). The following elements refer only to the main physicochemical parameters of the oil:

- **Density**

The oil must be floating (density of less than water density). The density of seawater varies, but it is 1.025.

- **Viscosity and thickness**

In the case of oil with a very low viscosity (about 10 cSt), thin films (sheen, rainbow, or metallic) which are silvery and/or coloured (in the case of light refined products or small widely spread spills), with a thickness of a few microns (< 50,000 l/km^2) can be difficult to detect.

- **Weathering (colour and natural dispersibility)**

Slicks can have varying appearances [20]:

- thin films (sheen, rainbow or metallic) which are silvery and/or coloured (in the case of light refined products or small widely spread spills), with a thickness of a few microns (< 50,000 l/km^2);
- slicks of varying thickness with dark discontinuous colour (black or brown depending on the product), often surrounded by thin films (sheen, rainbow or metallic), depending on the degree of weathering – thickness of 50 to 200 μm (50,000 to 200,000 l/km^2):
  - black slick and thin film: recent spill, light weathering; and
  - brown to red slick with gradual disappearance of thin films: emulsion weathered by several days at sea;
- thick patches with clear edges, usually dark brown to orange in colour and sometimes surrounded by thin films (patches of very weathered emulsion having been at sea for a week or more), substantial in thickness, 0.2 to 3 cm and more, i.e., 200,000 to 30,000,000 l/km^2, or more in the case of extremely viscous oil or emulsions; and
- tar-balls of emulsion resulting from the fragmentation of thick patches into increasingly small elements, which are increasingly difficult to detect.

For aerial detection, the pollutant must remain floating and not disperse naturally.

4.1.2. Application to biodiesel blends with marine bunker fuels

Regarding the three biodiesel blends with marine bunker fuels studied in this project, these three oils have a relative density under 1,025.

Nevertheless, for the B30 FAME/VLSFO and the B30 HVO/VLSFO, the tests in Polludrome® showed that their density increases close to 1.000. Thus, if the weathered pollutant drifts into brackish water, it may pass below the surface, making aerial detection more difficult, if not impossible.

In addition, for the B30 HVO/VLSFO, its weathering leads to a fragmentation of the slick in tar-balls of emulsion (Figure 14), which are increasingly difficult to detect.

For the B30 FAME/MGO (fresh or weathered), thin films (sheen, rainbow or metallic) can appear in case of slick with a thickness of a few microns (< 50,000 l/km^2), which can make aerial observation more difficult.

Furthermore, for the weathered B30 HVO/VLSFO, in case of rough seas, its natural dispersion will make aerial detection impossible (Figure 14).

Table 10 summarizes the physicochemical properties that influence the effectiveness of aerial detection and compares them with those of three biodiesel blends with marine bunker fuels studied in this project.

Outside the limits indicated above, EMSA SAR detection and/or the other detection methods presented in Table 9 is suitable for these products.

Table 10. Summary of physicochemical properties affecting aerial detection efficiency.

Note: Green numbers indicate a property suitable for aerial detection. Red numbers indicate a property not suitable for aerial detection. Grey properties indicate a property not influential for aerial detection.

Properties	Oils characteristics (Literature data)	B30 FAME/VLSFO		B30 HVO/VLSFO		B30 FAME/MGO	
		Fresh	7-days weathered	Fresh	7-days weathered	Fresh	7-days weathered
Density	< d sea water (approx. 1,025)	0.912	1.001	0.884	1.004	0.846	0.871
Viscosity (cSt)	Oil with a very low viscosity can be difficult to detect in case of high spread	156	6360	200	80,000	3	9
Pour point	/	24	No data	18	No data	-18	No data
Vapor pressures	/	No data	No data	No data	No data	No data	No data
Flash Point (°C)	/	> 100	> 100	93.5	> 100	70	> 100
Evaporation	/		0		0		0
Emulsification (%)	/	0	85.4	-	85	-	1.2
Thickness (mm)	More difficult with low thickness	Significant spread expected	Moderate spread expected	Significant spread expected	Low spread expected	Very large spread expected	Very large spread expected
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Comments	Tar balls of emulsion resulting from the fragmentation of thick patches into increasingly small elements, which are increasingly difficult to detect				Formation of tar-balls of emulsion		

4.1.2 In-situ burning

■ Overview

In-situ burning (ISB) is the controlled combustion or burning of spilled oil's hydrocarbon vapours in place.

The fundamentals of ISB are like those of any fire, namely that fuel, oxygen, and heat are required for oil to ignite. In the event of an oil spill, the oil vapours provide the fuel to support combustion. Fresh oil will typically ignite once an ignition source is applied. As oil vapor burns, the heat causes more vapours to be released, known as vaporization. The burn rate is limited by the amount of oxygen available, and the heat radiated back to the oil. The burn rate will also rely on the type of oil and its weathering degree, e.g. evaporation, emulsification [21].

ISB operation release large amounts of soot, carbon dioxide, sulphur dioxide, nitrogen oxides, and other harmful pollutants into the atmosphere, contributing to air quality degradation and potential health risks for nearby communities and wildlife. At the same time, burn residue are generated during ISB operations. Even if volume of burn residue is very low compared to the volume of crude oil spilled, its mechanical recovery is difficult and rarely conducted. Therefore, burn residue tend to persist for years in the environment and most of the time on the seabed.

Due to these environmental drawbacks, ISB is not permitted in most countries and rarely integrated in contingency plans.

Figure 59. In-situ burning. Deepwater Horizon © US Coast Guard.

■ Equipment for in-situ burning

At sea, the basic process is as follows: (a) collect oil using a fire-resistant containment boom; (b) slowly pull the fire-resistant boom against the water current to push oil into the boom apex and increase the slick thickness; and (c) ignite the oil. In most cases, the fire-resistant boom is deployed downwind of the spill, and a tow is put in place [21].

Fire-resistant booms are designed to maintain their integrity during containment operations on a burning slick (controlled in situ burn or accidental fire) [21]. Fire booms are booms specifically developed to withstand extreme heat during burning. They are used to contain the oil slick, control its drift, and manage the burn by varying the thickness of the slick. Main manufacturers of fire booms are Elastec (American Fireboom and Hydro-Fire® Boom) and DESMI (PyroBoom®).

Igniters are launched in the thickest part of the slick. Some igniters consist of a 2L bottle filled with a mixture of diesel and gasoline. The easy ignition of this equipment heats the underlying oil, increasing its vaporization rate and potential for ignition. Once burning, oils will burn well, and even emulsified oil can break down and burn [21].

Figure 60. Elastec Fire Boom MKII ©EMSA.

Oil spill characteristics

Many parameters should be considered to use ISB in oil spill response (environmental conditions, type of oil, specific equipment, training, regulation, etc.).

The following elements refer only to the physicochemical parameters of the oil [20]:

- **Density and API gravity**

The oil must be floating (oil density lower than water density). The density of seawater varies, but it is 1.025.

Most crude oils are suitable for ISB, as long as their API gravity is at least 20° (specific gravity: 0.934) [23].

API gravity was identified by SL Ross Environmental Research as a single, good predictor of success for in situ burning. Light oils with API gravities higher than 35° (specific gravity: 0.850) burn easily, and heavy oils with API gravities lower than 20° (specific gravity: 0.934) are difficult to ignite or unignitable. Oils with intermediate API gravities ranging from 20° to 35° have various degrees of ignitability, depending on their degree of emulsification [23].

- **Flash Point and vapor pressures**

Oils with flash points below 37,8 °C and vapor pressures below 40 psi (about 275 kPa) should not be considered for ISB due to the risk of an uncontrollable fire. Such flammable products include gasoline [23].

The Globally Harmonized System of Classification and Labelling of Chemicals (GHS) define several categories of flammable products only for flash point up to 60°C.

- **Water content (Emulsification)**

In general, unstable oil emulsions can be ignited and will sustain burning, as the emulsion breaks down quickly during the burning process. By contrast, stable oil emulsions are difficult to ignite because of the large amount of energy required to heat the water (so that it vaporizes) and then heat the spilled oil [21].

As soon as the slick forms a water-in-oil emulsion with around 25% water content, the ignition capacity drops. Water-in-oil emulsion of over 50% will preclude in-situ burning of even light crudes or refined products, while much less than that is required for heavier crudes [24]. Highly emulsified and heavy oils are very difficult to burn compared to light oils as they do not readily vaporize. Emulsified oils typically have burning efficiencies of 30–60 percent, whereas very light oils, such as gasoline, burn at efficiencies of 95–99 percent [23].

- **Thickness**

Fresh crude oil needs to be at least 1 mm thick to yield enough vapours to allow ignition on water, while oil that has undergone extensive weathering may need to be between 2–5 mm thick. In general, most oils on water will burn if slicks are more than 2–5 mm thick [21], [23]. Once ignited, to burn on the water, oil must be thicker than 1-2 millimetres. During combustion, the oil vapours ignite and burn, rather than the liquid itself. About 2-3% of the heat generated by the combustion is returned to the oil layer, where it causes additional vapours to escape and burn. When the oil layer is thinner than 1-2 mm, the heat is lost in the underlaying water, not enough vapours are released, and combustion stops progressively [24].

- **Weathering and natural dispersibility**

ISB is most effective when employed shortly after the spill before the lightest chemical fraction is lost due to the evaporation process (within 72 hours for most oil types, or within 1-2 hours for heavy or thick oils) [23].

The pollutant must remain floating and not disperse naturally.

- **Oil compound and VLSFO**

Physicochemical properties of oil can also influence the efficiency of ISB.

During IMAROS project, three VLSFO were tested for in situ burning, using a dedicated test bench to assess the possibility of using the in-situ burning technique, in terms of both efficiency and potential impacts.

Following the usual protocol of 10 seconds ignition, burning of the 3 oils was considered not successful. Additional attempts were carried out by increasing the ignition time (not exceeding 10 minutes). Two of the three VLSFO tested by this way caught in fire. The last one burnt only with the addition of a jelly igniter.

Once burning was initiated (regardless of technique), it lasted about 10 minutes and was not characterized by a burning efficiency of more than 15%. These results suggest that this technique is not possible to be applied in real conditions considering a spill involving VLSFO.

■ Application of ISB to spills of biodiesel blends with marine bunker fuels

Due to their physicochemical properties – low concentration of light chemical compounds, high flash point –IBS is not applicable to the 3 blends of biodiesel with marine bunker fuel tested during this study. Furthermore:

- For the B30 FAME/VLSFO and the B30 HVO/VLSFO, these oils are in majority composed of VLSFO. Thus, and even though all VLSFOs are different, previous studies have shown that the ISB does not seem to apply to VLSFOs.
- For the weathered B30 FAME/VLSFO and the B30 HVO/VLSFO, the tests in Polludrome® showed that their density increases close to 1.000. Thus, depending on the water density, it may pass below the surface, making ISB more difficult, if not impossible.
- For the weathered B30 HVO/VLSFO, its weathering conduct to a fragmentation of the slick in tar-balls of emulsion (Figure 27), making ISB impossible.
- For the weathered B30 FAME/MGO, in case of rough water, its natural dispersion will make ISB impossible (Figure 38).

Table 11 below summarizes the physicochemical properties that influence the effectiveness of ISB and compares them with those of three biodiesel blends with marine bunker fuels studied in this project.

Table 11. Summary of physicochemical properties affecting ISB efficiency.

Note: Green number indicate a property suitable for ISB, red numbers indicate a property not suitable for ISB. Grey properties indicate properties not influential for ISB.

		B30 FAME/VLSFO		B30 HVO/VLSFO		B30 FAME/MGO	
Properties	**Oils characteristics (Literature data)**	**Fresh**	**7-days weathered**	**Fresh**	**7-days weathered**	**Fresh**	**7-days weathered**
Density	< d sea water (approx. 1.025)	0.912	1.001	0.884	1.004	0.846	0.871
API gravity	< 20° API (difficult to ignite or unignitable) > 35° API (easily ignited)	23.7	9.9	28.5	9.44	35.8	30.9
Viscosity (cSt)	/	156	6,360	200	80,000	3	9
Pour point	/	24	No data	18	No data	-18	No data
Vapor pressure	< 40 psi	No data	No data	No data	No data	No data	No data
Flash Point (°C)	< 37.8°C (for safety reason) < 60°C (for operational reason)	> 100	> 100	93.5	> 100	70	> 100
Evaporation	/		0		0		0
Emulsification (%)	> 25% (ignition capacity drops) > 50% (precludes ISB)	0	85.4	-	85	-	1.2
Thickness (mm)	> 2 mm - requires containment	Significant spread expected	Moderate spread expected	Significant spread expected	Low spread expected	Very large spread expected	Very large spread expected
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Comments					Formation of tar balls of emulsion		

4.1.3 Chemical dispersion

■ Overview

Dispersants are liquid mixtures of solvents and surfactants. The surfactants concentrate at the oil-water interface and modify the existing equilibrium between natural dispersion and emulsification: they limit the formation of a reverse emulsion sometimes called a, “chocolate mousse” (which contains water droplets in oil) and enhance dispersion (by fragmenting the surface oil film into droplets that are suspended in the water column, due to the reduction of interfacial tension between oil and water) [20].

In other words, the combined effect of spraying dispersants and the natural agitation of the sea surface contributes to reduce the emulsification process and to increase the proportion of oil suspended in water: this is the primary dispersion phase. Subsequently, the action of currents and natural turbulence will disseminate or “disperse” oil droplets in a larger volume of water: this is the secondary dispersion phase [20].

Dispersants can be sprayed by ships, helicopters, and planes (small, average, or large size) (Figure 61). Dispersants must be applied using a suitable spreading device to obtain an adequate and uniform plume (between 400 and 700 µm) [20].

Dispersants break oil into smaller droplets, which can sink and form underwater plumes, potentially harming benthic (seafloor) organisms and deep-sea habitats in case of high concentrations. This is the reason chemical dispersion must be deployed in open sea far from the shoreline or sensitive area to ensure a rapid dilution of oil plume.

Many countries require pre-approval or case-by-case authorization for dispersant use, often involving environmental impact assessments and coordination with multiple agencies.

Figure 61. Deepwater Horizon accident. Chemical dispersion. ©US Coast Guard.

■ Equipment for chemical dispersion

Chemical dispersion systems, also known as dispersant spreading systems, can be mounted on aircraft, ships, or carried by operators. Regardless of the support, they are typically composed of [20]:

- one or more dispersant tanks;
- a filter to remove solid impurities that could clog the system. Filters are usually placed upstream of the pump to protect it from clogging, and upstream of the nozzles to protect them from clogging;
- a feed pump. Depending on requirements, different types of pumps can be used (peristaltic, centrifugal, piston, gear, diaphragm, etc.);
- one or more supports for the nozzle(s). These supports can take the form of ramps, gantries, or various types of lances, for example; and
- one or more calibrated nozzles. These nozzles are preferably equipped with valves that close when the pressure decreases, thus preventing leaks and keeping the entire device full of dispersant when spraying stops. The whole piping system remains full when the pump stops, allowing for a very short response time when the pump is restarted. The nozzle influences the flow rate, the size of the droplets (diameter of the orifice), and the

shape of the spray (shape of the orifice). Nozzles can produce sprays:

- full cone;
- hollow cone - concentrating the dispersant on the outer edges of the cone; and
- flat or fan - producing a narrow elliptical spray.

The development of dispersion systems now makes it possible to spray droplets of an appropriate size, and for some, to vary the dispersant/oil ratio to cope with different slick thicknesses.

Depending on the viscosity of the dispersant, certain devices may be more appropriate. Indeed, the use of dispersants that are too viscous (for example, with a viscosity of 70 cSt at 20°C) can produce a stick-like jet rather than a homogeneous spray of droplets at the nozzle outlet with certain devices. In this case, this can cause the spray to break up.

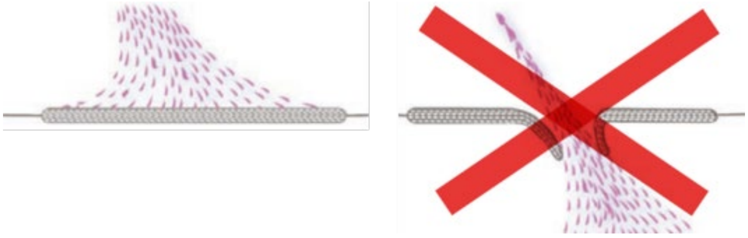


Figure 62. Dispersant has to be sprayed on the oil [20].

There are two main categories of dispersion devices:

- those in the form of ramps with multiple nozzles (Figure 63-67); and
- those in the form of a single nozzle (Figure 68-70).

Figure 63. Spraying dispersant using a helicopter and a bucket. © French Navy.

Figure 64. Spraying dispersant using a ship and a spray arm. © Total.

Figure 65. Aerial spraying of dispersants using an aircraft and a spray arm. © Cedre.

Figure 66. Spraying dispersant using a boat and two nozzles. © Clean Caribbean & Americas, s.d.

Figure 67. Spraying dispersant using a boat and a container based dispersant system. © Jason Engineering.

Figure 68. Spraying dispersant using manual equipment. © Vikoma.

Figure 69. Ayles Fernie Single Nozzle Boatspray 200 © Cedre.

Figure 70. New Naval ScoreSpray Arms YMC105 [22].

Oil spill characteristics

Many parameters should be taken into account in order to use chemical dispersion in oil spill response (environmental conditions, type of oil, type of dispersants, regulation, etc.) [20].

The following elements refer only to the main physicochemical parameters of the oil, which are essential in determining whether chemical dispersion is possible:

- **Density**

The oil must be floating (density of less than water density). The density of seawater varies, but it is 1.025.

- **Viscosity**

Oil viscosity is a reasonable indicator of the effectiveness of chemical dispersion [20], [23]:

- < 500 cSt (pollutant viscosity): Dispersion is easy;
- 500 cSt < pollutant viscosity < 5,000 cSt: Dispersion is usually possible;
- 5,000 cSt < pollutant viscosity < 10,000 cSt: Uncertain efficiency: dispersion is sometimes possible, but it must be checked on part of the slick whether the dispersant is effective before extending the treatment to the totality of the slick; and
- 10,000 cSt (pollutant viscosity): Dispersion is impossible.

- **Pour point**

Dispersion is impossible when the temperature is a few degrees below the pour point with paraffinic (waxy) oil [20].

- **Thickness**

As a rule, and because of the low persistence of the light fraction, chemical dispersion at sea is not considered a necessary/relevant option for micrometre-thick films (< 50 µm, corresponding to appearance codes 1 to 3).

- **Weathering and natural dispersibility**

The pollutant must remain floating and not disperse naturally.

For those staying afloat, due to the evaporation of light fraction and incorporation of water, the viscosity increases, and the oil dispersibility decreases. Each oil is characterized by a specific time window of opportunity for dispersant use.

Regarding LSFO, during IMAROS project, dispersibility test (according to IFP tests) performed at 15°C on 13 fresh oils, their residue 250°C+ and their emulsions formed from the residue 250°C+ with 50% water content show that some LSFO could be treated with dispersant when fresh. However, when weathered, the efficiency of this technique seems highly reduced. This response option seems thus to be very limited considering spills involving LSFO.

Regarding light products (e.g. petrol, diesel, kerosene), their treatment is possible, but is not recommended as the pollutant evaporates or disperses naturally [20].

Application of dispersants to spills of biodiesel blends with conventional marine fuels

Tests of chemical dispersion were conducted on the three blends of biodiesel with marine fuel oil:

- For the B30 FAME/VLSFO, the fresh blend can be considered as dispersible. However, due to the influence of the weathering process (emulsification in this case), the viscosity increases rapidly, and the chemical dispersion rate decreases at the same time. After 8 hours of weathering, the B30 FAME/VLSFO is considered as potentially dispersible. After 2 days of weathering, this blend is not dispersible. The time window-of-opportunity to disperse the B30 FAME/VLSFO must be considered.
- For the B30 HVO/VLSFO, due to its high viscosity value, this blend is not dispersible.
- For the B30 FAME/MGO, IFP test shows a chemical dispersibility of 82%. Nevertheless, its treatment is possible, but not necessary, due to its natural dispersion.

Table 12. Summary of physicochemical properties affecting chemical dispersion efficiency.

Note: Green numbers indicate a property suitable for chemical dispersion, red numbers indicate a property not suitable for chemical dispersion. Grey properties indicate properties not influential for chemical dispersion.

		B30 FAME/VLSFO		B30 HVO/VLSFO		B30 FAME/MGO	
Properties	**Oils characteristics (Literature data)**	**Fresh**	**7-days weathered**	**Fresh**	**7-days weathered**	**Fresh**	**7-days weathered**
Density	< d sea water (approx. 1.025)	0.912	1.001	0.884	1.004	0.846	0.871
Viscosity (cSt)	< 10,000 cSt	156	6,360	200	80,000	3	9
Pour point	Impossible when the temperature is few degrees below the pour point with paraffinic (waxy) oil Based on water temperature: 14°C*	24	No data	18	No data	-18	No data
Vapor pressures	/	No data	No data	No data	No data	No data	No data
Flash Point (°C)	/	> 100	> 100	93.5	> 100	70	> 100
Evaporation	/		0		0		0
Emulsification (%)	/	0	85.4	-	85	-	1.2
Thickness (mm)	> 50 µm (code 4 or 5 of Bonn Agreement)	Significant spread expected	Moderate spread expected	Significant spread expected	Low spread expected	Very large spread expected	Very large spread expected
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Chemical dispersibility (IFP tests) (%) **	/	0,7	Not dispersible	15	Not dispersible	82.2***	Natural dispersion
Comments							

*: By 2024, Europe's seas will have reached their mean annual surface temperature of 13.73°C (Copernicus Climate Change Services, 2025).

**: Chemical dispersibility tests have been done at Cedre with FINASOL ASR 52 dispersant at 20 °C

***: Possible but not recommended due to natural dispersion

4.1.4 Containment and recovery

■ Overview and equipment for skimmer recovery

Floating pollutants are recovered by specific means (individual skimmers, skimming barges, etc.) or by net- or trawl-type collecting devices. This equipment can be used in both static and dynamic mode.

Recovery at the water surface with a skimmer is more efficient when slicks are thick and unfragmented. It is therefore always best to recover the spill on the water as early and as close to the source as possible, provided it is safe to do so, and to concentrate the slick before recovery, either by promoting natural containment or by using containment booms [19], [25].

- *Containment boom*

Booms contain floating pollutants using a flexible or rigid screen maintained at the surface of the water body by one or more floats. Booms are kept upright in the water by their ballast. Within a boom section, 5 components can generally be identified: the flotation chamber, the skirt or screen, one or more longitudinal tension members, the ballast, and the connectors [19], [25].

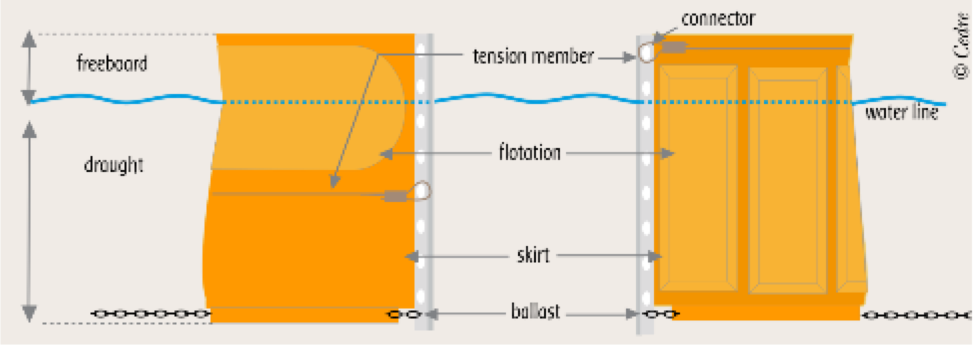


Figure 71. Schematic diagram of a boom © Cedre

Various types of booms could be employed, depending on the conditions (weather, sea state, open sea/harbour) and the area of sea surface involved. For instance, the overall height of booms used offshore can reach up to 3 m [19], [25].

Containment systems are limited by several factors [19], [25]:

- weather and sea conditions, particularly the sea state. Depending on the type of boom, containment is likely to fail in strong currents (> 2 knots) and high waves (>1m);
- availability of towing vessels;
- coordination necessary between vessels; and
- chemical compatibility.

- *Skimmers*

Recovery of a spill at the water surface comprises a chain of operations and equipment. Skimmers are specially designed to remove the pollutant from the water as selectively as possible and transfer it to a storage capacity using appropriate hoses. Skimmers should, therefore, be considered as one element in a broader set-up and are used in association with a pump system, which may be part of the skimmer, as well as a concentration and containment system, in the form of a manufactured floating boom. Such systems can be integrated on board a recovery vessel or port cleaning boat, which may or may not comprise its own storage capacity booms [19], [26].

There are two main methods of collecting the pollutant at the water surface contained by booms [19], [26]:

- mechanical recovery, which is based on the fluid properties of the water and pollutant mixtures and the differences in density between the pollutant and the water (Figure 72);
- oleophilic recovery, which is based on the adhesive properties of the pollutant on materials placed in contact with the water and the pollutant (Figure 73).

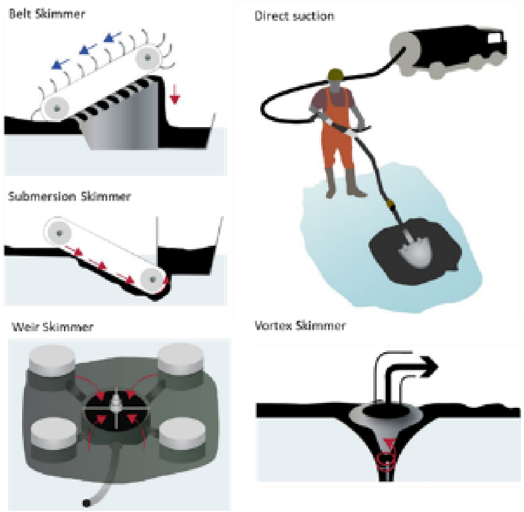
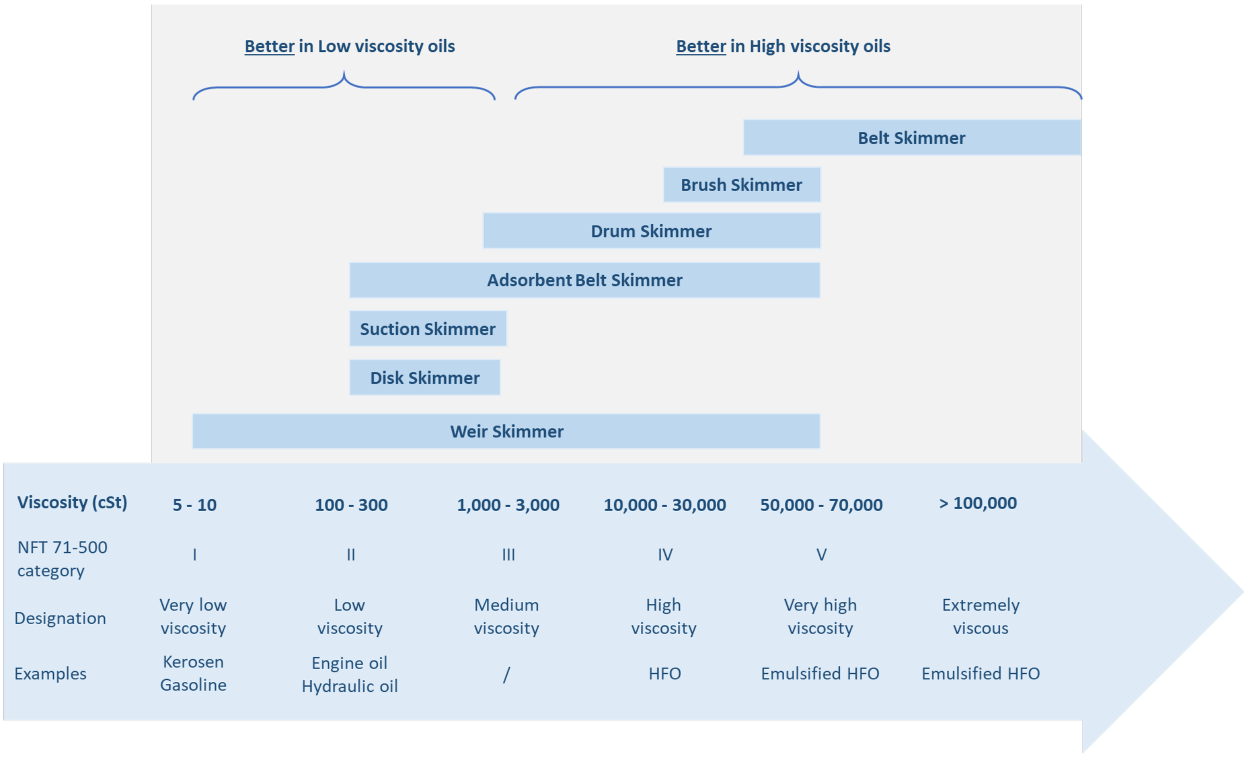


Figure 72. Mechanical skimmers (top five panels) © Cedre.

Figure 73. Oleophilic skimmers (top six panels) © Cedre.

Although most of the skimmers can be used with a wide range of viscosities, certain types of skimmers are more effective than others depending on the oil's viscosity (Figure 74).



Viscosity (cSt)	**5 - 10**	**100 - 300**	**1,000 - 3,000**	**10,000 - 30,000**	**50,000 - 70,000**	**> 100,000**
NFT 71-500 category	I	II	III	IV	V	
Designation	Very low viscosity	Low viscosity	Medium viscosity	High viscosity	Very high viscosity	Extremely viscous
Examples	Kerosen Gasoline	Engine oil Hydraulic oil	/	HFO	Emulsified HFO	Emulsified HFO

Figure 74. Most effective skimmer types to clean oil of varying viscosity © Cedre.

The flow rate of the skimmer is considered as:

- low (< 30 m³/h);
- medium (30 m³/h < x < 80 m³/h); and
- high (> 80 m³/h).

This depends on the collector (recovery capacity) and the pump.

- *Pumps*

The pumping equipment used in conjunction with the skimmer, whether required only to transfer the recovered pollutant to an ancillary storage capacity or also to channel the pollutant towards the skimmer, is a crucial element in the skimmer's performance. The pump may be incorporated within the skimmer (integral pump) or be separate. Integral pumps virtually only provide a discharge function and are often submersible pumps, while separate pumps provide both suction and discharge functions [26].

The selection of pumps suitable for recovering and transferring oil is often based on the oil's viscosity, whether intrinsic (e.g. heavy fuel oils) or due to weathering (e.g. evaporation of the light fraction) or emulsification at sea [26]. Nevertheless, the stickiness of the oil should also be considered. For example, Table 13 presents a summary of tests conducted on a very sticky VLSFO (the test method used to test skimmers is described in the French standard AFNOR NF T 71 500). Due to the stickiness of the oil, it was exceedingly difficult to transfer the oil, even if its viscosity was not too high (about 9,000 cSt). To improve the oil recovery flow rate, an annular water injection (AWI) was added.

Usually set up at the pump outfall, the AWI creates a ring of water between the walls of the discharge hose and the substance being transported. In this way, the pollutant is transported as if it were water, by injecting water at a flow rate representing only a small percentage of the pollutant flow rate.

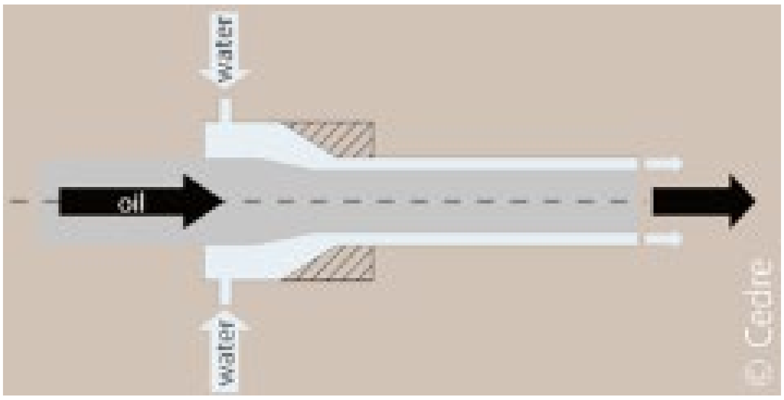


Figure 75. Annular water injection (AWI). ©Cedre

Table 13. Summary of test conditions and results on recovery of very sticky oil and use of AWI.

		1	2	3	4
Slick characteristics	Oil	Fresh oil – VLSFO			
	Water content	/			
	Viscosity (in cSt) ($10.s^{-1}$)	9 144 at 8°C			
	Oil layer	7.5 cm (homogeneous)			
Recovery system	Skimmer	Oleophilic drum			
	Discharge hose diameter	3 inches			
	Pump(s)	Centrifugal		Centrifugal + volumetric lobe pump	
	Additional equipment	/	+ Annular water injection	/	+ Annular water injection
Results	Does oil slick stay in direct contact with the skimmer during the test?	The oil flows naturally towards the skimmer.			
	Selectivity	98%	72%	95%	89%
	Oil recovery flow rate	0.70 m^3/h	2.97 m^3/h	1.96 m^3/h	6.56 m^3/h
	Test assessment		In this case, AWI significantly increases the oil recovery flow rate (from 0.7 to 2.97 m^3/h) of the recovery device by improving this parameter by a factor of ≈ 4. The selectivity is however, degraded because of the water input intrinsic to the system operation		In this case, AWI also significantly increases the oil recovery flow rate (from 1.96 to 6.56 m^3/h) of the recovery device by improving this parameter by a factor of ≈ 3. The selectivity is less degraded in this case, thanks to the help of the additional volumetric lobe pump

- *Storage*

A floating storage barge is a large, non-self-propelled vessel (barge) designed to sit at sea or nearshore and serve as a temporary storage unit for liquids (like crude oil, refined petroleum products, LNG, or chemicals) or bulk materials.

■ Oil spill Characteristics

- *Density*

The oil must be floating (density of less than water density). The density of seawater varies, but it is 1.025. If floating products tend to spread and disperse quickly, intervention should be performed promptly to optimize the operation.

Viscosity

For the recovery and pumping, it is required to have liquid pollutants floating at the sea surface in consistent quantities. Above 100,000 cSt, some skimmers and pumps can have difficulty transferring the oil [19].

In the case of the Erika spill (heavy fuel oil spill in December 1999), the recovery vessels were confronted with very thick, compact slicks (up to 30 or even 50 cm thick), which blocked the entrance to the skimmers and which sometimes had to be broken up with hoses in order to help skim by the weir skimmers [26].

Pour point

If the pour point is close to the ambient temperature, the product will behave almost like a solid and will, therefore, be very difficult to pump [26]. Difficulty can appear if the temperature is a few degrees below the pour point with paraffinic (waxy) oil (specific equipment required). Regarding VLSFO, the IMAROS project identified high pour point as one parameter preventing efficient mechanical recovery.

A heating system can be useful to fluidize the oil and improve its transfer.

Thickness

On light products and/or light fractions emanating from oil slicks spilled at sea (iridescent surface/ rainbow/metallic reflections), the effectiveness of mechanical recovery (skimmers, pumps) rapidly decreases with the thickness of the surface film. A film thickness of 0.1-0.2 mm (i.e. visual correspondence = "true colour", i.e. appearance code 4 or even code 5) is the minimum required for containment (booms) and mechanical recovery (pumping/skimming) operations.

Weathering and natural dispersibility

The pollutant must remain floating and not disperse naturally.

- **Sticky property**: On some oils that appear very sticky, pumps may have difficulty transferring the oil. In this case, an annular water injection can help.
- **Short oil property**: During the IMAROS project, one of the obstacles to mechanical recovery identified was the “short” behaviour of the oil. In this case, the oil in-flow into oil skimmers may be low, independent of the pour point of the oil. A water hole may then appear between the skimmer and the oil. This mechanism is poorly understood, and additional analysis is required to investigate this further. To overcome this problem, dynamic recovery is necessary.

  This phenomenon has also been observed during the recovery of biodiesel blends with marine bunker fuels at Cedre (B30 VLSFO/ MGO).

Figure 76. A hole created during VLSFO recovery ©Cedre

Application of containment and recovery to spills of biodiesel blends with marine bunker fuels

Regarding blends of biodiesel with marine bunker fuel tested during this study, containment and recovery apply (Table 14). Nevertheless, some limits or technical considerations seem important to specify for each product.

- *Fresh FAME/ VLSFO and HVO/ VLSFO blends tested at Cedre*

Based on the previous considerations, among EMSA equipment, combined containment and mechanical recovery systems seem appropriate to recover the fresh FAME/VLSFO and HVO/VLSFO blends at sea. These systems, used dynamically, should prevent the formation of holes in front of the skimmers.

However, the DESMI RoBoom 2000 should not be very selective, and the Lamor Work Boat LSLC 7400 should have a reduced flow rate due to its oleophilic brushes (e.g., less than 1 m^3/h), which are theoretically more suited to more viscous products.

Thus, considering the above considerations, the use of weir skimmers seems more appropriate than brushes, particularly with the NOFI Current Buster and the DESMI Speed Sweep 1500, which permit skimming thicker oil layers. The use of a disc or drum (grooved if possible) skimmer can also be a good option to combine selectivity (more selective than weir skimmer) and flow rate (higher flow rate than brush skimmer). This option can be considered when EMSA use floating storage with low capacity.

- *Weathered FAME/ VLSFO blends tested at Cedre*

The considerations expressed previously in the section “Fresh FAME/VLSFO and HVO/VLSFO blends tested at Cedre” remain valid. The increase in viscosity may make it possible to increase the flow rate when using an oleophilic skimmer.

- *Weathered HVO/ VLSFO blends tested at Cedre*

The formation of tar-balls of emulsified B30 HVO/VLSFO can make recovery difficult (Figure 34).

To recover the oil, an open weir skimmer, without a waste screen, could be considered. The containment with a side-sweep system or a fast current device will help to recover the tar-balls.

Optional tools like a heating system and AWI can be useful in case of viscous or sticky oil, or in case of oil with a low pour point.

- *Weathered FAME/ MGO blends*

The spread of FAME/ MGO blend can make recovery difficult.

In calm water, if the oil is contained before a large spread, the recovery with a skimmer seems possible. To do so, a brush skimmer will have a very slow flow rate (less than 1 m^3/h) and will not be recommended. Mechanical skimmers, like weir skimmers or oleophilic drum or disk skimmers, seem more appropriate.

In rough water or in open sea, the oil will be naturally dispersed, and the recovery will be difficult or impossible.

Table 14. Summary of physicochemical properties affecting containment and recovery.

Note: Green number indicate a property suitable with containment and recovery, red numbers indicate a property not suitable with containment and recovery. Grey properties indicate properties not influential for containment and recovery.

Properties	Oils characteristics (Literature data)	B30 FAME/VLSFO		B30 HVO/VLSFO		B30 FAME/MGO	
		Fresh	7-days weathered	Fresh	7-days weathered	Fresh	7-days weathered
Density	< d sea water (approx. 1.025)	0.912	1.001	0.884	1.004	0.846	0.871
Viscosity (cSt)	< 100,000 cSt (pumping system)	156	6,360	200	80,000	3	9
Pour point	Difficult (but possible) when the temperature is few degrees below the pour point with paraffinic (waxy) oil (specific equipment required) Based on water temperature: 14°C*	24**	No data	18**	No data	-18	No data
Vapor pressures	/	No data	No data	No data	No data	No data	No data
Flash Point (°C)	> 60°C for safety reasons	> 100	> 100	93.5	> 100	70	> 100
Evaporation	/		0		0		0
Emulsification (%)	/	0	85.4	-	85	-	1.2
Thickness (mm)	> 50 µm (code 4 or 5 of Bonn Agreement) - Requires containment	Significant spread expected, thickness depending on containment	Moderate spread expected, thickness depending on containment	Significant spread expected, thickness depending on containment	Low spread expected, thickness depending on containment	Very large spread expected, thickness depending on containment	Very large spread expected, thickness depending on containment
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Comments	On some oils that appeared very sticky, pumps may have difficulty transferring the oil. Furthermore the "short" behaviour of the oil can induce a reduction of the oil in-flow into oil skimmers. A water hole may then appear between the skimmer and the oil.	No data	No data	"Short oil" phenomenon observed ***	Formation of tar balls of emulsion	No data	No data

*: By 2024, Europe's seas will have reached their mean annual surface temperature of 13.73°C. (Copernicus Climate Change Services, 2025)

**: Dynamic recovery or heating system recommended

***: Dynamic recovery recommended.

4.1.5 Surface nets and trawls

■ Overview and equipment for trawling

For recovery of spilled oil from the sea surface by filtering, manual tools such as scoops, baskets, and towing nets can be used in case of floating solid substances or highly viscous liquids. They are used to recover heavy oils, such as weathered or emulsified crude, tar balls, or tacky burn residue.

Surface nets and trawls have been specially developed to recover solid, or at least extremely viscous, products, or oil slicks to which powdered sorbents have been applied. Several systems exist based on a trawl design consisting of two parts (Figures 77-79) [26]:

- the first section is a concentration device designed to contain and thicken slicks this is the "trawl" component; and
- the second section, referred to as the cod-end, collects the oil and, when full, can be removed from the trawl and closed to be either hauled aboard a storage vessel or towed to land to be unloaded.

The first section can be made either of netting or of boom sections, or of a combination of the two. The cod-end, usually designed to be disposed of after use, is made of a very fine mesh net (1 to a few mm) and can have a capacity in the range of a few m^3 to a few dozen m^3, but generally around the 10 m^3 mark [26].

One or two vessels are required for trawling. Certain devices may also be towed by a vessel associated with a paravane.

Figure 77. Synip Trawl
© French Navy.

Figure 78. Notil Trawl
© MarineTech.

Figure 79. Thomsea trawl
© French Navy.

Figure 80. Desmi Oil Trawl Net Ro-Trawl 1500.

Oil spill characteristics

Many parameters should be considered to use recovery nets and trawls in oil spill response (environmental conditions, speed, oil viscosity, etc.).

The following elements refer only to the physicochemical parameters of the oil.

Density

The oil must be floating (density of less than water density). The density of seawater varies, but it is 1.025.

Viscosity

Particular attention must be paid to viscosity, because if the product does not reach this level, trawling will be ineffective or even deleterious (splitting of the slick and production of micro-pellets). Depending on bibliographic sources, the viscosity must reach 100,000 cSt [19] to 400,000 cSt [27].

Trawling was, for example, carried out on very viscous oil during the Prestige (2002) and Grande *America* (2019) accidents.

During the *Prestige* accident, Cedre received a sample of pollutant. The initial viscosity of the oil was about 30,000 cSt at 15°C. 5 days after the grounding (on November 18, 2002), analyses conducted at Cedre on sample taken from the sea (and passing through skimmer and pump) had indicated a water content up to 45% and a viscosity of 79,000 cSt at 15°C. 2 months after the grounding (on January 16, 2003), analyses conducted at Cedre on oil sample taken from the sea showed a water content of 63% and a viscosity of 700,000 cSt at 15°C. The trawling operation started during mid-January.

Figure 81. Use of pibalour and landing net off the French Basque coast © Eric Rostand.

Figure 82. Seynip KingSize trawl trials at sea during the Prestige pollution © Cedre.

During the *Grande America* accident, Cedre received a sample of propulsion fuel oil to assess the weathering at sea, which, according to the supplier, had properties like the propulsion fuel oil escaping from the *Grande America*. A behaviour test was carried out at Cedre's Polludrome®. The initial viscosity of the oil was about 9,000 cSt. After 3 days, it was about 222,000 cSt, and after 10 days 418 000 cSt. The trawling operation started 3 days after grounding (March 15, 2019).

Figure 83. Thomsea trawl at sea during the Grande America pollution (2019) © Marine Nationale.

- *Pour point*

If the pour point is close to the ambient temperature, the product will behave like a solid and will, therefore, be easier to trawl. It can appear at a temperature few degrees below the pour point with paraffinic (waxy) oil.

- *Thickness and weathering (Emulsification / natural dispersibility)*

The pollutant must remain floating and not disperse naturally. The formation of an emulsion, with the evaporation of light fractions, is the phenomenon that has the strongest influence on the increase in viscosity of an oil pollutant as it ages at sea. The oil emulsification is therefore generally beneficial for the trawling.

Prestige, Sample taken at sea 5 days after the grounding

Prestige, sample taken at sea 5 days after the grounding, after 50 hours on the Polludrome®

Figure 84. Oil emulsification of a heavy fuel oil.

■ Application of surface nets and trawls to spills of biodiesel blends with marine bunker fuels

Regarding the B30 blends of biodiesel with marine bunker fuel tested during this study, the trawl recovery with nets does not apply (see Table 15), due to their too low viscosity (<100,000 cSt).

Nevertheless, regarding the B30 HVO/ VLSFO weathering given the formation of tar-balls of emulsified B30 HVO/ VLSFO (Figure 27), the increase of viscosity and its pour point of 18°C, it cannot be excluded that trawling works, and further tests could be conducted to investigate this possibility.

Table 15. Summary of physicochemical properties affecting trawling efficiency.

Note: Green number indicates a property suitable for trawling, red numbers indicate a property not suitable for trawling. Grey property indicates a property not influential for trawling.

Properties	Oils characteristics (Literature data)	B30 FAME/VLSFO		B30 HVO/VLSFO		B30 FAME/MGO	
		Fresh	7-days weathered	Fresh	7-days weathered	Fresh	7-days weathered
Density	< d sea water (approx. 1,025)	0.912	1.001	0.884	1.004	0.846	0.871
Viscosity (cSt)	> 100,000 to > 400,000 cSt	156	6,360	200	80,000	3	9
Pour point	Better when the temperature is few degrees below the pour point with paraffinic (waxy) oil (specific equipment required) Based on water temperature: 14°C*	24	No data	18	No data	-18	No data
Vapor pressures	/	No data	No data	No data	No data	No data	No data
Flash Point (°C)	> 60°C for safety reasons	> 100	> 100	93.5	> 100	70	> 100
Evaporation	/		0		0		0
Emulsification (%)	More effective on emulsified oil	0	85.4	-	85	-	1.2
Thickness (mm)	Generally used to recover heavy oils, such as weathered or emulsified crude, tar balls, or tacky burn residue	Significant spread expected	Moderate spread expected	Significant spread expected	Low spread expected	Very large spread expected	Very large spread expected
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Comments	More effective on emulsified oil (formation of slicks, patches, or patties)	/	/	/	Formation of tar balls of emulsion	/	/

*: By 2024, Europe's seas will have reached their mean annual surface temperature of 13.73°C (Copernicus Climate Change Services, 2025).

4.1.6 Use of sorbents

■ Overview

There are different types of sorbents:

- universal sorbents, which can absorb both hydrophilic (polar) and hydrophobic (apolar) substances; they can be of vegetable (e.g., sawdust) or mineral (e.g., zeolite) nature. As they also absorb water, they can sink and are, therefore, only used on solid surfaces; and
- hydrophobic sorbents, which can absorb only non-polar pollutants; they are synthetic products (organic polymers such as polypropylene and polyurethane). They tend to float and are therefore, suitable for use at sea.

Based on their shape and packaging, sorbents can be classified as: booms, sheets/rolls/pillows, pompoms, and bulk sorbents (powder, pellets).

Regardless of their shape and packaging, some of them are single use (sorbent pad), while others can be wrung out and reused (Figure 85).

Some sorbents are specially designed to trap viscous oil: the pompoms, also called mops. These sorbents are made up of strands joined together to form a light, open structure (pompoms or loose sorbent).

Polypropylene sorbent pads/sheets ©Cedre

Reusable polypropylene sorbent rolls – sweeps ©Cedre

Reusable polyurethane sorbent boom ©Cedre

Pompoms – mops ©Cedre

Pompoms – mops ©Le Floch Dépollution

Loose ©Cedre

Figure 85. Example of sorbents.

Figure 86. Example of sorbents kit.

Oil spill characteristics

Several parameters should be considered to use sorbent in oil spill response (environmental conditions, type of oil, etc.).

The following elements refer only to the main physicochemical parameters of the oil, which are essential in determining whether the use of a hydrophobic sorbent is possible:

- *Density*

The oil must be floating (density of less than water density). The density of seawater varies, but it is 1.025.

- *Pour point*

Sorption can be better when the temperature is few degrees below the pour point with paraffinic (waxy) oil (specific equipment required), but it is not a criterion for excluding the use of sorbents.

- *Viscosity and weathering (thickness and natural dispersibility)*

In the case of a fluid pollutant (e.g., diesel), sorption occurs rapidly (a few seconds to few minutes), but retention is less effective (risk of release). The pollutant must remain floating and not disperse naturally.

In the case of a viscous pollutant (e.g., heavy fuel oil), the substance simply adheres to the surface of the sorbent by adsorption and is not absorbed into the material. This phenomenon, therefore, reduces the sorption capacity of the different types of sorbents.

Application of sorbents to spills of biodiesel blends with marine bunker fuels

Sorbent efficiencies were tested on the three blends studied during the present project: B30 FAME/ VLSFO, B30 HVO/ VLSFO and B30 FAME/ MGO. Additional tests on a diesel as well as on a light crude oil (Arabian Light) were conducted for comparison. A sorbent made of polypropylene was used for these tests as it is representative of the sorbents available in the SOPEP kits.

The tests protocol followed the standard norm NF T90-360. Briefly, this test consists of measuring the retention capacity at saturation defined for a contact time of 20 minutes and a drip-off time of 30 minutes. Figure 87 presents a picture of the sorbent pads after the 50-minutes tests for the 5 oils tested.

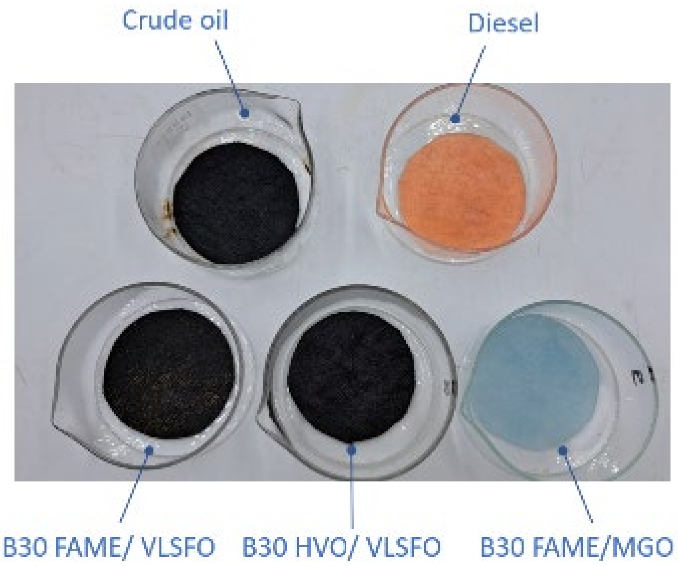


Figure 87. Pictures of sorbent pads after immersion in different oils.

The retention capacity is expressed in weight of oil absorbed (g) / weight of sorbent use (g). The results, presented in Figure 88, highlight that the retention capacity measured for the 3 blends of biodiesel with marine fuel is in the same range as that of the retention capacity measured for crude oil and diesel. Consequently, polypropylene sorbent appears as a suitable material for the recovery of blends of biodiesels with marine fuel.

It is important to note that these tests were conducted on fresh oils. Retention capacity of sorbent decreases significantly for weathered oils due to the emulsification process and viscosity increase. This phenomenon is observed for both crude oils and refined products. Even if the tests were not conducted on weathered blends, we can expect that this decrease of sorbent efficiency will also be observed for these products.

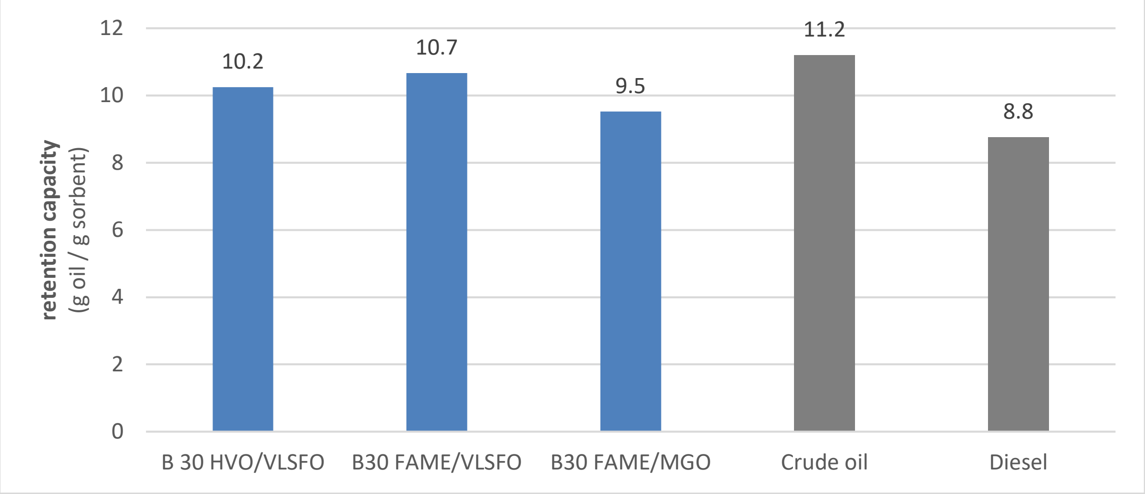


Figure 88. Comparison of retention capacity of a polypropylene sorbent between 3 blends of biodiesel with marine fuel oil, one crude oil and one diesel.

Table 16. Summary of physicochemical properties affecting sorbent efficiency.

Note: Green number indicates a property suitable for absorption, red number indicates a property not suitable for absorption. Grey property indicates a property not influential for absorption.

Properties	**Oils characteristics (Literature data)**	**B30 FAME/VLSFO**		**B30 HVO/VLSFO**		**B30 FAME/MGO**	
		Fresh	**7-days weathered**	**Fresh**	**7-days weathered**	**Fresh**	**7-days weathered**
Density	< d sea water (approx. 1,025)	0.912	1.001	0.884	1.004	0.846	0.871
Viscosity (cSt)		156	6,360	200	80,000	3	9
Pour point	/	24	No data	18	No data	-18	No data
Vapor pressures	/	No data	No data	No data	No data	No data	No data
Flash Point (°C)	> 60°C for safety reasons	> 100	> 100	93.5	> 100	70	> 100
Evaporation			0		0		0
Emulsification (%)	/	0	85.4	-	85	-	1.2
Thickness (mm)	> 50 µm (code 4 or 5 of Bonn Agreement) - Requires containment	Significant spread expected, thickness depending on containment	Moderate spread expected, thickness depending on containment	Significant spread expected, thickness depending on containment	Low spread expected, thickness depending on containment	Very large spread expected, thickness depending on containment	Very large spread expected, thickness depending on containment
Natural dispersion	Little or no natural dispersion	No data	No data	No data	No data	No data	Complete in rough water
Sorbent tests	$Cr_{sat} > 5$	11	No data	10	No data	10	No data
Comments					Formation of tar-balls of emulsion		

4.2 Recovery tests of biodiesel blend with conventional marine fuel

Within the framework of the EMSA project, Cedre carried out recovery tests on fresh and emulsified B30 FAME/VLSFO blend.

To assess the efficiency of the oleophilic recovery and the mechanical recovery, two skimmers were tested:

- an oleophilic skimmer: TDS 118 G from ELASTEC; and
- a mechanical weir skimmer: Foilex Mini from FOILEX.

For each test, recovery was tested on fresh and on emulsified B30 to evaluate the influence of viscosity and emulsification on the recovery efficiency (study of slick movement, recovery rate, and selectivity). Tests were performed at Cedre in a controlled environment: the slick thickness, the selectivity, the recovery rate as well as the water content of the oil (due to the emulsification) were measured before or during the tests.

4.2.1 Test oil specifications

A volume of 226 litres of fresh B30 FAME/VLSFO (70% VLSFO and 30% FAME) was especially prepared for the tests. The VLSFO used comes from a surplus remaining at Cedre since the European IMAROS 2 project. It is referenced as IM-28. The FAME was purchased from GIOMA VARO company.

Care was taken in preparing the mixture to ensure its homogeneity. The two oils were mixed in an IBC using an electric mixer for 24 hours at a temperature of 50°C.

After performing the tests with this “fresh” mixture, the emulsified B30 test product was prepared by adding seawater and mixing it with a high shear rate double screw pump.

The fresh and emulsified mixture was sampled and characterised at Cedre laboratory (Table 17).

Table 17. B30 FAME/VLSFO test oil specifications.

	Test tank temperature	Viscosity (10 s^{-1}) at ambient temperature	Density	Water content
B30 FAME/VLSFO fresh	20 °C	1980 cSt	0.921	-
B30 FAME/VLSFO emulsified	22 °C	4830 cSt	0.979	79 %

Figure 89. Release of B30 FAME/VLSFO into test tank.

4.2.2 Presentation of tested skimmers

- **Skimmer Elastec TDS 118 G**

The Elastec TDS 118 G oleophilic oil skimmer comprises two grooved drums and weighs 27 kg. It measures 1.33 m wide by 1.02 m long. Despite a total height of 0.46 m, its draught is only 8 cm according to the manufacturer. The outlet connection is a 3-inch (≈ 75 mm) female Camlock coupling.

The drums are driven by a hydraulic motor, accepting a maximum hydraulic flow of 19 L/min at a maximum pressure of 175 bar (manufacturer's data). During testing, the Elastec D10 hydraulic unit (portable unit with Kubota diesel engine) provided the hydraulic power required to rotate the drums.

The oleophilic drums are made of HDPE (high-density polyethylene). The model tested uses the grooved drum technology developed by the manufacturer. The advantage of these grooves over smooth drums is not limited to an increase in contact surface area, as there is also a ‘gutter’ effect, i.e., the grooves fill up as the drums rotate (Figure 90).

The drums also act as flotation devices, reducing the size of additional fixed floats and thus the overall bulk and weight of the unit. The use of marine-grade 5052 aluminium for the frame also contributes to this reduction in weight.

The maximum oil recovery rate announced by the manufacturer for this model is 20 m^3/h.

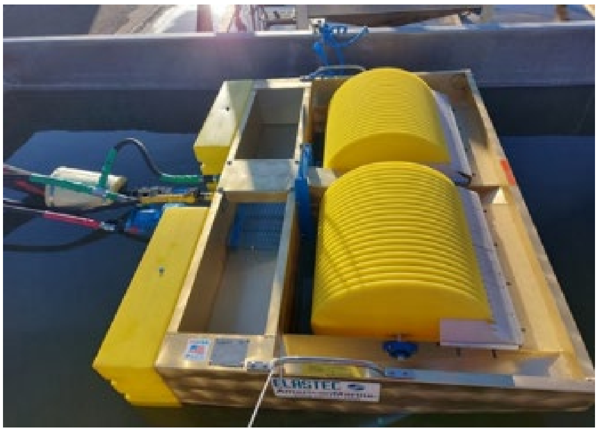


Figure 90. Oleophilic skimmer Elastec TDS 118 G ©Cedre.

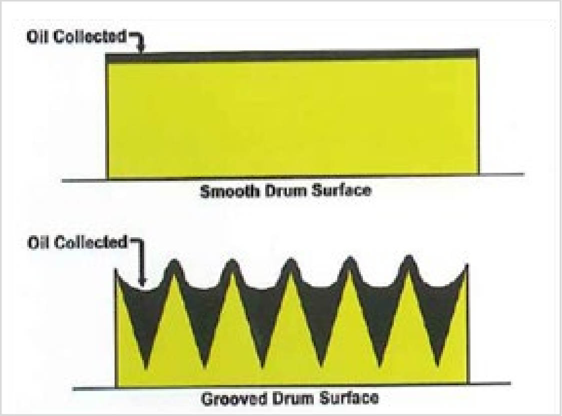


Figure 91. Oil collecting onto a grooved surface (source: Elastec).

■ Skimmer Foilex Mini

The Foilex Mini is a suction weir oil skimmer (Figure 92).

The operating principle of this recovery system consists of positioning a weir just below the surface level to use gravity flow to draw the oil floating on the surface towards a collection hopper, at the bottom of which a transfer pump is connected.

This skimmer is equipped with three floats that ensure good buoyancy and stability on the water.

The circular shape makes recovery as omnidirectional as possible, thereby promoting suction dynamics.

This skimmer weighs 40 kg and measures 1.69 m wide by 1.53 m long with a draught of 60 cm, according to the manufacturer.

The floats are made of polyethylene, whereas the frame is made of stainless steel.

Outlet connection is a 3-inch (≈ 75 mm) female Camlock coupling.

The nameplate maximum oil recovery rate for this model is 30 m^3/h.

Figure 92 : Foilex Mini skimmer (source: Foilex AB).

■ **Transfer pump Borger**

In order to ensure the comparability of results between the two skimmers, both were operated with the same transfer pump: Borger AN 70 (Figure 93).

This volumetric lobe pump is equipped with 2 helical bi-lobes and powered by a Yanmar diesel engine. Both inlet and outlet ports are 3-inch (≈ 75 mm) diameter and equipped with Camlock coupling.

The nameplate maximum flow rate for this model is 34 m^3/h at 0 bar discharge pressure.

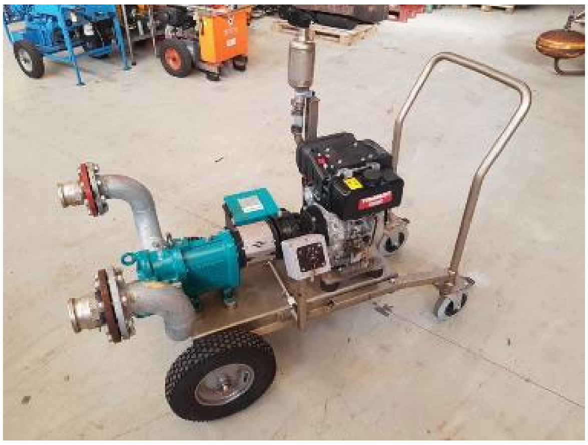


Figure 93 : Borger AN 70 pump, © Cedre.

4.2.3 Standards and references

The test method used to test skimmers is described in French standard AFNOR NF T 71-500 (Oil spill response equipment - Skimmers - Performance test methods in a controlled environment).

4.2.4 Test facility

The test area consisted of the following (Figure 94):

- ❶: A tank with a surface area of 10 m², previously filled with seawater, in which the skimmer is positioned, and the oil is released;

- ❷: A pump to transfer oil from the skimmer toward the discharge tank;

- ❸: A 6 m long, 3-inches (≈ 75 mm) diameter discharge hose to direct the flow to the discharge tank (❹) and take samples (❺);

- ❹: A discharge tank to recover and quantify by measuring the level increase; and

- ❺: Sampling beakers used to take samples of the collected product to determine its selectivity a posteriori (see protocol § 6.5).

Figure 94. Skimmer test facility, © Cedre.

4.2.5 Test protocol

The test protocol applied to all tests is detailed below.

A. Test preparation

   (a). Measurement of water temperature into test tank;

   (b). Measurement of oil density and viscosity at the temperature measured in A.a;

   (c). Spilling of the oil into the test tank;

   (d). Installation of the skimmer;

   (e). Determination of the thickness of the slick and adjustment of the skimmer accordingly;

   (f). Start the test until a homogeneous and stable discharge (water + oil) is achieved.

B. Start performance measurements

The time interval for each action performed during step B must be timed to determine the recovery rate and the time associated with each sample retrospectively.

(a). Flow measurements: level variation measurement into recovery tank;

(b). Selectivity and water content measurements: sampling at the outlet of the discharge pipe (at T0, then definition of the time interval based on the recovery flow rate).

C. End of the test

(a). Read the selectivity results after 20 minutes samples settling.

4.2.6 Results

Three parameters are measured/observed to estimate the performance of a skimmer:

- **the movement of the slick** is observed qualitatively by operators (movement or fragmentation of the slick by the skimmer);
- **the oil recovery flow rate** is measured based on the volume recovered and selectivity; and
- **selectivity,** which corresponds to the volume collected minus the variation in water content and free water, is determined after 20 minutes of settling (in accordance with standard NF T71 500) using samples taken at the outlet of the discharge hose, taking two parameters into account:
    - the amount of free water in each sample to determine the percentage of oil (emulsified or not) recovered; and
    - the change in the percentage of water in the oil, which corresponds to the emulsification of the oil by quantifying the variation in water content between the inlet and outlet of the recovery system.

Movement of the slick

Elastec skimmer tests

During the tests with the Elastec oleophilic skimmer, a marked attraction of the slick is first observed over an arc of approximately 180° on the front of the skimmer. This attraction was visible with both fresh and emulsified oil.

However, after a few minutes, a significant slowdown in attraction is observed. This is due to the presence of a thin film of water a few centimetres wide between the oleophilic drums and the edge of the oil slick. Simply stirring of the water manually is enough to make the slick “stick” to the drums again, but as soon as the stirring stops, the film of water reappears, thus impairing the proper functioning of this skimmer with this type of oil under static conditions.

Foilex skimmer tests

During the tests with the Foilex Mini skimmer on fresh product, the attraction of the slick is clearly visible over 360° and the three floats do not interfere with the flow of the pollutant towards the recovery device. The edge of the weir does not appear to impede the flow of the oil into the device. Visual observation shows very good attraction of the oil, but also attraction of the water present beneath the oil.

During the tests with emulsified oil, given the higher viscosity of this product, the edge of the weir acts as a barrier to the flow of the pollutant into the device. It is, therefore, necessary to increase the pump flow rate to immerse the weir edge more deeply in the water. As a result, the emulsified oil is effectively sucked into the device, however, more water is also sucked in simultaneously. Under these conditions, the surface current generated by the suction of water and oil causes the slick to be clearly attracted 360° around the skimmer, even though the three floats locally disrupt the flow.

Recovery flow rate and selectivity

Elastec skimmer tests

The grooved drums of the Elastec oleophilic skimmer are intrinsically capable of collecting B30 FAME/VLSFO, whether fresh or emulsified. Thus, when the pollutant is in direct contact with the drums, a flow rate of 3.3 m³/h is measured for fresh product (test # 1) and 5.4 m³/h for emulsified one (test #4). Under these conditions, selectivity is excellent (>98%). However, it is important to weigh these results against the rapid separation between drums and slick due to the rapid formation of a thin film of water under the static conditions of the test. As a result, the flow rate of the oleophilic skimmer drops down to null if there is no agitation of the water surface, allowing the oil slick to come into contact with the drums again.

- *Foilex Mini skimmer tests*

The Foilex Mini can recover B30 FAME/VLSFO in the static conditions of the tests but will also collect a lot of free water same time. Test #2 with fresh B30 FAME/VLSFO shows a recovery flow rate of 16 m^3/h and a poor selectivity of 27 %. Test #3 with emulsified B30 FAME/VLSFO shows a flow rate of 18.3 m^3/h and a medium selectivity of 50%.

Figure 95. Elastec TDS 118 G skimmer during emulsified B30 recovery (test #4), ©Cedre

Figure 96. Foilex Mini skimmer during fresh B30 recovery (test #2), ©Cedre

Summary of tests results

Table 18 summarises the results of the skimmer tests.

Table 18: Summary of recovery tests with Foilex Mini and Elastec TDS 118G results for fresh and emulsified B30 FAME/VLSFO.

	Test #1	Test #2	Test #3	Test #4
Skimmer	Elastec TDS 118 G	Foilex Mini	Foilex Mini	Elastec TDS 118 G
Oil type	B30 FAME/VLSFO fresh		B30 FAME/VLSFO emulsified	
Viscosity	1 980 cSt @20°C		4 830 cSt @ 22°C	
Density	0.921		0.979	
Water content	-		79 %	
Initial thickness	≈ 2 cm		≈ 8 cm	
Global recovery flow rate	3.3 m^3/h (if oil is in contact with drums) *	16 m^3/h	18.3 m^3/h	5.4 m^3/h (if oil is in contact with drums) *
Selectivity	>98 %	27 %	50 %	>98 %
Oil flow rate	≈ 3.2 m^3/h (if oil is in contact with drums)	4.3 m^3/h	9.2 m^3/h	≈ 5.3 m^3/h (if oil is in contact with drums)

*Note: For tests #1 and #3, flow rate results are measured when the oil is in contact with oleophilic drums. After a few minutes, a thin film of water appears between the oleophilic drums and the edge of the oil slick in static conditions. The flow rate then decreases sharply to null.

4.2.7 Overview of recovery tests of biodiesel blend with conventional marine fuel

During the tests, it appears that after a short period of satisfactory operation with excellent selectivity, Elastec TDS 118 G skimmer was quickly unable to recover oil due to the formation of a thin film of water between the drums and the oil slick. As the drums were then not in direct contact with the oil, the flow rate dramatically dropped down in this case. A simple stirring of the water manually is enough to make the slick “stick” to the drums again, but as soon as the stirring stops, the film of water reappears, thus impairing the proper functioning of this skimmer with this type of oil under static conditions. It is then necessary to use this type of skimmer in dynamic conditions to recover B30 FAME/VLSFO, to feed the skimmer with oil and avoid the formation of an “oil gap” in front of the drums.

Foilex Mini weir skimmer did not suffer from the problem of “oil gap” during the tests and managed to recover at a global flow rate comprised between 16 and 18.3 m^3/h depending on the type of oil. A hypothesis is that due to low selectivity of this skimmer, it drags sufficient water to create a dynamic movement on the surface avoiding generation of a static water film between the weir and B30 FAME/VLSFO slick. However, the large amount of free water implies the necessity of settling storage tanks on site (if technically feasible) to evacuate the free water and concentrate oil into tanks.

5. Conclusions of blends of biodiesels with conventional marine bunker fuels as marine pollutants and the response measures for their accidental releases

5.1 Current state of response measures to accidental spills of biodiesel-blend fuels

The maritime sector's experience with spills of biodiesel blends (e.g. FAME or HVO mixed with marine fuels) is still limited, and this is reflected in a significant knowledge gap. Many stakeholders and responders have had minimal direct exposure to these fuels, indicating a "technical know-how gap" and the need for dedicated training to handle such incidents. Nevertheless, early research and laboratory studies provide some understanding. Biodiesel blends behave in several ways like conventional diesel oil when spilled: they float on water and spread, forming surface slicks like mineral oil. At the same time, they have distinct characteristics – notably, they evaporate much less (due to low vapor pressures) and biodegrade faster than fossil diesel (about four times faster under favourable conditions). This high biodegradability means spilled biodiesel tends not to persist as long in the environment, and large portions can break down within weeks under microbial action. Importantly, the acute toxicity of biodiesel (FAME/ HVO) to marine life is lower (five times less) than that of conventional petroleum diesel. This suggests that, if a spill occurs, the environmental damage from acute toxicity would be less severe than an equivalent oil spill – a positive aspect of these alternative fuels. However, biodiesel's very properties also introduce new response considerations: for example, pure biodiesel is colourless and forms a much more subtle slick, which complicates visual detection and monitoring of spills. Responders cannot rely on the typical black or brown sheen appearance and may need to use sensors or satellite tools to track a biodiesel slick.

The established oil spill response techniques are applicable to biodiesel-blend fuel spills. Industry experts and regulators agree that containment booms, skimmers, and other mechanical recovery methods used for marine fuel oil spills "should be pretty much the same" approach for biodiesel blends. In practice, responders would initially treat a biodiesel blend spill as they would a diesel or fuel oil spill of similar viscosity. Indeed, international reviews have concluded that traditional response methods remain relevant for biofuel spills. At the same time, certain nuances must be kept in mind: biodiesel can have a high pour point (especially when blended with heavier fuel oils), meaning in colder water it may solidify or form waxy droplets. For example, spilled FAME in cold seas can solidify into floating clumps, which reduces spread but makes recovery more challenging. Responders thus need to be prepared for potentially viscous or semi-solid slicks in cooler conditions, using appropriate equipment to handle those. Additionally, because these fuels biodegrade faster and their slicks can be less visible, monitoring and decision-making might differ: responders may consider shifting to passive cleanup (letting microbes degrade residual pollution under supervision) sooner than they would for a crude oil spill. Overall, the current state-of-play is that knowledge is evolving. The maritime spill response community has a solid foundation (given years of oil spill experience) and early studies on biodiesel blends indicate no insurmountable new challenges. But documentation and real-world validation are still limited. As the report notes, the behaviour of these alternative fuels as marine pollutants and the effectiveness of response measures are "not well-documented," leaving risks that need further study and new frameworks. In short, the preparedness for biodiesel blend spills currently is based on extrapolation – treating them like oil spills with some adjustments – because comprehensive spill response protocols tailored specifically to these fuels have yet to be fully developed.

5.2 Scope for further research and studies

Given the gaps in empirical knowledge, the study underscores a clear need for further research to strengthen spill response for biodiesel and biodiesel blends. Several specific areas for future investigation were identified in the literature and by the study's experts, notably:

- influence of marine fuel nature (VLSFO but also ULSFO) and biodiesel nature (cashew nutshell liquid) on biodiesel blends with marine fuel fate and behaviour at sea;
- influence of biodiesel part (B10, B20, B30, B50) on blends behaviour at sea;

- field scale research on biodiesel blends with marine fuel to confirm lab and pilot scale experimental studies and feed modelling with field data;
- impact of biodiesel blends with marine fuel on shoreline environment: compared to conventional HFO, biodiesel blends with marine fuel oil are characterised by a low viscosity. These properties will increase their penetration and impact on marine sediment; and
- influence of FAME addition on fuel oil fingerprinting: assess how FAME variability (bio-feedstock nature) and biodegradation rates affect the blends fingerprinting.

“Green” dispersants and alternative countermeasures

Another promising area is the development of more eco-friendly spill response agents suitable for biofuels. Recent advances in biodegradable or bio-based dispersants (made from compounds like proteins, biosurfactants, or vegetable extracts) have shown effectiveness in lab settings. However, their real-world performance and environmental safety need validation. Future studies could scale up these “green dispersants” to field trials, assessing whether they can replace traditional chemical dispersants for biodiesel or blended fuel spills. Similarly, research into bioremediation (e.g. bioaugmentation or nutrient addition to accelerate biodegradation) in the context of biodiesel spills could be valuable, given that natural attenuation is a major mechanism for these fuels.

Operational and human factors research

The study’s stakeholder consultations highlighted the need for practical guidance and training, which in turn points to research needs. For example, developing evidence-based training programs, drills, and decision support tools will require studying human performance in spill scenarios involving alternative fuels. Additionally, investigation into how existing shipboard systems (like oil-water separators, bilge management, tank cleaning procedures) handle biodiesel blends can inform best practices (some of these aspects overlap with safety and operational research rather than spill response per se, but it’s related to preventing and managing spills).

In summary, the future research agenda should be broad and interdisciplinary, covering everything from fundamental science (fate and effects of biodiesel in marine settings) to applied engineering (response technology performance) and policy (frameworks for integrating new findings into contingency planning). The scope of further studies should extend to real-world validation, development of tailored countermeasures, and closing any knowledge gaps identified by this study. By doing so, the maritime community can move from the current extrapolation-based approach to a truly informed, fuel-specific spill response strategy.

5.3 Recommendations for developing the legal framework

Address regulatory gaps for alternative fuels

The study makes it clear that the existing legal and regulatory framework for marine pollution response lags the emergence of biodiesel and other alternative fuels. Current international conventions and protocols were designed with crude oil and petroleum products in mind, and do not explicitly cover many biofuel scenarios. For instance, the 2001 International Convention on Civil Liability for Bunker Oil Pollution Damage (Bunkers Convention) – which ensures compensation for spills from ships’ fuel tanks – may not clearly apply to pure biofuels like B100. A spill of neat biodiesel used as bunker fuel could fall outside the strict legal definition of “oil” under that convention, potentially leaving a gap in liability and compensation coverage. In fact, the study notes that a pure biodiesel spill today would be governed only by national laws, unless and until the HNS Convention – Hazardous and Noxious Substances – comes into force to cover it. This is a significant legal gap that needs closing to ensure victims of a biofuel spill, and the costs of clean-up, are adequately covered by international liability regimes.

Incorporate biodiesel blends into IMO guidelines and EU regulations

On the prevention side, maritime fuel regulations have only begun to adapt to biofuels. IMO's MARPOL conventions and codes were not originally written with biofuel blends in mind. As an example, MARPOL Annex I (which governs carriage of oil) has been amended in recent years to allow ships to carry biodiesel blends up to a certain limit (B30) in conventional fuel tanks, recognizing their use as fuel. However, there are no comprehensive IMO guidelines yet on how to handle higher biodiesel blends or pure biofuels in either normal operations or emergency situations. The absence of specific international guidance means countries and classification societies are left to interpret rules on their own – some stakeholders reported "no national framework to cover this area" for biofuel production or bunkering facilities, and classification societies are only slowly issuing guidance on non-standard fuels. A recommendation is for regulators to harmonize and clarify these guidelines: for example, updating the IMO's International Oil Pollution Preparedness, Response and Co-operation (OPRC) manuals to explicitly include alternative fuel spills, or issuing new guidelines under MARPOL addressing spill response for oils blended with bio-components. On the EU side, instruments like the FuelEU Maritime regulation and the Renewable Energy Directive (RED) can be adjusted to ensure that biofuel use is coupled with appropriate spill preparedness obligations (e.g. requiring ports and bunker suppliers to have response plans for biofuel spills).

- **Update standards and definitions**

In tandem, technical standards need to keep pace. ISO 8217 (the marine fuel standard) was updated in 2024 to encompass up to B100 biodiesel and HVO in fuels. This is a positive development, as earlier the lack of standard specifications for high biodiesel blends was identified as a gap. Moving forward, maintaining, and enforcing such standards will be key – they ensure that fuels meet certain quality and stability criteria, which reduces the likelihood of incidents (fuel quality issues can lead to spills or accidents). Additionally, consistent definitions of biofuels and their properties should be adopted across regulations to avoid ambiguity about whether they are treated as "oils" or "noxious substances" in various legal contexts. The study recommends the introduction of a marine-specific fuel standard or certification for biofuels to support this consistency, as well as alignment with sustainability criteria (so that only biofuels meeting certain environmental standards are promoted, in line with decarbonization goals).

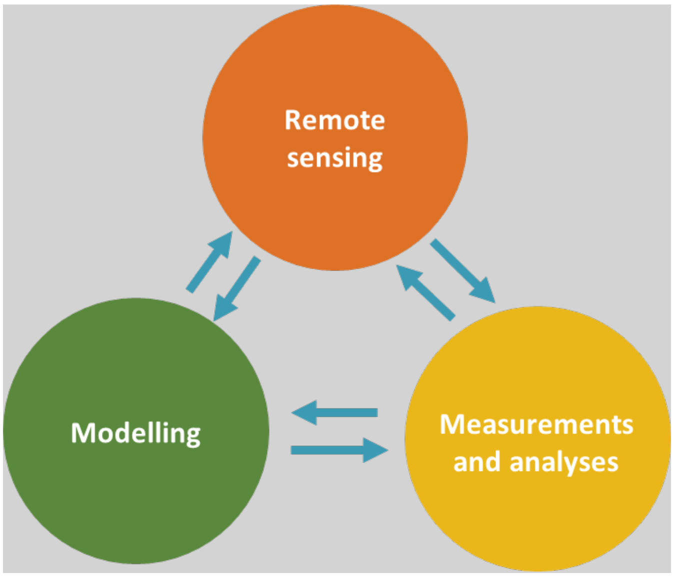
- **Enhance contingency planning and liability frameworks**

At the policy level, contingency plans and legal frameworks must be updated to reflect alternative fuels. This means that national and regional oil spill response plans should incorporate scenarios involving biodiesel blends, and stockpiles of response equipment (and funds like pollution response funds) should be sized for such incidents. Legally, authorities might consider either amending existing conventions or accelerating new ones: for example, clarifying that biofuels are included in "oil" for purposes of the Bunkers Convention, or promoting the ratification of the 2010 HNS Convention which could cover substances like methanol, ethanol, or biodiesel that are not covered as "persistent oils." The study findings point out the current ambiguity and thus recommend closing these gaps proactively.

The legal framework should evolve in parallel with the industry's shift to biofuels. Key recommendations include: (1) Incorporate biofuel blends into international pollution conventions and liability schemes, to guarantee coverage of spills; (2) Develop clear IMO guidelines or an annex for alternative fuel spills, addressing preparedness and response for substances like biodiesel; (3) Update and harmonize fuel standards and definitions (ISO, SOLAS/MARPOL codes) to include higher biofuel content; and (4) Encourage classification societies and national authorities to issue guidance and rules for biofuel use and transport (so that issues like tank material compatibility, corrosion testing, etc., are standardized and enforced). By implementing these measures, the legal and regulatory environment will better support effective responses to accidental releases of these "new" fuels and ensure no gaps in accountability.

5.4 Recommendations for response techniques and technology development

■ Detection and monitoring



After a spill and during response operations, various tools to survey and monitor marine pollution may be deployed, with their use adapted to the conditions encountered as discussed below.

- *Remote sensing*

It covers range of techniques used to detect and identify phenomena from a certain distance, either through human capacities or special sensors for which some of them can be used during low visibility or night conditions. In the case of aerial observation of oil pollution, remote sensing relies on the use of detection systems, including SLAR, FLIR, infrared and ultraviolet scanners. Behaviour and fate of some products may pose a challenge after a certain amount of time depending on the product and environmental conditions. Due to the weathering of the product and fragmentation of the slick into large lumps or patches, turning into smaller fractions, remote sensing could appear more difficult. The location and tracking of the drift of the B30 HVO/ VLSFO blend could be particularly complicated in case brown balls formed spread on large areas and are temporarily submerged.

Such behaviour is worth organising further experimentations to study the actual behaviour of weathered product spilled in water and test remote sensing efficiency.

- *Modelling*

The expected drift of an oil slick can be modelled using mathematical models integrating metocean data. The model must be regularly adjusted using observation data and or positions of buoys when they have similar drift to the pollutant. Model input data is obtained from pollution observation, including at least position and the time of observation, in addition to the spill's dimensions and appearance (degree of fragmentation, buoyancy) when possible.

The floating characteristics of biodiesel/marine fuel oil blends allow for drifting and weathering forecasts to be performed using standard modelling tools. Nevertheless, the reliability of modelling outputs must be confirmed with field data, especially obtained from incident review.

- *Measurements and analyses*

Physicochemical measurements and analyses are essential to feed database and represent useful input data for modelling tools. Beyond modelling purposes, knowing the values of density, viscosity, and pour point is also essential for operational planning and selecting appropriate spill response techniques, such as recovery or dispersion.

These physicochemical measurements, typically performed on conventional hydrocarbons, can also be applied on biodiesel/fuel oil blends, as demonstrated in task 1 of this study. Further work is needed on other blends, involving experiments with equipment (such as recovery devices) and products (such as dispersants), to confirm the correlation between physicochemical measurement results and the applicability of these tools and substances in real conditions.

Containment and recovery

In case of an oil spill, containment of the oil slick is essential to minimize the oil spreading, control its drifting and maximize the efficiency of recovery techniques.

Containment boom

Regarding the sills of biodiesel blends with marine fuel, containment booms remain a staple technology – they should be deployed quickly to corral the spilled fuel since fresh blends will spread rapidly on water. Compared to VLSFO, non-weathered biodiesel blends with marine fuel present a lower viscosity, therefore, conventional boom can be used for this product.

It is important to note that a submersion of biodiesel blends with marine fuel under the boom is highly probable in agitated conditions (wave or current). Indeed, due to the emulsification process, the density of weathered blend is very close to water density which significantly affect its buoyancy.

Mechanical recovery: skimmer

The present study confirms that conventional oil spill response equipment can be effective to recover biodiesel blend with marine fuels spills:

- A weir-type skimmer showed good results to recover B30 FAME/VLSFO slick but with a high-water content in recovered fluid, meaning responders must have decanting or separation capacity on-site to remove excess water;
- A drum skimmer (rotating oleophilic drum) showed excellent selectivity initially on a B30 FAME/VLSFO slick but had a low recovery rate due to the formation of a thin film of water between the drum and the oil preventing the oil adhering to their drums.

Considering these results, even if conventional skimmers are effective on biodiesel blends with marine fuel, some adaptations appeared necessary:

- Skimming systems should include on-board or portable settling tanks, oil-water separators, or similar, to handle the extra water if a less selective skimmer is used. Developing or improving integrated boom-and-skimmer systems (for example, advanced sweep systems or those used by EMSA's vessels) can be interesting;
- Development of skimmers with dynamic mode option to feed it continuously with semi-solid oils.

Mechanical recovery: Trawl; net equipment

If the spill occurs in cold conditions, some of the blend may solidify or become more viscous. In those cases, oil trawl nets or screens to capture any semi-solid chunks floating just below the surface (equipment like the DESMI Oil Trawl system, as noted in the report, could be suitable for such scenarios).

Recommendations:

- Test of trawls / nets recovery for oils characterized by a range of pour point values.
- Definition of operating protocols for high viscous / semi liquid oils recovery by using trawls and nets.

■ Dispersants and emerging agents

Chemical dispersants are a standard tool for responding to oil spills. Their purpose is to break the oil into tiny droplets that can diffuse throughout the water column, where native microorganisms degrade them.

However, blends of biodiesel with residual marine fuels—particularly VLSFOs—tend to form surface slicks whose viscosity increases rapidly. This quick thickening makes the use of marine dispersants ineffective. If dispersants were nevertheless to be considered, it would be essential to apply them within the first few hours following the spill, while the oil is still fresh and before its physicochemical properties have significantly evolved.

The application of dispersants on a pollution slick composed of a biodiesel–marine fuel mixture is not recommended.

That said, it should be noted that the biodiesel fraction—whether FAME or MGO—naturally tends to enter the water column and exhibits low ecotoxicity. In certain situations, dispersion may therefore be considered, particularly if the affected area hosts large numbers of seabirds. In such cases, conducting a SIMA (Spill Impact Mitigation Assessment) is essential.

Furthermore, recent developments in dispersant technology show the emergence of new so-called “green” formulations, which exhibit very low environmental toxicity and appear to offer better performance than conventional dispersants. Investing in R&D for these alternative products and testing them under real-world conditions will be important before they can be widely recommended.

■ In-situ burning

ISB as a technique works well for certain high-volatility oils or when other methods are limited (e.g., in an ice environment). The study suggests that ISB is not a very practical option for biodiesel blends, especially those containing heavier fuels. FAME and HVO fuels have high flash points (e.g., FAME’s flash point is > 93°C) and low evaporative loss, meaning they do not easily produce ignitable vapor. Additionally, blends with residual fuel (like VLSFO) can be quite viscous or even semi-solid, which further hinders burning. Past research and our understanding of VLSFO indicate that in situ burning “does not seem to apply” effectively to such high-flash-point oils.

ISB should not be relied upon as a primary response for biodiesel blend spills, except in specific scenarios where the blend is light and conditions are ideal. Even then, it would require significant pre-heating or a thick slick and calm conditions to sustain combustion. Responders should focus more on mechanical and chemical recovery for these fuels.

■ Summary of recommendations

In summary, the recommendations for response technology are to optimize and slightly tweak what we already have for oil spills.

Mechanical recovery remains the cornerstone – with an emphasis on maintaining oil encounter rate (dynamic skimming) and handling potentially higher water content.

Onboard resources like sorbents and containment kits are still valid – crews just need to use them swiftly.

High-tech aids in surveillance will play a bigger role due to the less visible nature of these fuels. And while specialized countermeasures like burning or dispersing are not ruled out, they take a backseat to more straightforward containment and recovery, complemented by letting nature’s biodegradation process do much of the clean-up (once the bulk is removed).

Developing guidelines, modifications, or new equipment (like skimmers designed to minimize the water film issue, or dispersants specifically formulated for biofuels) could further enhance response effectiveness.

The study emphasizes that ongoing innovation and testing in these areas should continue, so that response technology keeps pace with the changing fuel landscape.

5.5 Best practices for handling and responding to biodiesel blend spills

■ Preventive measures onboard

The best way to manage a spill is to prevent it in the first place. As shipping begins to use biodiesel blends more widely, ship operators should adopt certain best practices in fuel management and handling to reduce spill risks. Industry guidance (such as a recent DNV report) suggests several prudent measures: ensure fuel tanks and lines are thoroughly cleaned and prepared before switching to biodiesel blends (this avoids dislodging deposits or creating incompatible mixtures); verify with engine and equipment manufacturers that materials (seals, gaskets) are compatible with the fuel to prevent leaks; implement rigorous water drainage and moisture control in fuel storage (since biodiesel can absorb water, which can lead to microbial growth or stratification); and avoid onboard blending of fuels unless properly evaluated (uncontrolled mixing of biofuel and regular fuel could produce unstable fuel or sediments). By following these practices, ships minimize the chance of fuel handling errors, leaks, or fuel deterioration that could lead to accidents. The study also points to checklists and guidance for bunkering operations developed in an EMSA-sponsored project focusing on biofuels. Adhering to such standardized bunkering procedures – including proper connection of hoses, slow initial flow ("line flushing"), constant communication between ship and shore, and emergency shutdown drills – is critical when transferring biodiesel blends. These fuels behave like traditional fuels during bunkering, but operators should remember they have higher flash points (less fire risk) yet can still cause slips or pollution if spilled. Having spill containment gear ready during bunkering (drip trays, absorbent pads around manifolds, etc.) is a best practice regardless of fuel type.

■ Shipboard spill response

Despite precautions, if a spill or fuel leak occurs on board a vessel, the crew should respond immediately and in line with the ship's SOPEP (Shipboard Oil Pollution Emergency Plan). All vessels over a certain size are required to carry a SOPEP, which includes procedures and contact numbers for spill response, as well as onboard equipment lists. SOPEP spill kits are defined by Regulation 37 of "MARPOL Annex I" which requires that oil tankers of 150 gross tonnage and above and all ships of 400 gross tonnage and above carry an approved Shipboard Oil Pollution Emergency Plan (SOPEP). Thus, the SOPEP is a mandatory plan required by the International Maritime Organization (IMO) for ships to prevent, minimize, or manage oil spills. The plan must be approved by the relevant authority and is part of the ship's emergency response strategy (IMO, 2025). In general, the SOPEP spill kits contains PPI (gloves, googles) and various type of sorbent (boom, pad, loose).

Crew training is paramount – as noted, many crew are not yet familiar with biodiesel fuel properties, so regular drills involving a mock biofuel spill can build confidence. In the event of a spill on deck, the first step is to stop the source (shut valves, stop pumps) and then contain the spill. Ships usually carry spill kits that include personal protective equipment and various sorbents. For a biodiesel blend spill, crew should put on gloves and safety gear (the fuel is less toxic than oil, but it is still a pollutant and slick), then deploy absorbent pads and booms to soak up and corral the fuel's spread. Any deck scuppers or drains must be quickly sealed to ensure the fuel does not go overboard. One advantage is that biodiesel is not as flammable as gasoline or even marine diesel, so the safety perimeter can focus more on slip hazard and pollution control rather than fire (though good ventilation is needed as always). The used sorbents and any collected fuel should be stored in containers for proper disposal at port. Communication is also a best practice: the crew should notify the nearest coastal authorities or MRCC (Maritime Rescue Coordination Centre) about the incident if any significant amount goes overboard or if assistance might be needed. Prompt reporting allows external response resources to be alerted early.

■ Initial response to spills at sea

If biodiesel or a biodiesel blend is accidentally released into the marine environment (for example, a bunker tank breach or a fuel overflow at port), responders should act swiftly using conventional oil spill response strategies. Containment booms should be deployed as rapidly as possible around the spill source, especially since biodiesel blends (in warm conditions) will form a spreading slick as fast as a diesel spill. Early booming can prevent a small spill from becoming a wide slick. One thing to keep in mind: because biodiesel is lighter in colour, responders might not visually gauge the thickness of the slick accurately; erring on the side of deploying more boom and skimmers is wise until the situation is fully assessed via sensors. Skimming operations should start immediately after booming. Mechanical skimmers – whether vessel-mounted or portable – should be utilized in appropriate configuration (as noted earlier, using skimmers in an advancing mode or with local agitation to improve recovery). Since some biodiesel blends (especially with heavier fuels) can be very viscous or even partially solidify in cool water, responders may need to employ skimmers designed for heavy oil or use techniques like "snare" adsorbents and nets to capture chunkier residues. The use of steam lances or warm water has been an oil spill tactic to deal with waxy oils; while not always practical at sea, in a contained area like a port one might use warm water to re-liquefy congealed biodiesel for easier recovery. All equipment that works for conventional oil – booms, skimmers, pumps, storage barges – is applicable. The report specifically notes that combined containment-recovery systems are effective for fresh biodiesel blend spills, and these should be the go-to equipment at sea.

■ Use of dispersants

If conditions warrant (e.g., offshore spill, difficult to contain, small slick), responders can consider applying chemical dispersants to a biodiesel blend slick, but only with authority approval and after weighing pros and cons. The best practice here is to follow the same environmental trade-off analysis used in oil spills (Net Environmental Benefit Analysis, or NEBA). Because the toxicity of biodiesel to marine life is low and it will naturally dissipate, mechanical recovery and natural attenuation are usually preferred.

■ Shoreline cleanup

If a spill reaches the shoreline, cleanup crews will find that biodiesel and biodiesel-diesel mixtures can stick to shorelines like oil, though potentially in lesser quantities if biodegradation is active. Shoreline clean-up guidelines (like using sorbent boom, low-pressure washing, or manual removal of oily debris) remain applicable. One fortunate aspect: since biodiesel is biodegrading faster, any residues left in sand or soil will diminish faster than tar balls of heavy oil. Still, responders should remove what they can, especially any viscous remains or thick accumulations, to avoid smothering habitat. For ports and marinas, having a ready stock of absorbent booms and pads is a best practice, as those can contain and collect spills in confined waters effectively.

■ Concluding response and after-spill monitoring

After the bulk of a biodiesel blend with marine fuel spill is removed, a best practice is to conduct monitoring for a period to ensure no hidden impacts occur.

■ Summary of best practices

Overall, the best practices for biodiesel blend spills boil down to prepare well, act fast, use standard tools effectively, and take advantage of the fuel's biodegradability while mitigating its few unique challenges. Ships using these fuels should integrate these considerations into their emergency plans, and responders should update their playbooks to ensure that a spill of B20/B30, etc., is handled with appropriate tactics. Ensuring crew and responder familiarity through training exercises is an essential best practice to make all the above recommendations work in the field.

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Appendix A: Literature review, extended summaries

Yang et al. [28], [29], [30] conducted three studies on biodiesel environmental behaviour. The first study [29], which tracks 190 days of open-air weathering, shows that diesel components in B5 and B20 blend volatilize rapidly, whereas the fatty-acid-methyl-ester (FAME) fraction scarcely evaporates owing to its much higher boiling range; pure biodiesel exhibited virtually no mass loss at all. For spill response, this means that, after the initial diesel-like flash-loss phase, a viscous, persistent FAME film remains that is poorly removed by natural evaporation and must therefore be recovered mechanically (e.g., low-shear skimmers or sorbents) and monitored for longer persistence on shorelines. Moreover, because the presence of FAMEs does not impede diesel evaporation rates, volatile-organic-compound modelling for early safety zones can still rely on conventional diesel parameters while subsequent tactics must pivot to managing the slower-weathering biodiesel residue.

Building on that baseline, the photolysis experiment conducted by Yang et al. [30] under simulated sunlight demonstrates that FAMEs act as mild surfactants: they stabilize fine oil droplets in freshwater and, in doing so, slow UV-driven degradation of heavier alkanes and polycyclic aromatic hydrocarbons within the blend. Consequently, dispersed biodiesel-diesel plumes can persist in the water column longer than diesel alone, shifting exposure from surface slicks to sub-surface strata. From a mitigation standpoint, this finding endorses rapid containment (to limit droplet formation), incorporation of depth-profile monitoring, and cautious use of photo-oxidation or UV-enhanced treatments, which may be less effective once FAME-stabilized emulsions are established.

Yang et al. [28] complete the response framework by systematically characterizing neat biodiesel and its biodiesel–Petro diesel blends, providing fuel-property data indispensable for hazard assessment and forensic source-tracking. Biodiesel displays lower density, higher flash points, and reduced 48-h evaporation loss compared with petroleum diesels. Its narrow C15–C18 paraffinic signature and near-absence of aromatics enable chemical “fingerprinting” of spills and imply lower acute toxicity and fire risk during response operations. Integrating these metrics into contingency planning allows responders to (I) select equipment calibrated for slightly lighter, less volatile fuels, (II) prioritize analytical protocols capable of distinguishing biodiesel or biodiesel from conventional diesel to guide liability and clean-up decisions, and (III) anticipate longer on-water persistence yet diminished vapor hazards when biodiesel-rich blends are involved, thereby refining both safety zones and remediation endpoints.

Leme et al. [31], [32], [33] present a trilogy delineating the genetic and cellular hazards of biodiesel–diesel blend spills. In a controlled 40-litre freshwater tank that faithfully reproduces the earliest hours of a release, the first study [33] isolates the water-soluble fraction from B5–B100 fuels and records unequivocal mutagenic responses in Allium cepa root tips and fish erythrocytes, providing a sound basis for setting water-quality thresholds. The second investigation [31] applies the same leachates to human hepatoma (HepG2) and lung (A549) cell cultures, where it detects marked mitochondrial depolarization and apoptosis even at the lowest-blend concentration (B5), underscoring the need to retain diesel-level protective measures during response. Extending the scenario to land, the third paper [32] shows that these blends readily infiltrate soil, persist, and induce cyto- and genotoxic damage in Vicia faba roots. This highlights the importance of soil monitoring and targets bioremediation for shoreline or berm clean-ups.

Hollebone’s [34], [35] argues that biodiesel slicks float like diesel yet, being less dense and more viscous, quickly shear into fine, milky emulsions when agitated, a key physical cue for first-response assessment. Water-accommodated fraction tests give variable solubilities of 20–100 mg L-1, with biodiesels releasing heavier oxygenated esters and no BTEX aromatics, altering dissolved-phase hazard profiles. Soy- and canola-derived B100s disperse readily, and even B20 blends act as weak surfactants that pull co-spilled diesel into the water column, elevating composite toxicity. By contrast, high-viscosity tallow fuels resist breakup, underscoring the need to align containment and recovery tactics with feedstock rheology.

DeMello et al. [36] focus on biodiesel's biodegradation and environmental behaviour, as well as its mixtures with fossil diesel in the marine environment. The study was conducted using laboratory experiments where different fuel mixtures, including 100% fossil diesel, B8 (8% biodiesel), B25 (25% biodiesel), and B100 (100% biodiesel), were introduced into seawater microcosms collected from Vineyard Sound, Massachusetts. The analysis was carried out over 53 days using gas chromatography (GC-FID and GCxGC-FID) to monitor the degradation of hydrocarbons and fatty acid methyl esters

(FAMEs). Additionally, dispersion and emulsion experiments were performed to assess the physical behaviour of these mixtures in seawater.

The principal methodology involved monitoring the degradation process under controlled conditions, focusing on microbial degradation and physical changes. The study observed that FAMEs from biodiesel degraded at a similar rate to n-alkanes in fossil diesel and more rapidly than other hydrocarbon components. After a few weeks of biodegradation, residues from biodiesel and fossil diesel mixtures became chemically indistinguishable from those of fossil diesel alone. This indicates that distinguishing between biodiesel and fossil diesel spills in marine environments becomes difficult after biodegradation. The study also found that FAMEs did not significantly affect the evaporation rates of petroleum hydrocarbons. However, FAMEs increased the stability of small oil droplets in seawater, potentially influencing oil spills' transport, weathering, and ecological impacts.

DeMello et al. [36] identified several research gaps. However, they did not address the role of photochemical degradation or oxidation of FAMEs in seawater, which might play a significant role in real environmental conditions. Additionally, biodiesel's long-term ecological effects and toxicity remain unclear, particularly regarding the stabilized oil droplets in the water column. The behaviour of biodiesel derived from different feedstocks was also not examined, limiting the generalizability of the findings.

DeMello et al. [36] recommend that future research explore the photochemical degradation and oxidation of FAMEs in marine environments. It also suggests that field-scale studies are necessary to validate the laboratory findings under real-world conditions. Further research is needed to investigate the toxicological effects of biodiesel on marine ecosystems and to study the behaviour of biodiesel from diverse feedstocks to understand its environmental fate better.

Giwa et. al. [37] provide a comprehensive review of recent advances in developing and applying green dispersants for oil spill response in marine environments. Green dispersants are considered environmentally friendly alternatives to conventional synthetic chemical dispersants because they are derived from renewable, natural, or non-toxic materials. The review highlights four major categories of green dispersants: protein-based dispersants (from fish and marine waste), biosurfactants (produced by bacteria and fungi), vegetable oil-based surfactants (such as lecithin from soybeans and castor oil), and dispersants synthesized from ionic liquids.

The principal methodology of the article involves a critical review and analysis of recent research studies, experimental findings, and case studies related to the development, performance, and limitations of these green dispersants. The authors systematically compared the dispersant effectiveness (DE) of various green dispersant formulations under different environmental conditions, such as temperature, salinity, and mixing energy. The review also assessed the influence of surfactant type, solvent choice, and dispersant-to-oil ratios on the performance of these green dispersants.

The article's findings indicate that conventional chemical dispersants like Corexit have been widely used for oil spill response. However, their environmental drawbacks, including toxicity and persistence in marine ecosystems, necessitate greener alternatives. Green dispersants derived from proteins, biosurfactants, vegetable oils, and ionic liquids have shown promising results in laboratory settings, achieving comparable or even superior dispersion effectiveness in some cases. For instance, dispersants synthesized from shrimp waste hydrolysates or fish protein isolates achieved a DE close to 80%, comparable to Corexit under optimal conditions. Lecithin-based dispersants, especially in combination with other food-grade surfactants like Tween 80, also demonstrated high DEs and favourable environmental profiles. Moreover, ionic liquid-based dispersants exhibited high dispersion efficiencies with low interfacial tension values, although cost considerations may limit their large-scale application.

The research gap identified by Giwa et. al. [11] includes the limited field-scale validation of green dispersants under real-world spill conditions. Most studies have been conducted in controlled laboratory environments, and there is a lack of comprehensive field data to confirm these dispersants' effectiveness and environmental safety in diverse marine settings. Additionally, there is insufficient research on the long-term ecological effects and biodegradability of specific green dispersant components, especially ionic liquids and biosurfactants produced from novel microbial strains.

The article recommends that future research should focus on scaling up laboratory studies to field trials, assessing the real-world performance of green dispersants under varying environmental conditions. It also calls for more studies on the toxicological profiles and long-term environmental impacts of green dispersants, including their interaction with marine organisms and ecosystems. Furthermore, exploring cost-effective production methods for biosurfactants and ionic liquids could enhance their commercial viability for oil spill response.

Lisiecki et al. [38] investigate the long-term biodegradation behaviour of diesel/biodiesel blends in saturated sand microcosms. The study aimed to evaluate how varying concentrations of biodiesel in diesel fuel blends affect the biodegradation of both aliphatic and aromatic hydrocarbon fractions, using controlled laboratory conditions that simulate natural environments such as contaminated soil or groundwater systems.

The principal methodology employed in this study involved the use of saturated sand microcosms inoculated with a bacterial consortium known for its ability to degrade petroleum hydrocarbons. The diesel/biodiesel blends tested ranged from pure diesel (D) to pure biodiesel (B100), with intermediate blends such as B10, B20, B50, and B90. The experiment was conducted over an extended period of 578 days, allowing for the assessment of long-term biodegradation kinetics. Mineralization was monitored by measuring CO2 evolution as an indicator of microbial activity, while chemical analyses using GC-FID and GC×GC–TOF–MS were conducted to determine the residual amounts of aliphatic and aromatic hydrocarbons. Furthermore, real-time PCR was used to study changes in the bacterial community structure over time.

The study's main findings indicate that the biodegradation of diesel/biodiesel blends is an additive process, meaning the biodegradability of the blends can be predicted based on the individual biodegradability of diesel and biodiesel components. The presence of biodiesel increased the overall mineralization rates due to its higher biodegradability compared to diesel. However, adding biodiesel did not significantly influence the long-term biodegradation extent of either aliphatic or aromatic hydrocarbons in diesel fuel. Complete biodegradation of FAME (the main component of biodiesel) was observed in all tested microcosms. In contrast, residual amounts of petroleum hydrocarbons were still detected, except for pure biodiesel. Additionally, the study found that biodiesel stimulated certain bacterial groups, while others were suppressed, suggesting shifts in the microbial community composition depending on the biodiesel concentration.

The research gap identified by Lisiecki et al. [38] reveals the limited understanding of how biodiesel affects the fate of specific hydrocarbon compounds, particularly in shorter-term biodegradation scenarios or in different environmental matrices. The study emphasized that while biodiesel increases overall biodegradation rates, its effect on the biodegradation of individual hydrocarbon compounds might vary and require further investigation. Moreover, the long-term impact of biodiesel on microbial community dynamics, especially in natural field conditions, remains insufficiently explored.

Lisiecki et al. [38] recommend future research to focus on the biodegradation behaviour of individual hydrocarbon compounds within diesel/biodiesel blends, particularly over shorter timeframes and under varying environmental conditions. It also suggests studying biodiesel's role in mobilizing or solubilizing aged hydrocarbons in contaminated soils, which might enhance bioremediation effectiveness. Further investigation into the metabolic pathways utilized by different bacterial taxa in response to biodiesel presence is recommended to understand better the mechanisms driving these biodegradation processes.

Ng et al. [39] investigate the potential of using biodiesel as an environmentally friendly approach to enhance the biodegradation of petroleum diesel in oil spill scenarios. The research evaluates the synergistic effects of blending petroleum diesel with different types of biodiesels, such as Jatropha, palm, and soybean, to assess their impact on the biodegradation efficiency in simulated aquatic environments.

The principal methodology applied in this study involved laboratory experiments using CO_2 evolution tests to measure the biodegradation performance of pure Petro diesel, pure biodiesel, and various biodiesel-Petro diesel blends. The experiments were designed to mimic real-world conditions where the fuel blends were not pre-agitated, allowing the oil and microbial communities to interact naturally. Biodiesel and petroleum diesel were blended at different ratios by carbon mass (20%, 50%, and 80% biodiesel), and the degradation process was monitored over 20 days by measuring the amount of CO_2 evolved as an indicator of microbial activity.

The study's main findings show that blending biodiesel with Petro diesel significantly enhanced the biodegradation of the fuel mixtures compared to pure Petro diesel alone. The results revealed positive synergistic effects, with the highest enhancements observed at specific biodiesel blending ratios: 50% for Jatropha biodiesel (12.8% enhancement), 80% for palm biodiesel (19.4% enhancement), and 20% for soybean biodiesel (17.5% enhancement). The enhancement in biodegradation was attributed to two main factors: co-metabolism, where biodiesel serves as an additional energy source for microorganisms, and solvation effects, where biodiesel's surfactant-like properties increase the solubility and bioavailability of Petro diesel hydrocarbons, facilitating their breakdown.

The research gap identified by Ng et al., [39] highlights the limited understanding of the optimal blending ratios for maximizing biodegradation in real environmental conditions. Additionally, the impact of different biodiesel chemical compositions on their solubilizing properties and the resulting bioavailability of petro-diesel components requires further investigation. The study also suggests that while higher biodiesel content enhances solubility, it may not always translate to higher biodegradation due to potential limitations in the bioavailability of hydrocarbons within micelle structures formed by biodiesel components.

Ng et al. [39] recommend future research to explore the detailed chemical profiles of biodiesel blends undergoing biodegradation, the role of microbial community dynamics, and the long-term environmental effects of using biodiesel for oil spill bioremediation. Moreover, the study suggests investigating the applicability of this approach in different environmental settings, such as seawater or soil, and under varying oil spill conditions to understand the potential of biodiesel-assisted bioremediation fully.

Woźniak-Karczewska et al. [40] investigate the long-term biodegradation behaviour of diesel, biodiesel, and their blends (B10 to B100) in urban soil microcosms, focusing on the role of bioaugmentation using hydrocarbon-degrading bacteria. The increasing interest in biodiesel drove the research as an alternative fuel, and the need for effective bioremediation strategies to deal with potential soil contamination from fuel spills.

The main findings indicated that biodiesel was degraded entirely within 64.5 weeks in all blends, while 3–12% of total hydrocarbons (aliphatic and aromatic) remained in the microcosms. The addition of biodiesel enhanced the mineralization rate in the short term (first 28 days), particularly for blends with higher biodiesel content (above 30%). However, in the long term, the mineralization extent of diesel/biodiesel blends was not significantly dependent on biodiesel concentration. The study showed that bioaugmentation accelerated mineralization during the short-term phase (up to 140%), especially in blends with low biodiesel content (B10 to B30). Nevertheless, bioaugmentation had no significant effect on long-term mineralization extent or kinetics, and the bacterial community structure of bioaugmented samples eventually resembled that of non-augmented samples, suggesting poor survival or adaptation of the introduced bacteria over time.

Woźniak-Karczewska et al. [40] identify a research gap in the limited effectiveness of single bioaugmentation treatments for long-term bioremediation of diesel/biodiesel blends in soil. The study highlights the need to understand better the interactions between introduced and indigenous microbial communities and the factors influencing their long-term survival and activity.

For future research, Woźniak-Karczewska et al. [40] recommend exploring successive bioaugmentation strategies (multiple inoculations over time) to maintain the activity of hydrocarbon-degrading bacteria during long-term bioremediation. It also suggests investigating the influence of soil characteristics and environmental factors on bioaugmentation success and further understanding the microbial mechanisms involved in the degradation of different hydrocarbon fractions in diesel/biodiesel blends.

Abuoudah et al. [41] explore the development and evaluation of bio-based herding and gelling agents derived from cholesterol powders and their suspensions in organic liquids (gasoline, toluene, and biodiesel) for efficient oil spill clean-up in aquatic environments. The study aims to propose environmentally friendly and biodegradable alternatives to conventional chemical herders, focusing on performance in both freshwater and saline conditions at varying temperatures.

The principal methodology involved laboratory experiments assessing the herder effectiveness of four different cholesterol powders (CP/A, CP/B, CP/C, and CP/D) based on their physical and chemical properties, such as particle size, crystallinity, and thermal stability. The experiments measured oil spill surface area reduction on water using a MATLAB image processing code. Suspensions were prepared by mixing the best-performing cholesterol powder (CP/D) with biodiesel, toluene, or gasoline in various ratios. The study also applied Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) to model and optimize the herding effectiveness under different conditions of temperature, salinity, and agent-to-oil ratio (AOR).

The main findings indicated that cholesterol powders, particularly CP/D with small particle sizes (0.5–0.99 mm) and anhydrous crystal phases, were highly effective in forming gel aggregates with crude oil, achieving a herder effectiveness of 73.3%. The cholesterol-biodiesel suspension (CP-BD) outperformed other suspensions, achieving a herder effectiveness of 79.1% at a cholesterol-to-biodiesel ratio of 1:4. The study found that biodiesel was the most effective delivery liquid, reducing water surface tension from 73.5 to 28 mN/m. Optimization results revealed that water salinity and temperature significantly affected herder effectiveness, while the agent-to-oil ratio had an insignificant impact. The maximum predicted herder effectiveness was 79.5% at 45°C and zero ppt salinity, confirmed with 95% accuracy.

The research gap identified in this study pertains to the limited use of bio-based herding agents in oil spill remediation, especially under moderate or tropical climate conditions. Existing literature primarily focuses on synthetic herders in icy environments. The long-term stability, biodegradation behaviour, and scalability of cholesterol-based herders in different environmental settings remain insufficiently explored.

Abuoudah et al. [41] recommend future research to enhance the performance of bio-based herders in saline environments through material modification or functionalization. It also suggests expanding the application of cholesterol-biodiesel suspensions to field-scale studies, investigating their long-term environmental impact, and exploring the potential of other bio-based materials as sustainable herding agents for oil spill clean-up.

Owsianiak et al., [42] examine the biodegradation behaviour of diesel/biodiesel blends by a microbial consortium of hydrocarbon degraders, focusing on the effect of blend composition and biosurfactants (rhamnolipids) in enhancing biodegradation. The study was motivated by the increasing use of biodiesel in diesel fuels and the need to understand its impact on environmental biodegradation, especially in the case of fuel spills.

The principal methodology involved laboratory experiments in which different diesel/biodiesel blends (ranging from 0% to 100% biodiesel) were subjected to biodegradation tests using a microbial consortium isolated from crude oil-contaminated sites. The consortium included *Pseudomonas alcaligenes*, *Ochrobactrum intermedium*, *Sphingobacterium sp.*, and others. The study measured biodegradation efficiency over 7 days based on CO_2 evolution, residual oil analysis using gas chromatography, biomass production, and cell hydrophobicity changes. Additionally, emulsification tests assessed the effect of biodiesel and biosurfactant (rhamnolipids) on fuel dispersion in water.

The main findings revealed by Owsianiak et al. [42] that pure biodiesel exhibited higher biodegradation efficiency than pure diesel, with a 26% increase in mineralization. However, at low biodiesel content (10%), the overall biodegradation efficiency decreased by 10% compared to pure diesel, due to diminished petroleum hydrocarbon degradation. The study demonstrated that the biodegradation efficiency surpassed pure diesel only when the biodiesel content exceeded 30%. Adding rhamnolipids significantly improved the biodegradation of blends with 5–30% biodiesel, with the most notable enhancement (up to 15%) observed for the 10% biodiesel blend. Rhamnolipids increased biodegradation efficiency primarily in the lower hydrocarbon fractions but negatively impacted the biodegradation of heavier fractions.

The study also found that biodiesel promoted emulsion formation with water, improving the dispersion of fuel blends in aqueous environments. The presence of rhamnolipids further enhanced the emulsification process and modified the microbial cell surface hydrophobicity, favouring biodegradation in blends containing up to 30% biodiesel.

The research gap identified in this study is the limited understanding of the biodegradation dynamics of specific hydrocarbon fractions within diesel/biodiesel blends, particularly in the presence of biosurfactants. The impact of microbial community structure and their metabolic pathways in environmental settings remains underexplored.

Owsianiak et al., [42] recommend studying the detailed biodegradation behaviour of aromatic hydrocarbons within diesel/biodiesel blends under various environmental conditions for future research. They suggest further investigation into using other microbial consortia and biosurfactants to optimize bioremediation strategies. The study also highlights the need to understand the interactions between microbial cells, biosurfactants, and fuel components to enhance the biodegradation of complex hydrocarbon mixtures in contaminated environments.

Chrzanowski et al. [43] investigate the biodegradation of rhamnolipids and their effect on the biodegradation efficiency of diesel fuel and a biodiesel/diesel blend (B20), alongside the impact on bacterial community composition. The research was motivated by the increasing use of biosurfactants like rhamnolipids in environmental bioremediation and the need to understand their interaction with hydrocarbons and microbial communities in contaminated environments.

The principal methodology involved laboratory-scale biodegradation experiments under aerobic and nitrate-reducing conditions using a microbial consortium isolated from oil-contaminated soil. The consortium was tested for its ability to degrade diesel, B20 blend (20% biodiesel and 80% diesel), and rhamnolipids (150 mg/L concentration). The study employed gas chromatography for analysing fuel components and real-time PCR (ddCt method) to monitor changes in microbial community dynamics over a 7-day incubation period.

The main findings show that rhamnolipids were rapidly degraded under aerobic conditions within approximately 7 days, while their degradation was slower under nitrate-reducing conditions (taking up to 35 days). The biodegradation of biodiesel in B20 blends was faster than diesel, following the order of biodegradation susceptibility: biodiesel > rhamnolipids > diesel oil. Importantly, while rhamnolipids enhanced the biodegradation of B20 blends under aerobic conditions (increasing overall biodegradation by about 50%), they had no significant effect on the biodegradation of pure diesel. Under nitrate-reducing conditions, rhamnolipids showed no enhancement effect for either diesel or B20.

Regarding microbial community dynamics, the study found that the degradation of rhamnolipids did not result in significant shifts in the abundance of specific consortium members. This indicated that rhamnolipids did not disturb the microbial equilibrium during diesel and biodiesel degradation. However, their preferential degradation could lead to depletion of electron acceptors, potentially limiting the biodegradation of hydrocarbons in environments with restricted oxygen availability.

The research gap identified by Chrzanowski et al. [43] lies in the limited understanding of the impact of rhamnolipid degradation on long-term bioremediation, especially in real environmental settings like soil, where factors such as bioavailability and complex microbial interactions play a larger role. Furthermore, the study noted the absence of detailed knowledge on the differential degradation rates of specific rhamnolipid components under varying conditions.

Chrzanowski et al. [43] recommend future research to focus on field-scale validation of rhamnolipid-enhanced bioremediation, especially in soil environments contaminated with weathered hydrocarbons. Additionally, it suggests exploring the interaction between biosurfactant structure, microbial community composition, and environmental factors to optimize bioremediation strategies better using biosurfactants like rhamnolipids.

Moreira de Souza et al. [44] evaluate the biodegradation potential of the bacterium *Serratia marcescens* strain 110 UFRGS for various diesel and biodiesel blends (B5, B10, B25, and B100) in an aqueous environment. The study is motivated by the increasing replacement of diesel with biodiesel and the need to understand how this affects microbial degradation in the case of fuel spills in aquatic systems.

The study's methodology involved isolating S. marcescens from a harbour environment in Brazil. Laboratory experiments were conducted using mineral media, where different diesel and biodiesel blends were the sole carbon source. Parameters such as bacterial growth (colony-forming units), cell hydrophobicity, alkane monooxygenase gene (alkB) presence, and fuel degradation were analysed over 12 days. Redox indicators (TTC and DCPIP) were used to monitor metabolic activity, while infrared spectroscopy (FTIR) was employed to detect chemical changes in the fuels.

The study's main findings revealed that *S. marcescens* grew well in the presence of B5, B10, and B25 blends, but showed limited growth with pure biodiesel (B100). The bacterial cell hydrophobicity was highest in diesel-rich blends (B5 and B10), indicating a stronger interaction with hydrophobic diesel components. The strain was confirmed to possess the alkB gene responsible for degrading alkanes found in petroleum products. Infrared spectroscopy results indicated significant degradation of B5 and B10 blends, with lower degradation efficiency observed for B25 and almost no degradation for B100. These results suggest that *S. marcescens* prefers to utilize hydrocarbons from diesel rather than biodiesel components.

Moreira de Souza et al. [44] identified a research gap in the limited understanding of the biodegradation behaviour of pure biodiesel (B100) and the specific conditions or microbial adaptations required to improve its degradation. While blends with lower biodiesel content enhanced microbial growth and degradation, pure biodiesel posed challenges due to the lack of suitable hydrocarbons that support the bacterium's metabolism.

Moreira de Souza et al. [44] recommend future research on enhancing microbial adaptability or engineering microbial consortia capable of efficiently degrading pure biodiesel (B100). It also suggests studying the role of other genes and metabolic pathways in biodiesel degradation and evaluating the biodegradation performance in more complex environmental settings, such as contaminated soils or marine environments. Understanding the synergistic interactions between biosurfactants, microbial adhesion, and fuel composition could improve bioremediation strategies for biodiesel and diesel blend spills.

Xin et. al. [45] examine the behaviour, fate, and toxicological impacts of various bio-derived oils, including vegetable oils, biodiesel, and pyrolysis oils, when spilled into fresh and saltwater environments. The research was driven by the increasing global production and transportation of bio-derived oils, raising concerns over their environmental risks, especially during spill incidents.

The principal methodology employed in this study involved laboratory experiments to characterize the physicochemical properties of seven bio-derived oils and one petroleum diesel. The study used baffled flask tests to analyze oil dispersibility, solubility tests to determine dissolution behaviour, and Microtox bioassays to assess acute toxicity towards Vibrio fischeri. Total Organic Carbon (TOC) measurements were used to evaluate the extent of oil dissolution in water.

The main findings demonstrated distinct differences in the behaviour of oils based on their types. Vegetable oils and biodiesel floated on water, exhibited low TOC in water, and dispersed under mixing but recoalesced when agitation ceased. Pyrolysis oils (bio-oil and wood oil) showed contrasting behaviour; they tended to sink due to their higher density, released a high concentration of dissolved organic compounds into the water, and left approximately 35% of their mass as insoluble residue at the water bottom. The TOC values in pyrolysis oil-contaminated waters were 100 times higher than those from vegetable oils or biodiesel.

Xin et. al. [45] identified a research gap in the limited understanding of pyrolysis oils' environmental fate and toxicity, particularly their behaviour in sediment-rich environments, their anaerobic biodegradation products, and their long-term impacts on aquatic ecosystems. The study also highlighted the scarcity of research on the detailed chemical characterization of dissolved compounds from pyrolysis oils in water and their ecological implications.

For future research, the article recommends extensive studies on the anaerobic degradation behaviour and toxicity of pyrolysis oil residues, field-scale investigations under varying environmental conditions (including cold climates), and advanced chemical analysis of water-soluble fractions from pyrolysis oils. Moreover, it suggests that developing tailored emergency spill response strategies for pyrolysis oil spills, different from traditional petroleum oil response measures, is crucial for improving environmental protection and spill management practices.

Pikula et. al. [46] studied the aquatic toxicity of biodiesel derived from waste cooking oil (WCO) and its blends with petroleum diesel (B20) on marine microalgae species. The research addresses a growing environmental concern about the potential ecological impact of biofuels, particularly in aquatic environments, which are vulnerable to fuel spills.

The principal methodology involved a series of laboratory-based ecotoxicological bioassays using varies marine microalgae species. These tests measured growth inhibition over acute (96 hours) and chronic (7 days) exposure periods to pure biodiesel (B100), a 20% biodiesel/diesel blend (B20), and petroleum diesel (B0). The study utilized OECD standard methods for toxicity testing (OECD 201), coupled with flow cytometry analysis for accurate cell counting and viability assessment. Additionally, chemical characterization of the fuels was performed using LC–MS analysis to identify their composition.

The main findings revealed that pure biodiesel (B100) exhibited the highest toxicity towards the tested marine microalgae species. The acute EC50 values (concentration causing 50% growth inhibition) for B100 ranged between 3.75 g/L and 23.95 g/L across the four species, while chronic EC50 values ranged from 0.42 g/L to 16.09 g/L. Interestingly, the B20 blend also demonstrated significant toxicity, although generally lower than B100, but higher than pure diesel (B0). *Porphyridium purpureum* showed the highest resistance to all tested fuels. The research gap highlighted in this article is the limited knowledge of the ecotoxicological impact of biodiesel produced from waste cooking oils, especially concerning its behaviour and toxicity in aquatic environments.

For future research, Pikula et. al. [46] recommend extensive field-based ecotoxicity studies on a broader range of aquatic species to understand better the environmental risks associated with WCO-based biodiesel. Further investigation into the degradation behaviour of biodiesel components, the long-term ecological impact of biodiesel spills, and the identification of critical toxic compounds within biodiesel is essential.

Eremeeva et al. [70] explore the creation and characteristics of marine fuel that incorporates environmentally friendly components to replace traditional petroleum-based marine diesel. The research determined that the optimal quantity of biodiesel in low-viscosity marine fuel is up to 15 wt% (weight percent), which can be achieved without the utilization of supplementary additives. The authors found that adding lighter biodiesel to the marine fuel increases the flash point of the resulting mixture, making it safer to use in marine engines than traditional marine fuel. The authors note that while density and viscosity improve, an increase in the proportion of biodiesel will increase the solidification temperature, thereby requiring depressant-dispersing additives to maintain compliance with technical specifications.

In terms of environmental risks, burning biodiesel releases less carbon monoxide, carbon dioxide, and volatile hydrocarbons compared to petroleum diesel fuel while reducing sulphur content in the marine fuel, helping it meets strict requirements like the IMO's 0.1% sulphur limit for Emission Control Areas (ECA). Moreover, the core finding regarding spills is that biodiesel fuel decomposes on its own within a few months, which can solve the global problem of reduction of pollution of water bodies in case of accidents.

The authors recommend further investigation of introducing environmentally friendly components in the composition of low-viscosity marine fuels while the components from vegetable renewable raw materials are the most promising. Therefore, future research is implicitly required to translate this property into optimized response strategies, especially reduction of water pollution in case of accidents.

Gotovuša et al. [71] synthesized and characterized three types of pure biodiesel esters to predict their behaviour during a spill or remediation effort. These biodiesels have a lower density than both crude oil and water, supporting more efficient oil separation and collection. The synthesis utilized waste cooking oil (WCO), which is deemed the most suitable feedstock for biodiesel production in terms of sustainability, cost, and availability, thereby contributing to the implementation of a circular economy. Gotovuša et al. [72] also note that methanol is toxic, miscible with water, and can be adsorbed through the skin, highlighting the contribution of FAEE and FABE as potentially safer alternatives that can be produced from renewable raw materials

The authors demonstrated that FAME, FAEE, and FABE are successful crude oil remediation agents, achieving maximum removal efficiencies up to 94.98% from sand. A key strategic benefit is that the residual biodiesel left in the sediments after cleanup acts as an energy source for microorganisms, which accelerates the microbiological degradation of any remaining crude oil residues. For the future research, Gotovuša et al., 2024 highlighted the importance of assessing the efficiency of crude oil removal from biodiesel and procedure for preparing remediation agents of crude oil spill.

Khan, Warith, & Luk [72] identified biodiesel's suitability as an alternative fuel by examining its physical and operational characteristics (safe composition, flexibility in blending with diesel, and clean burning, low-emission properties). Biodiesel is safer to use, transport, and store than petroleum diesel because neat biodiesel (B100) has a minimum flash point of 127°C, which is significantly higher than that of regular No. 2 diesel (53oC). Based on mortality rate and lethal concentration (LC50) - values for freshwater organisms, a toxicity ranking was developed, concluding that diesel is more toxic than neat biodiesel and biodiesel blends. Khan, Warith, & Luk [73] also established that the more diesel fraction is contained in the mixture, the higher is the percentage of mortality.

However, biodiesel and its blends pose a significant risk to aquatic ecosystems in the event of a spill. Toxicity results showed that diesel was the most toxic, while B100 was the least toxic, with toxicity increasing with the proportion of diesel in the blend. The study also highlighted that the source of biodiesel feedstock can influence toxicity. Therefore, biodiesel still requires careful management and spill response.

Yildiz et al. [73] compared the environmental pollution costs between Japanese Industrial Standard Diesel No. 2 and biodiesel fuel from waste cooking oil when operating diesel engines at different load levels. When compared to conventional diesel fuel, the use of biodiesel results in reduced levels of particles, carbon monoxide levels, combustion products, and nitrogen oxides under specific conditions. However, the specific environmental pollution cost (SEP) and the life cycle based specific environmental pollution cost (SEPLC) values of the biodiesel fuel were also found to be higher than those of diesel fuel. At the highest load, the specific environmental pollution costs of biodiesel were higher than those of diesel. In addition, biodiesel had a longer environmental payback period.

Overall, diesel was considered a better choice than biodiesel in terms of environmental pollution costs. However, the authors did not suggest the future research regarding fuel properties, mitigating environmental risks through different means, or providing key input for spill response strategies.

Silva et al. [74] evaluated the effects of adding 10% and 20% soybean biodiesel to marine diesel under simulated storage conditions for 28 days. The results showed that sample B20 produced the largest microbial biomass, with a microbial community dominated by the genus Pseudallescheria. Silva et al. [75] contributed the finding that the Hawksworthiomyces genus played a decisive role in the production of the largest biomass observed in the B20 blend, and it was observed for the first time on fuels in this work.

Silva et al. [75] showed that the susceptibility to microbiological degradation increases with the unsaturation degree of the fatty acid methyl ester. The finding leads directly to a key contribution for mitigating risks that marine diesel oil mixtures with biodiesel should preferably be made with biodiesel produced from sources of saturated fatty acids (such as palm trees or beef tallow) or use smaller quantities of biodiesel to enhance stability. Silva et al. [75] also emphasized that the addition of biodiesel to marine diesel requires appropriate maintenance procedures to ensure fuel quality in storage. However, Silva et al., 2022 only mentioned spill response as background of the research.

Mathew & Abraham [75] examined the impact of natural gas emissions from oil spills and highlighted the need to avoid flaring due to the risk of greenhouse gases and explosions. Instead, bioremediation was proposed as an environmentally friendly cleanup technique, using indigenous bacteria and beeswax as a biostimulant to replenish missing nutrients. The experiment was conducted by adding diesel fuel to beeswax-containing seawater and monitoring parameters such as DO, pH, nutrients, and microbial density. The results showed that indigenous bacteria used oil as a carbon source and beeswax as a nutrient source, achieving an oil removal efficiency of 87%, much higher than the control sample of 59%. Mathew & Abraham 2022 also indicated that bioremediation reduces carbon emissions and is an environmentally friendly method of oil spill cleanup.

Appendix B: Findings of survey and interviews

■ Questionnaire results

The survey respondent pool is currently dominated by shipboard personnel, closely followed by researchers and maritime-education or training staff. Regulatory voices are also well represented. Other stakeholders including shipping-company personnel and classification-society surveyors are also surveyed, and responses are yet to be received from bunkering or fuel-supply companies.

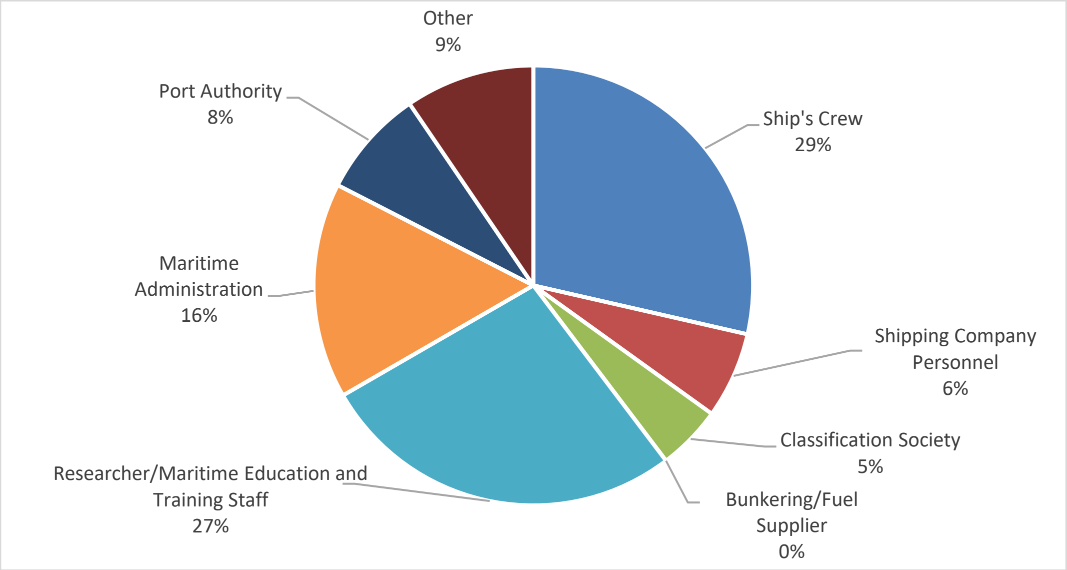

Figure 97. Survey questionnaire for participants' distribution

Respondents were asked to indicate the type(s) of fuel used by their current ship, bunker supplier, or port, with multiple selections permitted. Very-low-sulphur fuel oil (VLSFO) accounted for 19 %, whereas traditional distillates, ultra-low-sulphur diesel, marine gas oil and heavy fuel oil, accounted for about 11 % each. Transitional or emerging options such as biodiesel blends, low-sulphur fuel oil, marine diesel oil, and synthetic e-fuels cluster near 8 %, while methanol accounted for approximately 6 % and LPG, LNG, and generic biofuel below 3 %. No respondent cited dual-fuel systems. A discussion on the results under thematic areas ensues.

A quarter of the respondents reported prior specific experience with blends of biodiesel with conventional marine fuel which reflects the early stage of biodiesel adoption within the maritime industry and highlights a general lack of hands-on exposure among stakeholders. The limited experiential base may hinder informed decision-making, slow acceptance of alternative fuels and cause uncertainty regarding operational performance, compatibility, and compliance. Consequently, the gap underscores the need for practical pilot projects, knowledge dissemination, and targeted training programs to equip maritime personnel with the experience required to support a broader transition toward sustainable marine fuels.

Less than a quarter of the participants were familiar with biodiesel blend classifications such as B10, B20, and B100. This highlights a knowledge gap among maritime professionals regarding specific biodiesel blend types, underscoring the need for targeted training or awareness initiatives to ensure informed decision-making in transitioning to alternative marine fuels.

Furthermore, an understanding of the fundamental differences between biodiesel blends and conventional marine fuels, such as MDO and HFO appeared to be limited. This reveals a knowledge gap within the sample, which necessitates targeted education and operational exposure to facilitate informed decision-making and the safe integration of biodiesel technologies.

While a plurality believes regulations or standards for blends of biodiesel with conventional marine bunker fuel do exist, a notable minority either lacked certainty or acknowledged unfamiliarity. There is need for targeted outreach and education on regulatory developments to ensure that maritime stakeholders are not only technically informed but also compliant with evolving fuel governance standards

Concerns about fire risk prevail among maritime stakeholders, although they are not universally held which highlights the importance of providing clear, evidence-based guidance on the thermal and flammability properties of biodiesel blends to support risk assessment, onboard safety protocols, and informed decision-making.

A clear knowledge gap emerged in operational practices related to biodiesel handling, which is a critical safety and performance issue due to biodiesel's different oxidation stability, moisture absorption and microbial growth potential compared to fossil fuels. Lack of clarity on these procedures among most respondents signals an urgent need for standardised training and operational guidance specific to biofuel storage and handling on ships.

The majority (70%) of participants recognised the operational and safety risks associated with microbial growth, which can lead to fuel degradation, filter clogging, corrosion of storage systems and engine performance issues. This reflects a growing understanding among maritime stakeholders of one of the key technical challenges in biodiesel use.

The majority (70%) of participants believed biodiesel to have environmental risks comparable to traditional fuels which indicates limited awareness of the differences in biodegradability and toxicity between biodiesel and fossil fuels. Biodiesel is more biodegradable and less toxic to marine ecosystems than petroleum-based fuels, though it can still cause oxygen depletion and microbial imbalances in confined or sensitive areas. The perception captured in this data points to a knowledge gap that could influence emergency response protocols and environmental risk assessments. Addressing this through clear comparative information on spill behaviour, biodegradation rates and ecological impact is essential for informed risk management and regulatory compliance in biodiesel usage.

Views were split on adequacy of the onboard SOPEP kit for responding to biodiesel blend spills. This reflects a potential gap in preparedness and highlights the need to assess whether existing SOPEP provisions fully address the properties of biodiesel.

Quite naturally, the majority (86%) respondents agreed that current seafarer training is insufficient to address the safety and environmental risks of biodiesel blends which points to a clear consensus that existing training programs lack adequate content on alternative fuel management and highlights an urgent need to update curricula to reflect the realities of fuel transition in maritime operations.

Similarly, an overwhelming (87%) majority held that additional education and drills are needed to prepare crews for biodiesel-related incidents. This strong consensus highlights a recognised gap in current onboard preparedness and emphasises the urgency for targeted training and practical exercises related to biodiesel safety and response.

Whereas respondents clearly anticipate significant growth in biodiesel deployment across the sector and 74% support expanding biodiesel-blend use in maritime operations, only 7% of participants have had the opportunity to personally manage a biodiesel-blend spill, 20% knew of incidents without direct involvement, and the remaining 73% had no spill experience. This limited hands-on exposure contributes to the preparedness and training gaps reported elsewhere in the survey and flags a need to build practical response capability as biodiesel uptake increases.

■ Overview

Figure 98 presents a schematic overview of the questionnaire survey.

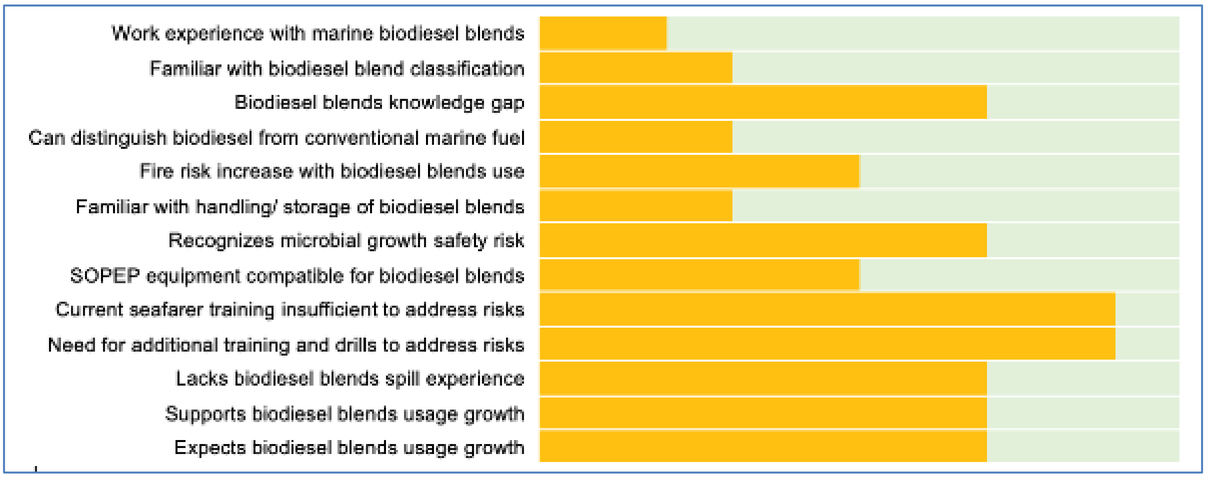

Figure 98. Survey questionnaire response

Taken together, the survey paints a coherent picture of a maritime sector that expects biodiesel-blend use to grow yet is not fully prepared to manage it safely or confidently. Although three-quarters of respondents support wider adoption and two-thirds anticipate a significant rise in usage over the next decade, only one-quarter have ever worked with biodiesel blends and fewer than one in ten have dealt with an actual biodiesel spill. This experiential deficit parallels multiple knowledge gaps: sizeable majorities are uncertain about blend classifications, storage and handling protocols, the distinct fire-behaviour of biodiesel, and the specific international rules that already govern its use.

Fuel-choice data reinforce the early-adoption narrative. Very-low-sulphur fuel oil dominates bunkering decisions, while biodiesel blends sit among a cluster of “emerging” options that together attract barely a tenth of selections. In other words, even stakeholders who endorse biofuels in principle still bunker with conventional distillates in practice; a divergence that reflects the operational doubts captured elsewhere in the survey.

Risk perceptions further illustrate this tension. Half the sample believes biodiesel blends heighten onboard fire risk and two-thirds equate their environmental hazards with those of conventional fuels, suggesting limited awareness of the blends’ higher flash points at B20 and their superior biodegradability. Consistent with those perceptions, respondents are split on whether existing SOPEP kits can handle biodiesel spills, while an overwhelming majority judge current seafarer training inadequate and call for more drills.

Overall, the survey results reveal a self-reinforcing sequence. Because stakeholders have little direct experience with biodiesel blends, significant knowledge and regulatory-awareness gaps persist. These gaps, in turn, heighten risk perceptions and create uncertainty about whether existing equipment is adequate. The combined effect is a continued preference for conventional fuels, even among respondents who say they support switching to biodiesel.

Breaking this chain will require coordinated action: practical pilot voyages to build experience; targeted curricula and drills to embed technical know-how; clear guidance on fire properties, microbial growth, and spill behaviour; and proactive dissemination of existing regulatory frameworks. Addressing these elements simultaneously will convert latent support into confident, safe, and compliant adoption of biodiesel blends across the fleet.

■ Thematic analysis of biodiesel blend stakeholder interviews

This thematic analysis synthesises insights extracted from nine semi-structured interview transcripts conducted between May and July 2025 with maritime stakeholders including ship operators, equipment manufacturers, class/flag representatives, regulators, port, and research personnel. Using an inductive approach, recurring ideas were coded and aggregated into higher-order themes that illuminate the opportunities and constraints surrounding the adoption of biodiesel-conventional fuel blends in shipping.

All interviews were transcribed verbatim and manually coded. Initial line-by-line coding generated a codebook of 48 items, which were iteratively condensed into seven overarching themes: (1) experiential knowledge and training; (2) technical and safety challenges; (3) regulatory and classification uncertainty; (4) environmental risk and spill preparedness; (5) equipment and operational compatibility; (6) economic and policy drivers; and (7) collaborative research needs. Only statements contained in the transcripts informed the analysis; no external sources were introduced.

- *Limited hands-on experience and training needs*

Many interviewees reported minimal direct exposure to biodiesel blends. A representative of a global spill response equipment manufacturer observed that "the amount of biofuel in use … is still very low, so there's not so much representative testing." Similar reservations arose from European policy actors who emphasized a "technical know-how gap" impeding local adoption and spill preparedness initiatives. Consequently, participants stressed the need for dedicated training and drills to familiarise crews with fuel properties and contingency procedures.

- *Technical and safety challenges*

Stakeholders highlighted uncertainties around corrosion, microbial growth, filter clogging, and cold-flow behaviour. A classification-society adviser noted the absence of standardised corrosion tests, arguing that "each fuel needs to be evaluated … we need a performance test." Engine-OEM guidance was deemed vital, especially given variable fuel quality between ports.

- *Regulatory and classification uncertainty*

Awareness of applicable regulations was a mixed bag. While some flagged recent MARPOL Annex I amendments permitting carriage up to B30, others admitted "no national framework to cover this area" for production facilities. Classification societies were perceived as "overloaded" and needing to "ramp up their efforts" to issue guidance on non-standard blends.

- *Environmental risk and spill preparedness*

Perceptions diverged on spill behaviour and response. Some believed biodiesel is "more biodegradable" than conventional fuel yet still capable of forming surface sheens that suffocate marine life. Others argued response procedures "should be pretty much the same" as for marine fuel oils, albeit with attention to high-pour-point floaters. Equipment adequacy, especially booms, skimmers and sensors, remained contested.

- *Equipment and operational compatibility*

OEMs and operators characterised biodiesel blends as a "drop-in" fuel requiring limited hardware modification, though stricter monitoring of temperature, water content and filter differentials was advised. Concerns were raised over oily-water separators, which are type-approved for Annex I but not Annex II cargoes, creating compliance ambiguities when B>24 blends are carried.

- *Economic and policy drivers*

Regulatory incentives emerged as the primary accelerator. An engine-equipment expert calculated that by 2028 a B10 blend "is already cheaper than paying penalties" under anticipated market-based measures. Conversely, high production costs and limited infrastructure were viewed as adoption barriers in developing regions.

- *Collaborative research and guidance*

All participants endorsed cross-sector research consortia and pilot trials. Projects linking shipowners with universities and classification bodies were cited as pathways to generate "evidence-based guidance" on fuel quality, engine performance, and spill response effectiveness.

■ Overview of the findings of the interviews

Collectively, the interviews reveal cautious optimism: biodiesel blends are technically feasible and policy-aligned, yet successful scaling hinges on closing knowledge gaps, clarifying regulations, and validating safety and environmental performance through shared experimentation and targeted training. Addressing these interrelated themes will be critical to realising biodiesel's contribution to maritime decarbonisation.

Appendix C: Hazard identification and assessment

This Appendix examines the safety hazards related to the use of biodiesel blends with conventional marine bunker fuel on board ships. The study further investigates the hazards of spills of biodiesel blends from ships to the marine coastal and ocean environment.

Introduction

The global fleet is increasingly bunkering biodiesel/diesel mixtures to meet CO_2 reduction targets. To keep pace with the rapidly evolving decarbonization regulations, the marine-fuel sector has focused on retrofitting existing bunker tankers. Following detailed risk assessments, blends up to B30 are now authorized for carriage under MARPOL Annex I in standard fuel tanks. Besides, FAME blends above B30 are also known to be certified by some IACS classification societies for transport under MARPOL Annex II and the IBC Code, showing that, with an innovative validation approach, higher-ratio biodiesel cargoes can be handled on conventional bunker vessels without the costly conversions normally required for chemical tankers [53].

While the B100 is not considered as safety challenge [54] yet each blend changes the classical “hazard landscape” of marine fuels. Using the MSDS data collated for WP 1.3, a sample SDS for B100, and publicly available SDSs for B20 and B30, this note distils the key safety and environmental hazards for blends B5, B10, B15, B20, and B30. Hazards are categorized around the five themes prescribed by IMO MSDS guidance: flammability/explosivity, oxidation, corrosion, reactivity, and environmental persistence.

Methodology

The safety and environmental hazards were evaluated through several steps as presented in Figure 99.

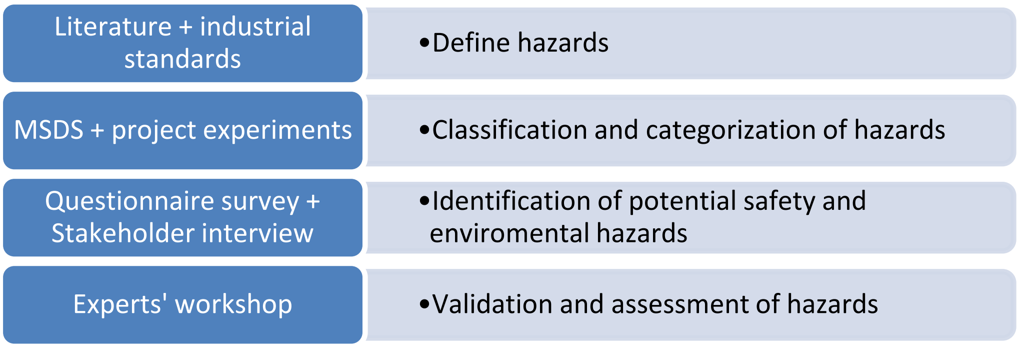

Figure 99. Methodology for hazard analysis.

When evaluating these hazards to uncover any new or latent risks, it is essential to establish clear, precise definitions for each hazard category. This is essentially the basis for the discussions on hazard identification HAZID). Thereafter, with a view to obtain the characteristics and catalogue the hazards, we surveyed Material Safety Data Sheets (MSDSs) for commercially available biodiesel blends, from conventional diesel (B0) through intermediate mixtures (up to B30) to pure biodiesel (B100). Any MSDS that did not align with IMO nomenclature was excluded, leaving 30 compliant documents for analysis. These were then classified according to the hazard classes and pictograms set out in the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) [55] recommended by the IMO [56].The study catalogued key onboard safety hazards for seafarers, flammability, explosivity, oxidising potential, corrosion, microbial growth and chemical reactivity. The catalogue of environmental hazards that could harm marine ecosystems, as identified from project experiments was dominated by concerns over bioaccumulation, poor degradability, toxicity, and persistence of substances in seawater. Potential safety risks onboard ships were discerned from major stakeholders – ship masters, chief and watch officers, engine-room staff, technical managers, and class-society surveyors – through a combination of questionnaires and interviews. The questionnaire helped capture participants’ views on potential hazards for risk identification and perception whereas the interviews delved into real-world issues and first-hand experiences with these fuel blends. An expert workshop, finally, aided in validation of assessed risks and their ranking. Figure 99 presents an overview of the methodology adopted for the HAZID assessment.

The review of biodiesel MSDSs reveals that B20 is the most documented blend with 8 entries, followed by B5 and B2 with 6 and 5 respectively, indicating strong regulatory and operational focus on these commonly used blends. B100 is covered by 3 MSDSs, reflecting its niche but established use. In contrast, B10 and B30 are underrepresented, with only 1 and 2 MSDSs respectively, suggesting limited commercial usage or documentation. Notably, B24 lacks any MSDS coverage, exposing a critical gap in safety characterization. This uneven distribution highlights the need for broader data coverage to support risk assessment across the full range of biodiesel blends. Figure 100 details the MSDS collected.

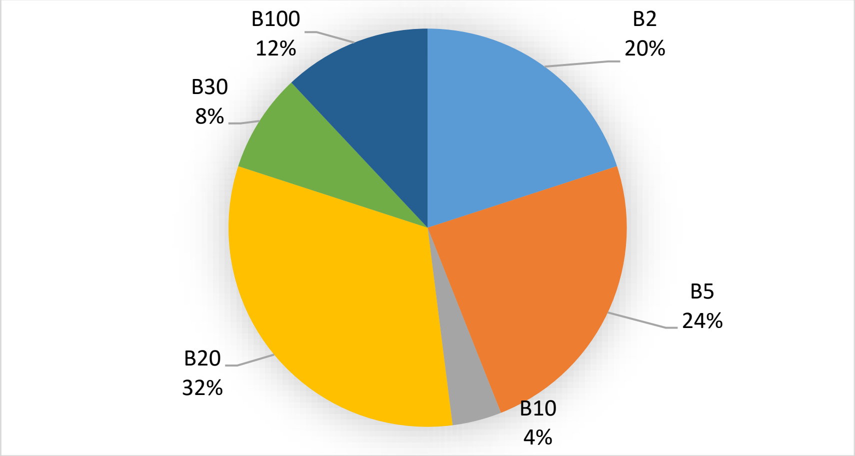

Figure 100. Biodiesel blends' Material Safety Data Sheet reviewed.

The MSDS review yielded properties and hazard information for biodiesel blends ranging from B2 to B20 within the same document. For instance, the flash point is typically reported as a range, often between 38°C and 82°C, based on the Pinsky-Martens closed cup test. This implies that B2 blends exhibit a flash point above 38°C, while B20 blends approach 82°C. However, the properties of intermediate blends (e.g., B5, B10, B15) are not individually specified, leaving a significant degree of uncertainty in this range.

Considering this uncertainty, a precautionary approach is adopted. Fuel operators and users should assume the worst-case scenario when specific data is unavailable. In this context, applying the lower bound of the flash point, 52°C, to all blends between B2 and B20 reflects a fundamental safety principle: in the absence of precise data, operational decisions should prioritize higher risk to ensure adequate protective measures are in place.

■ Biodiesel blends’ safety hazards

○ *Flammability and explosivity*

The low level of familiarity with biodiesel blends threatens seafarers’ safety on board. The WMU survey indicated that a significant majority had not worked with biodiesel blends in shipping operations. This lack of experience can delay risk detection and make prevention measures ineffective, increasing the likelihood of undesirable consequences. 33% of surveyed sample suggest a limited understanding of the fundamental differences between biodiesel blends and conventional marine fuels, such as MDO and HFO. The typical safety hazards onboard associated with any alternative fuel are flammability and toxicity. Flammability can be defined as the ability of a substance to catch and sustain fire [55], [57], [58], whereas flashpoint can be defined as the minimum temperature at which the liquid will give off flammable vapor to ignite [59]. Flashpoint is used in all national and international standards for classification of flammable liquids, namely liquids with a flash point less than 93^{0}C [55], following the global harmonized system (GHS).

GHS flammability in liquids has been categorized into four classes, based on the flashpoint. The flash point of biodiesel blends appears to rise linearly with biodiesel content (closed-cup values: B5 ≈ 52 °C, B10 > 60 °C, B20 ≈ 82 °C, B30 ≥ 93 °C). Consequently:

- B5 remains a GHS Cat 3 flammable liquid (23 °C ≤ FP < 60 °C) and must be placarded “flammable”;
- B10–B20 fall into Cat 4 combustible (60 °C ≤ FP < 93 °C); still ignitable by engine-room hot surfaces or static discharge; and
- B30 lies above 93 °C and is not classed as flammable under GHS, but light-end vapours from the fossil fraction can still accumulate in ullage spaces.

Table 19 presents a synopsis of the flammability hazards associated with biodiesel blends. Light hydrocarbon vapours can accumulate in the tank headspace, creating a fire or explosion risk even at temperatures below the nominal flash point. This observation aligns with the WMU survey result that 50% of respondents believe blending biodiesel with conventional marine fuels increases the risk of onboard fires.

Table 19. Biodiesel blend GHS classification and key safety concern.

Blend	Flash-point (°C)	GHS flammability	Key safety concern
B5	~52	Cat 3 Flammable	Vapor ignition during bunkering; diesel-like soot
B10	60–70	Cat 4 Combustible	Static ignition; elastomer swelling is minimal
B15	70–78*	Cat 4 Combustible	On-board oxidation (>3 months storage)
B20	~82	Cat 4 Combustible	Peroxide build-up; injector deposits
B30	≥ 93	Not flammable (GHS)	Filter fouling if cold; seal compatibility

Table 20 draws on information from the MSDSs to present details of the drivers of safety hazards.

Table 20. Biodiesel blends’ safety hazards’ drivers drawn from MSDS (n=30).

Safety Hazard	B2	B5	B10	B15	B20	B24	B30	B100
Flashpoint (°C) Closed Cup	52	54	60	65 (est.)	78.1	82	87	130 [ASTM D6751, [60]
Flammability Range LEL–UEL	0.6–6% (est.)	0.7–6% (est.)	0.7–6%	0.7–6%	0.7–6%	0.7–5.5%	0.7–5%	0.6–4.9%
Oxidation Stability (hrs)EN 14112	6.5 (est.)	6.2 (est.)	6.0 [60]	5.0 (est.)	3.0 [60]	2.5 (est.)	2.0 [61]	3.0 [EN 14112, ASTM D6751]
Reactivity	Low	Low–Moderate	Moderate	Moderate–High	High	High	Very High	Very High
Viscosity (mm²/s @ 40 °C)	1.6	1.9	2.5 (est.)	3.0 (est.)	4.1–5.0 [ASTM]	4.2–5.1	4.5–5.2	4.5–5.8 [61]
Conductivity (pS/m)	1–2 (ULSD)	3–5 (est.)	25–80 (est.)	120 (est.)	177 [60]	200 (est.)	350 (est.)	3000–4000

The flash point of biodiesel is notably influenced by both the feedstock type and the production method used. Biodiesel derived from palm oil exhibits higher flash point compared to that produced from waste cooking oil (WCO). For instance, palm oil biodiesel synthesized using graphite and silver electrodes achieved flash points exceeding 115°C, whereas biodiesel from WCO using similar electrodes reached slightly lower, but still substantial, values around 120°C. These variations are largely attributed to the higher free fatty acid (FFA) content and oxidation by-products in WCO [61], which result from repeated thermal exposure during cooking and tend to reduce fuel stability by increasing volatility.

Additionally, the electrode material used during electrolysis significantly affected the flash point outcomes. Graphite and silver electrodes were associated with the highest flash points, especially when used with WCO, reaching up to 120°C. In contrast, the use of platinum electrodes, although effective in maximizing yield and reducing impurities, resulted in slightly lower flash points (around 110°C), due to enhanced reactivity that may favour the retention of more volatile compounds. Importantly, all produced biodiesel samples met or exceeded the ASTM D6751 minimum flash point requirement of 93°C, confirming their safe handling characteristics [61].

Table 21. Biodiesel blends' feedstocks and production method vis-à-vis associated flash point [61].

Blend	Feedstock	Production Method	Flash Point (°C)	Notes
B2	FAME/ULSFO	Conventional	54	-
	Palm Oil	Conventional	68	Slight increase over diesel baseline (ULSD ~60 °C)
	WCO	Conventional	65	Slightly lower due to higher volatiles from WCO
B5	Palm Oil	Electrolysis (Graphite)	78	Enhanced purity raises flash point
	WCO	Electrolysis (Platinum)	76	Improved yield, moderate flash point
B10	Palm Oil	Conventional	88	Strong ester profile begins to dominate
	WCO	Conventional	85	Still stable, but impurities influence value
B20	SOME/diesel	Conventional	82	-
	FAME/ULSFO	Conventional	82	-
	Palm Oil	Electrolysis (Silver)	115	Highest values due to clean ester profile
	WCO	Electrolysis (Graphite)	120	High flash point despite WCO due to graphite effect
B30	Palm Oil	Electrolysis (Platinum)	110	Slightly lower due to FAME dominance
	WCO	Electrolysis (Silver)	118	Silver moderates' thermal reactivity and improves flash point
B100	RME/FAME	Conventional	>101	-
	Palm Oil	Electrolysis (Graphite)	170	High purity biodiesel from palm oil gives strong stability
	WCO	Electrolysis (Platinum)	160	Lower flash points due to degraded components in WCO

- *Autoignition and fire risks*

Oxidized biodiesel can lower the flash point of fuel blends (especially if alcohol residues are present), raising the risk of autoignition in hot engine compartments. While biodiesel itself has a higher flash point than diesel, degraded or contaminated blends may behave unpredictably, especially in poorly ventilated engine rooms or during maintenance operations involving heated fuel lines. Associated risk mitigation measures would include:

- use of antioxidant additives (e.g., TBHQ, BHT) at blending or bunkering stages;
- ensuring regular turnover of fuel to avoid long storage durations;

- applying nitrogen blanketing in storage tanks to reduce oxygen exposure;
- maintaining filtering and separator systems optimized for biodiesel contaminants; and
- conducting periodic fuel quality testing, particularly acid number, and peroxide values.

Static electricity

Static electricity poses a significant ignition hazard during the handling of biodiesel and diesel blends, particularly during operations such as filling, tank cleaning, or switch loading. While grounding and bonding are essential, they may not fully eliminate the risk, especially when transitioning between products of differing flash points.

Onboard ships, comprehensive procedural controls, including slow-loading protocols and reference to standards such as NFPA 77 and API RP 2003, are critical to mitigating static-related fire hazards. This hazard can exist even within a fuel sampling operation; therefore, the bonding procedure should be followed during such operations.

Ultra-low sulphur diesel (ULSD) typically exhibits very low electrical conductivity, around 1–2 pS/m[62], due to hydrotreating processes that strip away natural polar species [62]. In contrast, biodiesel (FAME), such as soybean-oil B100 at 25 °C, demonstrates much higher conductivity, in the range of 3,000–4,000 pS/m [61], [63]. For blends of polar and non-polar fuels, a mixing rule is commonly applied: the DC conductivity is primarily influenced by the volume fraction of the polar phase, and a linear interpolation provides a first-order approximation. This method is often used in industry for rapid screening, though more precise work requires direct measurements of each batch. Even the lowest estimated conductivity value for B5 blends, around 177 pS/m, well exceeds the ASTM D7467 and D6751 minimum requirement of 25 pS/m for B6–B20 and B100 fuels [60]. Regarding safety, risk is generally assessed based on the widely recognized 50 pS/m threshold for charge accumulation, as outlined in petroleum safety guidance [64].

Oxidation

Biodiesel blends stored on board ships, especially in warm, humid, and oxygen-rich environments, are highly susceptible to oxidation-induced degradation [65]. This process is driven by the presence of unsaturated fatty acid methyl esters (FAMEs), which readily react with oxygen, leading to the formation of harmful by-products such as peroxides, aldehydes, ketones, acids, and polymeric compounds. As oxidation progresses, the fuel’s viscosity increases, impairing injector performance, while sludge and gum formation can clog filters and fuel lines. Additionally, the acid number increases, promoting the corrosion of metal components and posing long-term reliability risks to shipboard fuel systems. In addition to chemical degradation, oxidized biodiesel blends can adversely affect combustion quality and engine performance**.** The degraded fuel may combust incompletely, resulting in increased engine knocking, higher exhaust temperatures, and unstable flame characteristics. These combustion issues can lead to the deposition of carbonaceous residues in the combustion chamber and exhaust system, significantly elevating the risk of localized overheating and fire. Furthermore, injector fouling, caused by sticky oxidation products, disrupts spray uniformity, creating hotspots that exacerbate engine wear and elevate fire hazards, particularly under high-load conditions [64].

Oxidation stability is a critical parameter that reflects the resistance of biodiesel to degradation when exposed to oxygen, heat, and light. Biodiesel blends like B20 have been reported to exhibit an oxidation stability of up to 6 hours [60], significantly higher than B100, which typically shows around 3 hours [60]. This enhanced stability in B20 arises from the dilution of the more oxidation-prone FAME components with petroleum diesel, which contains fewer unsaturated compounds and may also include natural antioxidants. In contrast, B100, being composed entirely of biodiesel, contains higher levels of unsaturated fatty acid methyl esters that are susceptible to oxidation, especially during long-term storage. The improved oxidative performance of B20 over B100 highlights the role of blending in extending fuel shelf life and maintaining fuel quality under standard storage conditions [64].

The use of antioxidants; polar or non-polar, can extend biodiesel blend stability for up to 12 weeks [65]. Christensen and McCormick [65] further contend that non-polar antioxidants, even under humid storage conditions with low water content, mitigate stability loss more effectively than polar antioxidants. Their experiments, however, were limited to B20 and B100, restricting the generalisability of the findings across all blend ratios. The study nonetheless underscores the importance of maintaining a dry storage environment for biodiesel blends [65]. Reflecting this uncertainty in practice, 50% of WMU survey respondents reported not being sure about the correct storage and handling procedures for biodiesel fuels or their blends with conventional marine fuels.

Low thermal stability (physicochemical fuel weakness under heat)

Thermal stability refers to a fuel's resistance to decomposition at elevated temperatures. Low thermal stability means the fuel breaks down or reacts unfavourably when exposed to heat, even in the absence of oxygen [66]**.** The ship's crew need to demonstrate high risk perception and a deep understanding of such properties. However, at least a third of the participants surveyed by WMU suggested that were not familiar with biodiesel blend classifications such as B10, B20, and B100 physiochemical properties.

Blending biodiesel-FAME originating from MDO produces a dual-phase chemical system, where the biodiesel provides oxygenated esters to improve the biodegradability from an environmental perspective, but reduces the thermal stability from an operational approach. MDO contains unsaturated hydrocarbons, a higher degree of unsaturation lowers cetane number and worsens ignition quality, even though it helps cold-flow behaviour [67].

As for the related safety issues onboard ships, the reduced thermal stability influences acid formation and peroxide degradation affect blend quality and increases the corrosion potential, as well as leads to deposits and sticky residues that cause clogging and reduced ignition capabilities. They tend to polymerize into sludge or gel, creating another challenge for the storage and handling system, complicates tank-cleaning and hot-work permits. It should be noted that thermal stability declines with higher FAME content. B20 and B30 can polymerize into gum during prolonged exposure to >150 °C injector tips, raising sticking and fire-back risks.

Microbial growth

Biodiesel blends with conventional marine fuels are more hygroscopic and oxygen-rich than pure distillates, so they absorb water and provide nutrients that favour bacterial and fungal growth during storage.

Microbes colonise the fuel-water interface, forming biofilms that generate acids and sludge while accelerating corrosion of tanks and lines. Growth rates rise with higher FAME content, warm temperatures, stagnant fuel, and frequent exposure of headspace air that condenses moisture.

The results are clogged filters/injectors, deteriorated cetane quality, and off-spec fuel properties that jeopardise reliability and safety.

Mitigation hinges on rigorous water management, routine microbiological testing, approved biocide dosing, and keeping storage systems clean, dry, and well mixed. 70% of participants in the WMU survey recognise the operational and safety risks associated with microbial growth, which can lead to fuel degradation, filter clogging, corrosion of storage systems and engine performance issues. This reflects a growing understanding among maritime stakeholders on one of the key technical challenges in biodiesel use

Corrosion

Neat biodiesel is an efficient solvent. Blends above B20 can swell nitrile and natural-rubber seals and leach deposits from legacy diesel tanks, initially overloading filters. Most elastomer issues disappear at B5, are manageable at B10-B15, and re-emerge at B30 unless Viton- or fluorocarbon-based seals are fitted. Metals such as brass, copper, and zinc catalyse peroxide formation; their use in pumps and sampling lines should be always avoided.

The associated safety concern includes the corrosion of storage tanks onboard. Seven-month storage tests of palm-based biodiesel in floating-roof tanks showed localised pitting in stainless steel but generalised corrosion in carbon and galvanised steel, with fuel viscosity, acidity and water content increasing over time [68]. Contamination remained lowest in stainless tanks, while the greatest corrosion, and hence leak risk, concentrated at the tank base rather than the walls or roof [68].

Biodiesel blends' environmental hazards

Biodiesel-conventional marine fuel blends pose environmental hazards, toxicity to marine organisms, potential bioaccumulation of certain constituents, and oxygen depletion during degradation. Spills or chronic leaks can persist as stable emulsions, impair water quality, and release corrosive by-products, stressing ecosystems and complicating clean-up efforts. The WMU survey findings suggest that majority (70%) participants perceive biodiesel to present environmental risks comparable to traditional fuels and yet have no prior response experience for spills of biodiesel blends with conventional marine fuel.

Bio accumulation

Bioaccumulation refers to the process by which a substance (such as a chemical or pollutant) accumulates in an organism at a faster rate than it is expelled or metabolized. This leads to increasing concentrations within tissues over time, especially when the organism is exposed repeatedly or chronically.

Biodiesel blends from B2 to B10 contain low percentages of FAME (fatty acid methyl esters) and are characterized by high biodegradability. These oxygenated compounds are rapidly broken down in aquatic environments, particularly under aerobic conditions, which significantly reduces the risk of membrane-level accumulation in marine organisms. Consequently, the potential for bioaccumulation at these blend levels is minimal [17]. As the biodiesel content increases to B20, the persistence in water slightly increases; however, the blend still maintains rapid aerobic degradation, resulting in much lower bioaccumulation factors than those associated with conventional petroleum diesel. In contrast, B100 (pure biodiesel) shows the fastest degradation under oxygen-rich conditions but degrades more slowly in anaerobic environments such as sediments. Despite this slower breakdown in certain conditions, B100 remains less bio accumulative due to its inherent chemical structure and overall biodegradability.

Degradability

When spilled into the marine environment, thermally oxidized biodiesel exhibits altered weathering behaviour compared to fresh biodiesel. It may form insoluble degradation products, such as gums and resins, which are more difficult to disperse or recover using conventional mechanical or chemical methods. Additionally, the increased viscosity of the oxidized fuel slows its spreading and alters the dynamics of the surface slick, potentially complicating containment strategies.

The effectiveness of chemical dispersants is also reduced when dealing with oxidized biodiesel blends. These degraded components often resist dispersion due to their higher molecular weight and lower surface activity, which undermines the performance of dispersants designed for lighter, more volatile hydrocarbons.

Furthermore, bioremediation becomes more challenging. While fresh biodiesel, especially FAME, is typically highly biodegradable, its thermally degraded counterparts may become less bioavailable or even toxic to marine microorganisms. This not only slows natural attenuation processes but may also disrupt microbial communities critical to ecological recovery.

Toxicity

All blends exhibit low acute toxicity (LC_{50} > 1,000 mg/L for fish), yet incomplete diesel removal means B5/B10 retain polyaromatic fractions that can narcotize pelagic species. Bioaccumulation potential decreases with the FAME proportion because ester-based fuels hydrolyse and metabolize faster than paraffinic diesel. No blend between B5 and B30 triggers GHS chronic aquatic toxicity ≦ Cat 3, but B5 may be rated H412: Harmful to aquatic life with long-lasting effects if aromatic content is high [69].

Persistence

U.S. MARAD (2021) study demonstrated that B20 and lower blends retained diesel-like surface behaviour in early stages, with delayed dispersion and intermediate toxicity profiles, leading to classification as moderately persistent. It was also noted that the persistence behaviour is non-linear, meaning that even a 10–20% biodiesel content significantly affects slick formation and evaporation compared to pure diesel, but not enough to ensure rapid dissipation or full biodegradation as seen in B100.

The environmental persistence of biodiesel/diesel blends in marine settings can be characterized using key degradation parameters such as biodegradation half-life, evaporation rate, and surface slick behaviour. The biodegradation half-life in seawater, defined as the time required for 50% mass loss due to microbial activity, varies significantly across blends. Pure petroleum diesel (B0) and low-blend fuels, such as B5, exhibit half-lives ranging from 15 to 30 days. In contrast, intermediate blends, like B10 and B20, degrade more quickly, with half-lives of approximately 7 to 15 days. In contrast, pure biodiesel (B100) exhibits rapid degradation, with half-lives typically ranging from 2 to 5 days under standard marine microbial and temperature conditions. Evaporation behaviour within the first 24 hours further distinguishes these fuels: diesel-rich blends (B0-B5) tend to lose 55-60% of their mass via evaporation due to higher volatility, whereas biodiesel-rich blends (B20-B100) exhibit lower evaporation losses, typically around 30-50%, reflecting biodiesel's lower vapor pressure. Surface slick characteristics also differ markedly. Persistent blends, such as B0 and B5, tend to form thick, stable emulsions that resist breakup. Moderately persistent blends such as B10 and B20 produce thinner surface films, which typically fracture into droplets within one to two days. B100, on the other hand, does not form persistent slicks and instead disperses rapidly into the water column with minimal emulsification, significantly reducing its long-term presence on the water surface.

Table 22. Persistence in water of blends of biodiesel with marine fuel

Blend	Half-life in Seawater	Evaporation Loss (24 h)	Slick Thickness Stability	Persistence Category
B0	20–30 days	~60 %	High–forms thick, stable emulsions	Persistent
B5	15–25 days	~55 %	Moderate – retains sheen, some emulsions	Persistent
B10	10–15 days	~50 %	Lower thickness; begins fracturing	Moderately Persistent
B20	7–12 days	~45 %	Thin slick; breaks into droplets	Moderately Persistent
B100	2–5 days	~30 %	Rapid dispersion; minimal emulsions	Non-persistent

As FAME content rises, marine persistence falls. Typical half-lives in seawater drop from 15-25 days (B5) to 7-12 days (B20) and <5 days for neat B100; slick thickness and evaporation loss decline in parallel. Thus, B20–B30 slicks disperse more readily than diesel but still linger long enough to justify containment and recovery; they are classified as *moderately persistent* under ITOPF criteria. B5 remains “persistent” and behaves much like conventional MGO.

The following may be noted in this regard:

- absence of blend-specific behaviour is apparent in the current response model;
- there is no numerical, or proportional relationship, between the biodiesel blends and conventional bunker fuel and weathering elements; and
- majority (86%) of the respondents surveyed by WMU agreed that current seafarer training is insufficient to address the safety and environmental risks of biodiesel blends.

The prioritisation of safety and environmental risks of blends of biodiesels with marine bunker fuels in bunkering and cargo operations is presented at Annex V.

Annex I: Symbols, abbreviations and acronyms

ABS	American Bureau of Shipping
API gravity	American Petroleum Institute gravity, or API gravity, is a measure of how heavy or light a petroleum liquid is compared to water: if its API gravity is greater than 10, it is lighter and floats on water; if less than 10, it is heavier and sinks in fresh water. The formula to calculate API gravity from specific gravity (SG or relative density) is: $\text{API gravity} = 141.5/\,SG - 135.5$
AWI	Annular Water Injection
BD+CMF	Biodiesel blends with conventional marine fuel
Biodiesel	Any fuel produced from renewable sources used in diesel engine
Biofuel	General term used to define any fuel (gas, gasoline, diesel) produced from renewable organic matter (biomass), such as plants, agricultural waste, used cooking oil or animal fat
Bonn Agreement (1969)	Mechanism by which ten Governments, together with the European Union, cooperate in dealing with pollution of the North Sea by oil and other harmful substances. The Oil Appearance Code is as follows: ○ Code 1: Sheen (silvery grey): 0.04-0.30 µm of layer thickness; ○ Code 2: Rainbow: 0.30-5 µm of layer thickness; ○ Code 3: Metallic: 5-50 µm of layer thickness; ○ Code 4: Discontinuous True Oil Colour: 50-200 µm of layer thickness; ○ Code 5: Continuous True Oil Colour: >200 µm of layer thickness.
CleanSeaNet	European satellite-based oil spill and vessel detection service
cSt	Unit of measurement for viscosity 1 cSt (centistoke) = flow of 1 mm^2/s
Density	Mass per unit volume (usually reported in g/cm3 or kg/m3)
DNV	Det Norske Veritas
DM	Distillate Marine Fuel (ISO 8217) - lighter cuts, distillate-grade (DMA, DMZ, DFA, DFZ, etc.)
DF	Distillate Fuel with FAME (ISO 8217) - Bio-distillate counterparts of DMA/DMZ
ECA/ (D)ECA	(Domestic) Emission Control Area - areas where stricter Sulphur/NO_x limits apply
Emulsification	Formation process of an invert emulsion (water in oil). Petroleum products subjected to agitation in the presence of water (natural wave action, passage through a recovery pump, etc.) form invert emulsions when loaded with polar compounds, incorporating water droplets into the oil phase: these invert emulsions, which can contain up to 80% water, appear as a sticky, viscous fluid, varying in colour from light to dark brown, hence their nickname “chocolate mousse”
EMSA	European Maritime Safety Agency
EU MRV	EU Monitoring, Reporting & Verification Regulation (for shipping emissions).
Evaporation	Transformation of a liquid into a vapor via its free surface, at a particular temperature. The rate of

	evaporation of oil depends mainly on the proportion of volatile products and the combination of hydrocarbons, as well as environmental factors such as the wind speed, the water and air temperature, the roughness of the sea surface and extent of spreading. The lightest fractions evaporate first, and the heaviest volatile fractions form a residue, with a higher density and viscosity than the original product
FAME	Fatty Acid Methyl Ester - biodiesel produced by the esterification of fatty acids
Flash point	Lowest temperature at which the concentration of vapours emitted is sufficient to cause ignition upon contact with a flame, spark, or hot spot, but is insufficient to propagate combustion in the absence of a pilot flame. By definition, a product is extremely flammable when its flash point is below 0°C, highly flammable when it is between 0 and 21°C and flammable when it is between 21 and 55°C
Fischer Tropsch	Chemical reaction which converts carbon-containing feedstocks (such as biomass, natural gas, or coal) into liquid hydrocarbons, including a diesel-like fuel (Gas to Liquid diesel - GTL) (biodiesel)
FMEA	Failure Mode and Effect Analysis
FLIR	Forward Looking Infra-Red: Infrared sensor used for remote sensing of oil slicks. In optimal atmospheric conditions, it can detect a slick approximately 20 nautical miles from the aircraft when flying at 3,500 feet. It can detect Bonn Agreement code 2 (rainbow) slicks and has no upper thickness limit. It can also be used to read the name of a vessel at night.
Fossil fuel / conventional fuel	Any fuel (gas, gasoline, diesel, heavy fuel oil) produced from fossil energy sources including oil, coal, and natural gas, being non-renewable resources
FT	Fischer–Tropsch Synthesis from Syngas ($CO + H_2$) to produce synthetic diesel
GC-FID	Gas Chromatography coupled to a Flame Ionization Detector
GCMD	Global Centre for Maritime Decarbonisation (publisher of several FAME analytical reports)
GC-MS	Gas chromatography coupled to a mass spectrometry detection
GHG	Greenhouse Gases
HVO	Hydrotreated Vegetable Oil (also called renewable diesel) - biodiesel produced by hydrogenating fatty acids
HAZID	Hazard Identification
HSFO	High Sulphur Fuel Oil (0.5 % < S < 3.5 %) / heavy fuel oil
IBIA	International Bunker Industry Association
IDID	Internal Diesel Injector Deposits
IMAROS	European project improving response capacities and understanding the environmental impacts of new generation low sulphur marine fuel oil spills (including VLSFO)
ISO	International Organization for Standardization
Invert emulsion or water-in-oil	Emulsion may be made up of a large proportion of water (often 60%, can be up to 80%). It varies in colour from brown to orange and is often referred to as “chocolate mousse,” which gives an

emulsion	indication of its consistency IR (Infrared).
LR	Lloyd's Register (maritime decarbonization hub)
MDO	Marine Diesel Oil - a heavier marine distillate fuel (ISO 8217 grade DMB)
MGO	Marine Gas Oil - a lighter marine distillate fuel (ISO 8217 grades DMA/DMZ)
MARPOL	International Convention for the Prevention of Pollution from Ships
Natural dispersion	Formation of oil droplets of varying sizes, due to wave action and turbulence on the sea surface. These droplets either stay in suspension in the water column or resurface to form another slick.
NPSH	Net Positive Suction Head
NO_x	Oxides of Nitrogen.
PAH	Poly Aromatics Hydrocarbons
P&I	Protection & Indemnity (Club)
Polludrome®	Cedre's test channel aiming to recreate natural phenomena such as the wind, current, and temperature to study the behaviour of pollutants in conditions close to those found in the natural environment.
POME	Palm Oil Methyl Ester - FAME derived specifically from palm oil
Pour point	Temperature below which a substance no longer flows. If a substance's pour point is above ambient temperature, it is less fluid. Pour points are measured in laboratory conditions and are not an accurate representation of the behaviour of a particular product in an open environment.
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RED II	EU Renewable Energy Directive
Relative density	Ratio of the density (mass of a unit volume) of a substance to the density of water for a liquid substance. Also called specific gravity.
RM	Residual marine fuel (ISO 8217) - unblended heavy fuel oils
RPN	Risk Priority Number
RF	Residual fuel blended with FAME (ISO 8217) - e.g., RF-25 for up to 25 % biodiesel blends
SAR	Synthetic Aperture Radar
SLAR	Side-Looking Airborne Radar
SLR	Systematic Literature Review
Solubility	Ability of gas, liquid, or solid products to dissolve in solvent or water. For petroleum oils, this natural process mainly involves lightest aromatic compounds as well as some polar compound.
SOPEP	Shipboard Oil Pollution Emergency Plan
UCO	Used Cooking Oil - feedstock for waste-oil biodiesel
UCOME	Used Cooking Oil Methyl Ester - FAME produced from used cooking oil
ULSFO	Ultra-Low Sulphur Fuel Oil (S < 0.1 %).

Vapor pressure	Partial pressure of gas molecules in a state of equilibrium with the liquid phase for a given temperature
Viscosity	Property of resistance to uniform pouring without shaking, inherent in the mass of a substance. It is expressed in centistokes (common units include pascal-seconds (Pa·s), centipoise (cP), or centistokes (cSt))
VLSFO	Very Low Sulphur Fuel Oil (0.1 % < S < 0.5 %).
WHOI	Woods Hole Oceanographic Institution

Annex II: Qualitative thematic analysis of the academic studies on biodiesel blends with conventional marine bunker fuels

■ Theme 1: Environmental behaviour and fate of biodiesel in marine and aquatic systems

Biodiesel's fatty acid methyl esters (FAMEs) are more readily metabolized by marine microbes, leading to higher biodegradability than fossil diesel [47], [48]. However, biodiesel stabilizes oil droplets in seawater, reducing coalescence and prolonging microdroplet transport [34], [35]. Its unsaturated FAMEs photolyze rapidly under UV, yet may shield heavier hydrocarbons in blends, inhibiting their photodegradation [49], [50].

■ Theme 2: Biodegradation processes and spill response strategies

Blending biodiesel with marine fuels generally boosts hydrocarbon breakdown, but outcomes depend on blend ratio, temperature, salinity, oxygen, and nutrients [51], [52]. Key enhancement strategies include:

- Biosurfactants (e.g., rhamnolipids) to increase bioavailability [42], [44];
- Bioaugmentation with specialized consortia for early-stage degradation[36], [43]; and
- In situ bioreactors to sustain aerobic conditions in groundwater [47], [53].

Spill response techniques for biodiesel include:

- Booming & skimming are effective but less so as dissolution increases [17], [54];
- Chemical dispersants have reduced efficacy and may raise toxicity [41];
- In-situ burning is impractical for pure biodiesel due to its high flash point [55];
- Bioremediation shows promise but needs site-specific nutrients and microbes [56]; and
- Sorbent performance varies with biodiesel type; bio-based herders enhance recovery [37],[41].

■ Theme 3: Toxicity, genotoxicity, and ecological impacts of biodiesel

Pure biodiesel and its water-soluble fractions elicit acute toxicity and genotoxicity in organisms like Daphnia magna and freshwater mussels [32], [38].

■ Theme 4: Storage stability and behaviour of biodiesel in spill scenarios

Biodiesel resists evaporation more than diesel, owing to higher-boiling components [48]. Yet it undergoes oxidative degradation during prolonged, oxygen-exposed storage, altering spill-behaviour characteristics such as volatility, spreading, and response-technique efficacy [57], [58].

■ Theme 5: Green dispersants and bio-based spill response tools

Research into eco-friendly dispersants and herders, derived from biosurfactants and plant oils—shows laboratory effectiveness comparable to conventional chemicals [37], [41]. Novel cholesterol-based herders delivered via biodiesel demonstrate potential for slick containment, though field-scale validation of their biodegradability, toxicity, and operational feasibility is still needed [53], [59].

Annex III: List of individuals that have conducted significant research on biodiesel spill response and environmental impact and Inventory of industry research and projects on biodiesel blends with conventional marine fuel and their accidental release at sea

Table 23. Individuals that have conducted significant research on biodiesel spill response and environmental impact, 1997-2024 (n=46).

	Article Reference	Title (Abridged)	D	B5	B8	B10	B15	B20	B24/25	B30	B40	B50	B100
1.	Miller & Mudge, 1997	Effect of biodiesel on crude oil weathering in sand columns											X
2.	Pereira & Mudge, 2004	Cleaning oiled shores with vegetable-oil biodiesels											X
3.	Fernández-Álvarez et al., 2007	Biodiesel as bioremediation agent (Prestige shore)											X
4.	Khan et al., 2007	Acute toxicity on aquatic organisms	X	X				X				X	X
5.	DeMello et al., 2007	Biodegradation in seawater	X	X	X	X						X	X
6.	Junior & Mariano, 2009	Biodegradation by Candida Viswanathii		X				X					X
7.	Hollebone et al., 2008	Aqueous solubility, dispersibility, and toxicity of biodiesels		X				X					X
8.	Hollebone & Yang, 2009	Biofuels in the environment	X										X
9.	Herndon, 2010	OHMSETT biofuel-spill testing						X					X

10.	Sueiro et al., 2011	Mutagenic assessment + biotreatments											X
11.	Leite et al., 2011	Toxicity of water-soluble fractions											X
12.	Leme et al., 2011	Cytotoxicity in human cells		X									X
13.	Leme et al., 2012	Soil pollution toxicity review											X
14.	Johnson et al., 2014	Spill on turfgrass		X									X
15.	Ng et al., 2015	Biodegradation study											X
16.	Lim et al., 2016	Remediation technologies						X					
17.	Nguyen et al., 2017	Impact index sustainability											X
18.	Ryndov, 2017	Sorbent materials											X
19.	Ambrosio et al., 2017	Photocatalytic degradation											X
20.	Thomé et al., 2017	Bio stimulation + infiltration											X
21.	Jezequel et al., 2019	Impact Assessment of Biodiesels in the Case of an Accidental Spill	X			X							
22.	Kass et al., 2021	Spill behaviour of HVO								X			X
23.	Brantson et al., 2022	Coconut/palm-wine biodiesel											X
24.	Abuoudah et al., 2022	Bio-herding agents											X
25.	Wilms et al., 2023	Biodiesel half-lives review						X					X

26.	Giwa et al., 2023	Green dispersants											
27.	Xin et al., 2024	Behaviour/toxicity of bio-oils											X
28.	Yang et al., 2024	Fuel blend characterization	X	X						X			X
29.	Faksness et al., 2024	Weathering/toxicity of FAMEs						X					X
30.	Leme et al., 2012	Genotoxicity via Salmonella		X				X				X	X
31.	Lisiecki et al., 2014	Biodegradation in microcosms	X			X							X
32.	Yang et al., 2013	Weathering in storage	X	X				X					X
33.	Yang et al., 2015	Photolysis in freshwater		X									X
34.	Pikula et al., 2019	Toxicity bioassay of waste cooking oil-based biodiesel on marine microalgae	X					X					X
35.	Moreira de Souza et al., 2016	Biodegradation potential of diesel/biodiesel blends		X		X			X				X
36.	Chrzanowski et al., 2012	Effect of biosurfactant dissipation on diesel fuel/B20 blend						X					
37.	Owsianiak et al., 2009	Effect of the type of blend and the addition of biosurfactants	X			X				X		X	
38.	Woźniak-Karczewska et al., 2019	long-term biodegradation of diesel/biodiesel blends	X	X		X		X		X	X	X	X
39.	Kass et al., 2022	Properties of biodiesel blends with a very-low		X		X	X	X	X				

		sulphur fuel oil (VLSFO)											
40.	Longanesi et al., 2022	Oxidative stability of biodiesel: recent insights	X	X				X					X
41.	Eremeeva et al., 2025	Development of Biofuel as Marine Fuels	X										X
42.	Gotovuša et al., 2024	Biodiesel from Higher Alcohols Cleans Crude Oil Spills	X										X
43.	Khan, Warith, & Luk 2007	Toxicity of Biodiesel and Diesel on Aquatic Organisms	X					X				X	X
44.	Yildiz et al., 2019	Environmental Pollution Costs of Biodiesel and Diesel Fuels	X										X
45.	Silva et al., 2022	Microbial Sludge in Biodiesel Blended Marine Diesel Storage	X					X	X				X
46.	Mathew & Abraham, 2022	Bioremediation of Marine Diesel Oil Using Beeswax	X										

Table 24. Articles contributions to biodiesel maritime spill response planning and elements,1997-2024, (n=46).

	Reference	Governance & Preparedness	Detection	Initial Assessment (fate & toxicology)	Strategy Selection (technique choice)	Operational Deployment	Shoreline Cleanup	Health & Safety	Waste Management	Post-Incident Monitoring	Environmental Restoration	Research & Improvement
1.	Miller & Mudge 1997			✓							✓	✓

2.	Pereira & Mudge 2004				✓	✓	✓		✓		✓	✓
3.	Fernández-Álvarez et al. 2007			✓	✓	✓	✓			✓	✓	✓
4.	Khan et al. 2007			✓				✓				✓
5.	DeMello et al. 2007			✓						✓	✓	✓
6.	Júnior & Mariano 2009										✓	✓
7.	Hollebone et al. 2008			✓	✓							✓
8.	Hollebone & Yang 2009	✓		✓	✓							✓
9.	Herndon 2010				✓	✓						
10.	Sueiro et al. 2011							✓			✓	✓
11.	Leite et al. 2011			✓				✓				✓
12.	Leme et al. 2011							✓				✓
13.	Leme et al. 2012 (review)			✓				✓			✓	✓
14.	Johnson et al. 2014					✓	✓		✓		✓	
15.	Ng et al. 2015			✓						✓	✓	✓
16.	Lim et al. 2016				✓	✓	✓		✓		✓	✓
17.	Nguyen et al. 2017	✓										✓
18.	Ryndov 2017				✓	✓	✓					
19.	Ambrosio et al. 2017								✓		✓	✓
20.	Thomé et al. 2017						✓			✓	✓	✓
21.	Jezequel et al. 2019 (Cedre)	✓		✓	✓	✓		✓		✓	✓	✓
22.	Kass et al. 2021		✓	✓	✓							✓
23.	Brantson et al. 2022				✓	✓	✓				✓	✓
24.	Abuoudah et al. 2022			✓	✓	✓						✓
25.	Wilms et al. 2023	✓		✓						✓		✓
26.	Giwa et al. 2023				✓	✓		✓				✓
27.	Xin et al. 2024			✓				✓				✓

28.	Yang et al. 2024	✓		✓								✓
29.	Faksness et al. 2024			✓	✓			✓		✓		✓
30.	Leme et al. 2012 (genotox)							✓				✓
31.	Lisiecki et al. 2014									✓	✓	✓
32.	Yang et al. 2013	✓							✓			✓
33.	Yang et al. 2015										✓	✓
34.	Pikula et al. 2019			✓				✓				✓
35.	Moreira de Souza et al. 2016									✓	✓	✓
36.	Chrzanowski et al. 2012				✓						✓	✓
37.	Owsianiak et al. 2009				✓						✓	✓
38.	Woźniak-Karczewska et al. 2019									✓	✓	✓
39.	Kass et al., 2022		✓	✓			✓	✓		✓		✓
40.	Longanesi et al., 2022	✓		✓			✓	✓		✓		
41.	Eremeeva et al., 2025	✓		✓							✓	
42.	Gotovuša et al., 2024	✓		✓	✓	✓	✓		✓			
43.	Khan, Warith, & Luk 2007	✓		✓	✓	✓		✓				✓
44.	Yildiz et al., 2019			✓	✓							
45.	Silva et al., 2022	✓		✓	✓							
46.	Mathew & Abraham (2020).			✓			✓		✓		✓	✓

Table 25. Projects on biodiesel blends with conventional marine fuel and their accidental release at sea

Title / project	Organization/ authors	Summary of conclusions
Safe Bunkering of Biofuels [60] – Final Report (2024)	European Maritime Safety Agency (EMSA), conducted by DNV. Authors: Per Einar Henriksen, Øyvind Sekkesæter, Santiago Soria, Benjamin Barbette, Sarath Raj, Magnus Jordahl, Håkon Jonsson Ruud, Koen	This EMSA-commissioned study (Contract 2023/EMSA/OP/11/2023) aimed to develop a technical guidance document for the safe bunkering of biofuels, focusing on bio-methanol, FT-diesel, DME, HVO, and FAME. The study included: 1) Safety characterization of these biofuels; 2) HAZID and risk assessment workshops with industry stakeholders; 3) Development of a practical bunkering guidance with checklists. Key conclusions: HVO, FAME, and FT-diesel pose similar operational risks to conventional fuels, mainly requiring proper storage and compatibility checks. Bio-methanol and DME require stricter controls due to low

	Pieter Houweling, Åsa Snilstveit Hoem (DNV)	flashpoints and toxicity. Bunkering risks were primarily during fuel transfer operations. The study produced 59 recommendations for safeguards and operational measures. Developed structured guidance for all bunkering phases (pre-bunkering, transfer, disconnection) and provided ready-to-use checklists. While focused on bunkering safety, the study provides valuable insights applicable to spill prevention and risk mitigation strategies in marine biofuel operations.
Potential of Biofuels for Shipping [61]– Final Report (2025)	Ecofys Netherlands B.V. for EMSA; Authors: Anouk Florentinus, Carlo Hamelinck, Arno van den Bos, Rob Winkel, Maarten Cuijpers	This study assessed the viability, integration potential, and policy implications of biofuels in shipping, with emphasis also on biodiesel (FAME) and straight vegetable oils (SVO). Key conclusions: Biodiesel (FAME) blends up to B20 were considered most promising due to compatibility with marine distillate fuels (MDO/MGO) and minimal system modifications. Safety & Environmental Risk: FAME is biodegradable and has zero Sulphur content, making it advantageous in case of spills compared to fossil marine fuels. HSSE benefits in spills include lower toxicity and faster degradation. However, risks include fuel instability (oxidation, microbial growth), water contamination (acidity), and cold-flow challenges. Existing marine fuel infrastructure can accommodate low-level blends with minor adjustments. For higher blends or pure biofuels, onboard storage and handling practices need to be adapted, especially for water management and filter clogging. → Legislative gaps were identified: ISO 8217 did not fully cover high biodiesel blends; MARPOL Annex VI lacks dedicated guidance for alternative fuels beyond Sulphur limits. Policy Recommendations: Introduce a marine-specific fuel standard for biofuels; adjust RED to place obligations on bunker suppliers; promote blending at bunker level (not onboard); support dedicated R&D on HSSE aspects of 100% biodiesel blends and long-term storage impacts. The study recognized biodiesel as a viable sustainable marine fuel with clear environmental advantages but highlighted the need for further technical validation, regulatory alignment, and market incentives to scale adoption.
Fate, Behaviour and Potential Damage & Liabilities Arising from a Spill of Biofuels into the Marine Environment [62] (2024)	ITOPF (International Tanker Owners Pollution Federation) for International Group of P&I Clubs Alternative Fuels Working Group	This ITOPF report (May 2024) assesses the fate, behaviour, environmental impacts, and liabilities from accidental spills of biodiesels (FAME & HVO) in marine environments. Key conclusions: Biodiesel (both FAME & HVO) floats on water, spreads like conventional diesel, but evaporates less due to low vapor pressure. Biodegradation is 4x faster than for fossil diesel, but depending on temperature and conditions, biodiesel can persist for weeks to months. In cold waters, FAME can solidify, reducing spread but complicating recovery. Primary environmental impacts: smothering of wildlife (especially in warmer waters) and oxygen depletion (risk of hypoxia in sheltered areas). Toxicity is significantly lower than conventional diesel (5x less acute toxicity). Response techniques like oil spills: booms, skimmers, recovery. Monitoring is more difficult due to colourless appearance of biodiesel slicks. Main liability aspects like fossil fuel spills: clean-up, wildlife response, environmental restoration, property damage (e.g., oiled vessels, port structures), and economic losses (e.g., fishing bans, port closures). Biofuel spills not directly covered under 2001 Bunkers Convention; pure biodiesel as bunker fuel falls under national laws or future HNS Convention provisions. The study provides valuable guidance for spill response preparedness, highlighting that response techniques can largely follow existing oil spill protocols but require awareness of biofuel-specific behaviour (solidification, rapid biodegradation, visibility challenges).

Biodiesel Handling and Use Guide [63] (2023)	National Renewable Energy Laboratory (NREL)	This manual provides essential guidance for the safe handling and use of biodiesel and its blends in marine applications. It highlights the importance of material compatibility, noting that biodiesel may degrade certain elastomers and metals. Key findings emphasize the need for proper storage to prevent oxidation and water absorption, as well as routine filtration and microbial control to maintain fuel quality. The manual confirms that blends up to B20 perform comparably to diesel but require vigilant system monitoring. Overall, it underscores the value of proactive maintenance and crew training to ensure safe and efficient biodiesel use.
Biofuels as Marine Fuel – Sustainability Whitepaper [64] (May 2021)	American Bureau of Shipping (ABS)	This ABS whitepaper assesses the viability of marine biofuels—especially FAME, HVO, FT diesel, DME, and bio-methanol—as "drop-in" replacements for marine gas oil (MGO) and heavy fuel oil (HFO). Key conclusions: Safety: FAME and HVO are biodegradable and less flammable than fossil fuels. FAME's flashpoint exceeds 93°C; however, fuel oxidation, corrosion risk, microbial growth, and cold-flow issues are significant concerns. Environmental Impact: Biofuels have lower Sulphur, PM, and GHG emissions than fossil fuels. Their carbon footprint depends on feedstock type and production path. Lifecycle GHG benefits are maximized with waste-based or lignocellulosic feedstocks. Spill Behaviour: Biofuels are biodegradable in marine environments but behave similarly to fossil fuels upon release. Oil sheen, water column toxicity, and oxygen depletion may occur before full degradation. Standard marine spill response techniques (booms, skimmers) remain applicable. Regulatory Fit: Biofuels are partially covered under ISO 8217 and MARPOL Annex VI, though some ambiguity exists (e.g., NOx implications under Reg. 13). Certification schemes like ISCC and RSB ensure sustainability but are voluntary. Operational Considerations: ABS rules allow onboard use of biofuels if vessel systems (e.g., tanks, pumps, seals) are compatible. Bunkering safety depends on blend control and quality assurance. Maintenance challenges include filter clogging, corrosion, and cold storage performance. Conclusion: Biofuels are viable for near- and mid-term decarbonization with minimal vessel retrofits, but require dedicated safety, maintenance, and fuel management protocols. The paper supports their safe operational use while recognizing the need for tailored handling and spill mitigation strategies.
Fuel for Thought – – Biofuel [65] (2024)	Lloyd's Register (LR) Maritime Decarbonization Hub	This report provides a comprehensive assessment of biofuels (mainly FAME and HVO) as marine fuels, focusing on safety, operational considerations, regulatory framework, lifecycle emissions, and environmental implications. Key conclusions: Biofuels (especially FAME and HVO) are viable drop-in fuels for shipping, offering immediate GHG emission reductions without major engine retrofits. Spill Behaviour: FAME is biodegradable and less persistent than fossil fuels but may form floating residues if spilled; HVO behaves similarly to diesel fuel. Standard spill response (booms, skimmers) is applicable, but monitoring might require adaptation due to biofuel characteristics. Safety Considerations: Both fuels require attention to oxidation stability, microbial growth potential (especially FAME), and storage conditions (temperature, moisture). FAME may have compatibility issues with metals and seals. Regulatory Fit: ISO 8217 (2024) now covers FAME blends up to B100 and HVO. IMO MARPOL Annex VI applies, with restrictions above B25 blends for IBC Code compliance. Environmental Impact: FAME and HVO offer lower SOx, PM, and lifecycle CO2 emissions compared to fossil fuels. Environmental risks from spills are lower but not negligible, particularly in confined or cold environments. Operational Considerations: Quality monitoring, storage management, and supplier certification (ISCC or RSB) are crucial to ensure safe use. LR recommends a risk-based approach with due diligence for fuel quality and operational risk

		assessment prior to trials or regular use. The report supports the broader adoption of biofuels but highlights challenges in feedstock availability, regulatory gaps (especially for higher blends), spill response preparedness, and fuel standardization across supply chains.
Biofuels for the Marine Shipping Sector [66]– Final Report (October 2017)	DNV GL (now DNV), prepared for IEA Bioenergy Task 39 & University of Copenhagen	This report provides a comprehensive assessment of biofuels for maritime use, covering fuel characteristics, infrastructure, regulations, and environmental implications. Key conclusions: Biofuels (especially FAME and HVO) offer potential to reduce GHG emissions in shipping but require consideration of lifecycle emissions and feedstock sustainability. Drop-in biofuels (like HVO) are preferable for marine use due to higher compatibility with existing engines and fuel systems. FAME may present operational issues, such as oxidation, microbial growth, and lower cold-flow properties. Spill Behaviour: The report indicates that biofuels, particularly biodiesel (FAME), are biodegradable and less persistent than conventional fuels in marine environments. Existing oil spill response methods (booms, skimmers) are applicable but monitoring and recovery may require adaptations due to rapid degradation and lower visibility of slicks. Regulatory Environment: Current marine fuel standards (ISO 8217) partially accommodate biofuels; however, there is a need for further regulatory clarity, especially for high blend levels and pure biofuels (B100). Operational Considerations: Quality assurance, blending controls, and monitoring of stability are critical to mitigate risks during storage, handling, and bunkering. The study supports biofuels as a transitional marine fuel but highlights challenges in supply availability, fuel standardization, and ensuring consistent environmental performance across different biofuel types.
Biofuels in Shipping – Current Market and Guidance on Use and Reporting [67] (2025)	DNV Maritime; Authors: Øyvind Sekkesæter, Per Einar Henriksen, Øyvind Endresen, Eirik Ovrum, Håkon Hustad, Olav Tveit, Marius Leisner, Tore Longva, Jan Kvålsvold	This DNV Whitepaper provides an updated market analysis, regulatory overview, and operational guidance on biofuel use in shipping, with a specific focus on FAME and HVO. Key conclusions: Global biofuel supply remains limited, with shipping consuming only ~0.6% of global liquid biofuel production in 2023. Uptake is growing but constrained by sustainability feedstock availability, competition with aviation/road sectors, and logistic challenges. FAME and HVO are the most used biofuels in maritime applications, typically blended up to B30. Operational experience shows that with proper planning and controls, both fuels can be safely used onboard. Spill Behaviour: FAME is readily biodegradable but sensitive to cold temperatures and prone to oxidation and microbial growth. HVO behaves similarly to conventional diesel, posing minimal risks beyond standard oil spill concerns. Existing spill response techniques apply but monitoring and fuel degradation require attention in spill scenarios. Operational Challenges: FAME may cause corrosion, fuel filter clogging, material compatibility issues, and degradation over time. HVO has better stability but lower lubricity. ISO 8217:2024 now covers both up to B100, but off-spec fuel risk remains high. Regulatory Context: Biofuels can provide significant benefits under IMO CII, EU ETS, and Fuel EU Maritime regulations, provided sustainability and GHG reduction criteria are met and verified (Proof of Sustainability - PoS required). Recommendations: Best practices for ship operators include tank cleaning prior to FAME use, verifying fuel specs with engine manufacturers, ensuring water drainage and moisture control, monitoring filter clogging, checking fuel oxidation stability, and avoiding uncontrolled blending onboard. The report reinforces biofuels as a near-term decarbonization solution but highlights the need for fuel quality control, spill preparedness awareness, and operational diligence.
Tracking the Propensity of	Global Centre for Maritime	This study traced the physicochemical stability of FAME-based biofuels (UCOME) across real-world maritime supply chains from production to

Biofuels Degradation Across the Maritime Supply Chain [68] (2024)	Decarbonization (GCMD); Authors: Dr. Prapisala Thepsithar, Dr. Sanjay C. Kuttan, Monique Vermeire, et al.	onboard consumption over five months. Key conclusions: No significant degradation was observed under commercial storage and handling conditions in terms of acid value, viscosity, microbial contamination, or net calorific value. FAME was stable even in blended fuels (B20/B24 with HSFO/VLSFO), complying with ISO 8217 fuel property limits. Degradation concerns (oxidation, hydrolysis, microbial growth) noted in lab studies did not materialize in real-world settings, confirming the importance of appropriate fuel system management. Storage tank design (sealed tanks), moisture control, and adherence to fuel quality specifications (e.g., 0.5% max water content) are critical for maintaining biofuel integrity. The study reinforces the viability of using FAME as a marine drop-in fuel, provided that operational safeguards (like moisture control, optional antioxidants/biocides, and proper fuel turnover) are maintained. Findings support the development of assurance frameworks for green fuel adoption and call for more field data to guide future marine fuel quality standards and spill preparedness.
Progress Towards Biofuels for Shipping [69] (2021)	IEA Bioenergy (International Energy Agency), Authors: Warren Mabee, Task 39 team	This report provides a global overview of biofuels development for marine shipping, focusing on technological readiness, sustainability challenges, and operational considerations. Key conclusions (specific to biodiesel/FAME/HVO): FAME is technically mature for use in shipping, especially in blends up to B20 under current ISO 8217 standards; HVO is more compatible as a drop-in fuel with superior storage stability. Safety and Spill Behaviour: FAME and HVO are biodegradable and have lower environmental persistence than fossil fuels. Spill response techniques applicable to diesel remain relevant but monitoring and recovery operations should consider faster degradation and possible reduced slick visibility. Operational Risks: FAME poses risks related to oxidation, microbial contamination, and cold-flow properties. HVO presents fewer operational challenges, but supply remains limited. Regulatory Gaps: No comprehensive IMO guidelines yet for higher biofuel blends or pure biodiesel use in shipping; national practices vary widely. Future Research Needs: Standardization of biofuel quality, improved spill response procedures tailored for biofuel properties, and further study on long-term environmental impacts of large-scale biodiesel use in the marine environment. The report concludes that biodiesel blends (especially FAME and HVO) offer an immediate pathway to decarbonization of shipping but require dedicated operational management and preparedness for safe bunkering, storage, and potential spill response.
Fate, Behaviour and Impact Assessment of Biodiesels in Case of an Accidental Spill [51] (2019)	CEDRE (Center for Documentation, Research and Experimentation on Accidental Water Pollution)/Ronan Jezequel et. al,	Provide Fate, Behaviour, and Impact Assessment of Biodiesels in the Case of an Accidental Spill
Spill behaviour, detection, and mitigation for emerging non-traditional marine fuels [17] (2021)	Oak Ridge National Laboratory for the U.S. Maritime Administration (MARAD)/Michael D. Kass, C. Scott Sluder	Authored the 2021 “Spill Behaviour, Detection and Mitigation for Emerging Non-traditional Marine Fuels” report that benchmarks biodiesel, HVO, and other alternatives for ship-fuel risk models
Weathering and toxicity of biofuels (FAMEs and HVOs) and their dispersant effectiveness, a	SINTEF Ocean (Norway)/Liv-Guri Faksness, Per S. Daling, Kristin Sørheim	Runs Arctic-temperature weathering and toxicity programs on FAME and HVO fuels.

laboratory study [59] (2024)		

Annex IV: Weathering test protocol

Description of the test-tank

The hydraulic canal, set in an air-conditioned room (0°C to 30°C), consists of a loop through which water can be circulated. The tank is equipped with a wave generator with an adjustable period, a current generator and UV lights. With this equipment, it is possible to weather dedicated oil in similar climatic conditions to those encountered in the oil field from which it is extracted or in shipment. This equipment is used to study the behaviour and weathering of chemicals and oils, in the framework of the response to real accidents. Details of the Polludrome are given in Table 26.

Table 26. Cedre flume tank details

Flume (circulation) length - inner wall	16.4 m
Flume (circulation) length - outer wall	20.2 m
Flume height	1.4 m
Flume width	0.6 m
Wind speed	1.2 m/s
Seawater depth	0.90 m
Surface area	8 m^2
Water volume	7.2 m^3
Temperature	20°C
Oil volume	20 L
Wave height	25 cm
Wave frequency	6 s
Current speed	20 cm/s
Wind speed	3 m/s

The test was conducted under conditions approximating sea state 2-3 on the Douglas scale (smooth sea state), corresponding to wave heights between 0.1 and 0.5 meters in real conditions. A simulated wind speed of 10 knots was used, which was calibrated using real environmental data, considering the safety fan installed in the system. The photo-oxidation process (simulating solar energy exposure) was recreated using two UV lights (Hönle UV technology lamps, 2000 W each). For each test, 20 litres of blend were released onto the water surface to observe the weathering processes under controlled conditions. Oil samples were regularly taken at the water surface. This operation was implemented using a large funnel fitted with a tap to separate the free water from the oil which was then transferred into a separatory funnel. To facilitate sampling, the slick was temporarily concentrated into a thick layer by a boom installed across the width of the tank.

Table 27. Sampling times

Sample reference	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17
Time (hours)	0	1	2	4	6	8	14	24	26	30	34	48	53	72	77	96	101	168

Measurement methods

Flash point

The flash point was measured according to the NF EN ISO 13736 standard (AFNOR, 2013) by using Anton Paar ABA 4 Flash Point Tester. This parameter was assessed until it reached 100°C, considering this value as a reasonable limit in terms of the risk of ignition of an oil slick.

Density

The density of the samples of surface oil was determined according to the ASTM method ASTM D5002: 2013 (ASTM, 2013) by using an Anton Paar D4500 density meter. This measurement gave the real density of the emulsion that would remain on the sea surface.

Viscosity

The viscosity of the oil samples was measured by establishing the rheological curve using a Rheolab QC Rheometer (Anton Paar) viscosimeter at test temperature, to determine the evolution of the viscosity at dedicated shear rates (e.g., 1, 10, 100 s-1).

Oil adhesion

The evolution of oil adhesion was measured by weighing the amount of oil that sticks to a given oleophilic plate. This test provides information on the possibility of using oleophilic skimmers.

Emulsification

Emulsification was assessed by measuring the water content in the oil samples in three different ways:

- the water which separated naturally from the oil;
- the water which settled after addition of 0.1% demulsifier (Demulsip); and
- the water that was distilled using the ISO Dean & Stark method, equivalent to the ASTM D95-05 (2010) Standard Test Method for Water in Petroleum Products and Bituminous Materials by Distillation.

From these measurements, it was possible to determine the kinetics of emulsification as well as the maximum water uptake. The assessment of the stability of the emulsion resulted from the comparison of these data.

Evaporation and chemical composition

The saturate and aromatic fractions were analysed using gas chromatography. Chromatograms of these compounds at different weathering times show the evolution of their distributions. To assess the evaporation rate of the whole oil, a calibration curve was established from samples of the initial oil evaporated in the laboratory by distillation at various temperatures (typically topped at 150, 200 and 250°C).

Oil biodegradation

A protocol adapted from De Mello et al. (2007) was used to simulate the biodegradation process. Around 10 mg of product, dissolved in 50 µL of acetone, was biodegraded at the laboratory scale, in a 125 mL glass bottle containing

100 mL of seawater. Nutrients were added to the water, in accordance with the French standard NFT 90-347 (AFNOR, 1990). This method is applied within the French dispersant approval procedure and aims at assessing the biodegradation of dispersed oil. The hydrocarbon-degrading microorganisms came from a chronically contaminated site. The bottles were loosely plugged with autoclaved cotton wool, placed onto a shaker table, in the dark and agitated for 28 days. The residual oil was extracted and purified prior to analysis by GC-FID (Gas Chromatography coupled to a Flame Ionization Detector). The GC was an HP 7890N (Hewlett-Packard, Palo Alto, CA, USA equipped with a split/splitless injector (Splitless time: 1 min, flow 50 mL/min). The injector temperature was maintained at 300°C. The GC-FID temperature gradient was from 50°C (1 min) to 300°C (20 min) at 5°C/min. The carrier gas was Hydrogen at a constant flow of 1 ml/min. The capillary column used was an HP-5 MS: 30 m×0.25 mm ID×0.25 µm film thickness.

Chemical dispersibility

The chemical dispersibility of the surface oil was measured using the IFP test method (NF 90-345 French Standard) at a test temperature of 20°C and with a reference dispersant (Finasol OSR 52). Tests were conducted on samples collected during weathering experiments in the flume. To calibrate the experimental design, additional dispersibility tests were carried out with a model dispersant using the French procedure for dispersant approval. These tests were performed at 20°C with a reference oil (FOREF), a mixture of Heavy Fuel Oil and Arabian Light topped at 110°C, with a viscosity of 1200 ± 200 mPa.s at 20°C. Under these conditions, the reference value is 76% ± 3%, and the results of the calibration should fall within this range. Oil samples were extracted using dichloromethane, and the concentration was measured by UV spectrophotometry at 580 nm.

Table 28. Composition of the model dispersant

Denomination	% weight
Dipropylene-glycol-n-butyl-ether	18.5
Span-80	6.5
Tween-80	12.9
Tween-85	19.1
Aerosol-OT-75 (14/05/14)	27.8
Exxsol-D80	15.2
Total	100.0

Oil degradation

A protocol adapted from De Mello et al. (2007) was used to simulate the biodegradation process. Around 10 mg of product, dissolved in 50 µL of acetone, was biodegraded at the laboratory scale, in a 125 mL glass bottle containing 100 mL of seawater. Nutrients were added to the water, in accordance with the French standard NFT 90-347 (AFNOR, 1990). This method is applied within the French dispersant approval procedure and aims at assessing the biodegradation of dispersed oil. The hydrocarbon-degrading microorganisms came from a chronically contaminated site. The bottles were loosely plugged with autoclaved cotton wool, placed onto a shaker table, in the dark and agitated for 28 days. The residual oil was extracted and purified prior to analysis by GC-FID (Gas Chromatography coupled to a Flame Ionization Detector). The GC was an HP 7890N (Hewlett-Packard, Palo Alto, CA, USA equipped with a split/splitless injector (Splitless time: 1 min, flow 50 mL/min). The injector temperature was maintained at 300°C. The GC-FID temperature gradient was from 50°C (1 min) to 300°C (20 min) at 5°C/min. The carrier gas was Hydrogen at a constant flow of 1 ml/min. The capillary column used was an HP-5 MS: 30 m×0.25 mm ID×0.25 µm film thickness.

Ecotoxicity test

Test on a marine bacterium Aliivibrio fisheri

This protocol aims to evaluate the ecotoxicity of the blends on the bioluminescent marine bacteria *Aliivibrio fisheri* towards the inhibition of its quorum sensing by toxic compounds. This test is conducted not on the oil itself but on the Water Accommodated Fraction (WAF) which represents the soluble fraction of the oil.

WAF preparation

WAF were prepared following the CROSERF protocol (Hokstad et al., 2000). Briefly, seawater was added to a bottle (headspace/water volume ratio ~1:4), and oil (10g/L) carefully applied to the water surface. A magnetic stirrer provided very gentle mixing of the water without creating any vortex and without dispersing any oil droplets into the water. After 24 hours of stirring, samples of the WAF were withdrawn through a valve approximately 3 cm above the bottom of the bottle, allowing sampling without disturbing the oil/water interface. WAF preparation was done at controlled temperature. WAF were stored at 4°C without light and used within 3 days.

Bacteria preparation

The strain Lv8 has been isolated and sanctuarised by Leo viridis company (France) and stored in glycerol at - 80°C. Frozen stock has been reanimated with its reference culture medium freshly prepared according to its optimal growth parameters.

The bacterium Lv8 was cultivated under axenic conditions in its reference medium, according to its metabolic profile, both for maintenance cultures and for microplate incubations. These cultures were carried out to obtain the strain in the exponential growth phase (monitored with a McFarland reader). For each culture, the strain was systematically and previously streaked onto a Petri dish and incubated under its optimal growth conditions. Subsequently, from these Petri dishes, a monoclonal colony was sampled to inoculate the liquid reference medium. The reference biocide was sodium azide (0.2% 0.2% m/V final).

Ecotoxicity protocol

To assess the ecotoxicity of the WAF, microtox test were realized in 96 wells white sterile microplate (flat bottom). First, 100 µL of bacterial culture in exponential growth phase ($1{,}5.10^8$ bacteria. mL^{-1} – control Mac Farlan) were added to 100 µL of non-diluted WAF, positive control (seawater and medium) as well as reference biocide (NaN_3, 0.2% m/V final). Bacterial bioluminescence was measured by spectrophotometry using a microtiter plate reader (Tecan Infinite M200 Microplate Spectrophotometer) over a 23-hour period, at 20°C, with agitation and readings taken every 10 minutes by random multipoint measurement (n = 9) in each well.

Annex V: Prioritisation of risks of biodiesel blends with conventional marine fuel

Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is a structured, team-based technique in which a system, process or procedure is broken down into its constituent elements, and for each element the team systematically records its function, the ways it could fail (failure modes), the mechanisms driving those failures, the resulting consequences, how and when the failure could be detected, and any built-in safeguards that would mitigate it.

The exercise is also extended to rank each failure mode by criticality, typically by multiplying qualitative ratings for severity (S), likelihood as occurrence (O) and ease of detection (D) to give a Risk-Priority Number (RPN).

FMEA outputs' worksheets of failure modes with their causes, effects, existing controls and criticality rankings, plus recommended actions focus monitoring on the most significant risks, although the method's single-failure-mode focus and the effort needed for complex systems remain recognised limitations.

Within the FMEA framework, detection represents the probability that either the crew or an automated response system will identify a failure condition and intervene before its consequences fully materialise. A low detection score signals strong monitoring and prompt corrective capability, whereas a high score indicates that the problem is unlikely to be noticed in time to prevent harm.

Severity gauges the gravity of the consequences should the failure mode manifest and remain unmitigated; higher scores are assigned to outcomes that threaten life, breach regulation, cause major environmental releases, or incur substantial operational and financial losses, whereas trivial, easily reversible effects receive the lowest ratings.

Occurrence, by contrast, measures the expected frequency or probability of that failure mode. arising under normal operating conditions, drawing on historical data, expert judgment, or reliability calculations; frequent or inevitable events obtain high scores, while rare or hypothetical ones score low.

Table 29 shows the five-point scales adopted for the FMEA, defining how each dimension is scored. Severity spans from 1 = “negligible” to 5 = “catastrophic,” capturing the escalating consequences of an undetected failure. Occurrence rates the expected frequency, moving from 1 = “remote” through 3 = “probable” to 5 = “very frequent.” Detection is inversely framed: 1 = “almost certain” indicates a failure is highly likely to be caught before impact, whereas 5 = “very low” means it is unlikely to be detected in time. Together, these scales translate qualitative judgements into quantitative scores for calculating each risk-priority number.

Table 29. FMEA five-point scale for severity, occurrence, and detection.

Factor	1	2	3	4	5
Severity (S)	Negligible	Minor	Serious	Major	Catastrophic
Occurrence (O)	Remote	Occasional	Probable	Frequent	Very frequent
Detection (D)	Almost certain	High	Moderate	Low	Very low

Table 30 defines the interpretive bands for the Risk-Priority Number (RPN) calculated in the FMEA. A RPN of 80 to 125 falls in the “extreme” zone, signalling an unacceptable condition that demands immediate, large-scale controls before operations can continue. Scores between 40 and 79 are classed as “high,” requiring targeted mitigation to bring the risk down. Values from 20 to 39 are judged “medium” and may be tolerated provided they are periodically reviewed and monitored, whereas ratings from 10 to 19 warrant cautious progression but typically no capital intervention. Finally, RPNs below 10 are deemed “low,” justifying acceptance without further action.

Table 30. Risk quantitative score and action plan.

80≤ RPN ≥125	Extreme – Immediate action needed; not acceptable without major controls
40≤ RPN <80	High – Action required to mitigate risk
20≤ RPN <40	Medium – Tolerable with review and monitoring.
10≤ RPN <20	Above low, proceed with caution
1≤ RPN <10	Low – Acceptable, no action required.

■ Development of the risk matrix

The identification and assessment of hazards associated with shipboard use of biodiesel blends considered the following maritime scenarios:

- Coastal trade using biodiesel blends as bunker fuel;
- Deep-sea trade using biodiesel blends as bunker fuel;
- Coastal trade carrying biodiesel blends as cargo; and
- Deep-sea trade carrying biodiesel blends as cargo.

The assessment considered factors such as explosivity, flammability, oxidation, corrosion, reactivity, bioaccumulation, degradability, persistence, and potential human health hazards and environmental impacts.

The risk matrix evaluates the likelihood and severity of critical events associated with the shipboard use of biodiesel blends. The severity (S) and occurrence (O) ratings were derived through an expert workshop. The expert group for the study consisted of scholars from marine engineering, maritime safety, and environmental protection disciplines, each with background knowledge in fuel properties and bunkering operation. Using the guidance of IEC 60812 and ISO 31010, the expert group applied a structured consensus approach to assign numerical ratings. Severity scores reflected the worst credible outcomes of each failure mode, aligned with IMO FSA consequences definitions. Occurrences scores were based on expected frequency after prevention control, reference DNV likelihood classes and empirical findings from academic literature on biodiesel degradation, microbial growth, and fuel system failures. Final ratings represent academic consensus and provide a defensible, methodologically rigorous basis for calculating the RPN.

The risk matrix integrated qualitative data from stakeholder inputs and expert consensus with quantitative data from historical records, experimental studies, and simulations and experiments results from the previous work packages.

Overall, the development process of the risk matrix included:

- identification of potential critical events and evaluation of their likelihood and potential consequences using FMEA risk assessment frameworks;
- ranking identified risks based on multiplying occurrence, severity, and detection to produce risk priority number RPN according to their significance and impact; and
- validating the risk matrix through scenario testing and sensitivity analysis, with feedback from external experts to refine the matrix for accuracy and reliability.

■ Risk register for shipboard use of blends of biodiesel with conventional marine fuel and spill response

Table 31 presents the risk register and identifies potential hazards, their consequences, and preliminary control measures associated with the shipboard use of biodiesel blends and spill response.

Table 31. Risk register for shipboard use of blends of biodiesel with conventional marine fuel and spill response.

	Hazard ID	Hazard description	Potential consequences	Existing controls	Recommendations/ mitigating measures
Hazards as a bunker fuel	H-01	Leakage during fuel transfer (biodiesel or blends)	Spill into marine environment; rapid dissolution of polar components; potential localized toxicity	Standard fuel transfer procedures; containment booms and drip trays	Crew training focusing on biodiesel-specific properties (solubility, slower spreading); Use of double-walled piping; Enhanced transfer monitoring systems
	H-02	Storage tank corrosion or microbial growth due to biodiesel's hygroscopic nature	Tank degradation; fuel quality deterioration; microbial contamination leading to clogging and engine damage	Regular tank inspections; fuel quality monitoring	Use of corrosion-resistant materials; Water removal systems in storage tanks; Microbial growth inhibitors; Improved fuel turnover practices
	H-03	Hose or loading-arm rupture during bunkering	Spill into marine environment	Break-away couplings, ESD links, drip trays	CCTV
	H-04	Incompatibility with fuel system materials (seals, gaskets)	Fuel leakage, equipment failure, operational delays	Manufacturer guidelines for acceptable blend ratios	Material compatibility assessment for high-blend biodiesel; Pre-delivery blend testing; Maintenance protocols updated for biodiesel use
	H-05	Injector-tip polymerization & fire-back	Fire-back	Filtration 10 µm, periodic nozzle flushing, hot-surface shields	
	H-06	Filter blockage blackout / loss of propulsion	Loss of propulsion	Heat tracing, change-over filters, cold-flow improvers	
Hazards with spill response	H-07	Inadequate spill response capability specific to biodiesel properties	Poor recovery of dissolved fractions; possible increased toxicity from WSF; extended environmental damage	Standard oil spill kits designed for hydrocarbons	Develop and deploy biodiesel-specific response strategies: • Use of sorbents optimized for biodiesel • Bio-based herding agents • Nutrient addition for bioremediation • WSF monitoring procedures
	H-08	Fire hazard from certain biodiesel blends (ethanol/methanol inclusion) or storage of oxidized biodiesel	Fire or explosion during storage or bunkering; peroxide formation in aged biodiesel	Certified fuel quality standards; Fire suppression systems onboard	Routine flash point and oxidation stability testing; Storage guidelines limiting biodiesel aging; Updated bunkering and ventilation procedures
	H-09	Enhanced biodegradation leading to oxygen depletion in semi-enclosed marine environments	Localized hypoxia affecting marine life	Natural attenuation; Limited monitoring	Monitoring of dissolved oxygen levels in spill areas; Potential use of aeration or controlled bioremediation where applicable
	H-10	Formation of toxic degradation products (aldehydes, ketones) during weathering	Potential acute and chronic toxicity to marine organisms	Not explicitly controlled in current response plans	Research to characterize degradation by-products; Development of toxicity monitoring protocols post-spill
	H-11	Variability of biodiesel feedstock composition leading to unpredictable behaviour	Difficulties in spill modelling, response planning, and toxicity prediction	Adherence to fuel standards (EN 14214, ASTM D6751)	Require declaration of biodiesel feedstock origin and composition during bunkering; Update spill behaviour models for biodiesel variability
	H-12	Sub-surface plume remains undetected	Weak monitoring		Towed fluorometers, water-column sampling plan

■ Decomposition of bunkering of biodiesel blends

As the first stage of FMEA, Table 32 decomposes the end-to-end bunkering chain for biodiesel blends with conventional marine fuel into eight sequential blocks, assigns routine checkpoints plus blend-specific controls to each block, and then lists representative failure modes with their underlying mechanisms. In procurement, for example, flash-point non-compliance may arise from supplier mis-labelling, whereas in bunkering static-spark ignition stems from high initial flow through a dry hose. This structured breakdown establishes the groundwork on which severity, occurrence and detection will be scored in the subsequent FMEA steps.

Table 32. Biodiesel blends with conventional marine fuel bunker process stages, checkpoints, and safety controls.

Stage	Key actions & checkpoints	Biodiesel-specific focus areas
Procurement & specification	▪ Agree blend grade (e.g., B10, B20, B30) under ISO 8217 / ASTM D7467 ▪ Verify traceability of feedstock and sustainability certificates (e.g., ISCC, RSB) ▪ Require certificate of analysis (density, viscosity, flash point, oxidation stability, water)[70].	▪ Confirm antioxidant package and cold-flow improver, if any [71]. ▪ Ensure flash-point margin ≥ 60 °C for SOLAS compliance (Cat 4 blends must still be ≥ 60 °C) [72].
Shoreside storage & delivery logistics	▪ Keep the blend in dedicated, water-free tanks; nitrogen blanket where possible [73]. ▪ Circulate slowly to avoid stratification; sample top/middle/bottom weekly. ▪ Plan “first in, first out” rotation to limit residence time.	▪ Monitor acid number & Rancimat hours; dose antioxidant when stability < 8h. ▪ Heat tracing kept ≤ 40 °C to prevent polymerization [74].
Pre-bunkering preparations aboard	▪ Check material compatibility of bunker lines, seals, and hoses. ▪ Bond/ground all metal components; ensure low-spark tools ready. ▪ Empty or segregate tanks that previously held neat diesel unless blend compatibility confirmed. ▪ Complete pre-transfer checklist (ESD link test, drip trays, scupper plugs) [73].	▪ Confirm tank heating coils operational and set to hold > 2 × cloud point (for B20/B30). ▪ Fit 100-mesh strainer at manifold in case of sludge mobilisation.
Bunkering operation	▪ Start at 25 % planned flow for 5 min to dissipate static, then ramp up [75]. ▪ Maintain vapour return line (where fitted). ▪ Take MARPOL six-point samples in dedicated glass bottles. ▪ Monitor manifold pressure, temperature, flow rate, ullage, and drip trays in real time.	▪ Keep loading velocity $< 7\ \mathrm{m\ s^{-1}}$ until conductivity reading confirmed $> 50\ \mathrm{pS\ m^{-1}}$. ▪ Deploy portable gas detector to check ullage H_2S and methanol traces.
On-board storage & conditioning	▪ Assign service/settling tanks that can be heated and purged. ▪ Use automatic water drains or daily manual draining from storage-tank sump. ▪ Turn over bulk tanks at least every 30 days to limit oxidation [76].	▪ Dose metal passivator if copper-bearing equipment present. ▪ Check acid number, peroxide value fortnightly; recirculate through purifier if limits approached. ▪ Maintain head-space inerting for B5–B20 where local rules allow.
Fuel treatment & transfer to engines	▪ Centrifuge or depth-filter to 10 µm; supply booster pump with minimum 2 bar NPSH[10]. ▪ Warm to 40–50 °C (or per OEM cold-flow chart).	▪ Watch for filter ΔP rise; sludge or polymer hints at thermal instability. ▪ Calcium-free lubricity additive may be needed (calcium soaps contribute to IDID[11]).

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[10] **Net Positive Suction Head (NPSH)** is the measure of how much fluid pressure is available at a pump’s suction port, above the fluid’s saturation (vapour) pressure, to keep the liquid from flashing into vapour as it enters the impeller.

[11] **IDID stands for** *Internal Diesel Injector Deposits*. Unlike the better-known external or tip deposits, IDIDs build up **inside** the high-pressure control passages, needle-guide surfaces and valve seats of modern common-rail injectors, where they can cause sticking, timing scatter and hard fire-back events.

	- Route through automatic viscosity controller if blend ratio varies voyage-to-voyage.	
Combustion & performance monitoring	- Log specific fuel-oil consumption, exhaust temperature spread, and smoke number. - Inspect injectors each maintenance interval for deposits or sticking. - Track lube-oil BN depletion and metal wear.	- If IDIDs observed, shorten injector-cleaning interval or adopt purge routine at shutdown. - Compare NO_x / PM stack data versus diesel baseline; biodiesel fraction generally lowers PM but can raise NO_x.
Residual management & tank cleaning	- Plan cargo tank or bunker-tank wash with MDO flush or approved detergent. - Dispose of sludge under MARPOL Annex V via licensed reception facility. - Record cleaning in Oil Record Book part I [77].	- Schedule heavy-fuel tanks for lining inspection; biodiesel tends to leach legacy asphaltenes first months. - Hot-work permits stricter after high-FAME carriage, extra gas-free testing required [77].

Potential failure modes in bunkering of biodiesel blends

Table 33 lists the dominant safety-critical failure modes that can arise at each point. For every mode, it also summarises the underlying physical or procedural mechanism, whether supplier mis-labelling, charge build-up, oxidative corrosion, or microbial fouling, which converts routine activity into a potential incident. By juxtaposing procurement risks (e.g., sub-spec flash-point) with shipboard hazards (e.g., injector deposits, hot-work ignition), the table provides a holistic view of where and how biodiesel-specific weaknesses can compromise conventional marine-fuel operations. This breakdown serves as the starting inventory for the FMEA scoring of severity, occurrence, and detection. It thus ensures that all credible hazards are captured before numerical prioritisation begins.

Table 33. Bunkering process stagewise potential safety-critical failure mode and failure mechanism.

Process stage	Potential failure mode (FM)	Failure mechanism
Procurement & specification	S.1. Blend delivered with flashpoint below 60 °C or wrong FAME ratio. S.2. Antioxidant or cold-flow additive omitted.	- Supplier mis-labels product, wrong batch loaded, or CoA values mis-read. - QA lapse during additive dosing; bulk tank blending not properly mixed.
Shoreside storage & logistics	S.3. Stratification and water bottoms form, giving non-homogeneous fuel. S.4. b. Oxidative degradation raises acid number and viscosity.	- Density difference between FAME and diesel plus inadequate circulation. - Warm, oxygen-rich headspace plus metal-ion catalysis accelerates peroxide formation.
Pre-bunkering preparations aboard	S.5. Elastomer seals in manifold swell or crack. S.6. Static charge not dissipated before transfer.	- Biodiesel swells nitrile/natural-rubber gaskets; early leaks appear under pressure. - Bonding clip omitted or corroded; low-conductivity pockets of diesel allow charge build-up.
Bunkering operation	S.7. Flammability / vapour explosion and static electricity Static sparking ignites Cat-3/Cat-4 vapours.	- High initial flow velocity plus dry hose produces electrostatic discharge in ullage.
On-board storage & conditioning	S.8. Peroxide/acid build-up corrodes carbon-steel tank base. S.9. Microbial growth and sludge clog suction strainers.	- Unsaturated FAME oxidises; acids pit steel, especially at water–fuel interface. - Water bottoms supply nutrients; heterotrophic bacteria generate biomass and corrosive by-products.
Fuel treatment & transfer to engines	S.10. Fine filters block, starving engines; blackout risk. S.11. Booster pump cavitates. S.12. Incompatibility with fuel system material (seals, gasket). S.13. Static-electricity ignition• Charge build-up when	- Polymerised gums and calcium soaps from oxidised biodiesel accumulate in 10 µm elements. - Low temperature raises viscosity; NPSH falls below pump requirement.

		switching between low-conductivity diesel pockets and high-conductivity biodiesel	
Combustion & performance monitoring	S.14.	Injector-tip deposits cause sticking / fire-back.	▪ FAME polymers bake onto tips at >150 °C; calcium-sodium deposits (IDID) restrict needle lift. ▪ Oxygenated fuel raises peak flame temperature when combustion timing not retarded.
Residual management & tank cleaning	S.15. S.16.	Legacy asphaltenes and fresh biodiesel sludge remain; later mobilise and foul fuel system. Hot-work ignition during tank entry.	▪ Biodiesel solvency loosens old diesel sediments; if not flushed out, they resettle elsewhere. ▪ Inadequate gas-free testing leaves light-end vapours in crevices; spark from tools ignites them.

■ Prioritisation of risks with bunkering of biodiesel blends

Table 34 translates qualitative hazards into quantifiable priorities for risk reduction. For each mode, the table records the assigned severity (S), outlines the single most effective prevention control intended to lower its likelihood, and lists the corresponding occurrence (O) score. It then specifies a critical detection control that improves the chance of early discovery, together with the detection (D) rating. Multiplying S, O and D yielded the risk-priority number (RPN), which guides whether immediate action, routine monitoring or simple acceptance is warranted under the ranking thresholds defined in Table 30.

Table 34. Risk priority number for biodiesel blends with conventional marine fuel bunker process failure mode-safety hazard.

	Potential failure mode FM	Severity (S)	Prevention control	Occurrence (O)	Detection control	Detection (D)	RPN
S.1.	Blend delivered with flashpoint below 60 °C or wrong FAME ratio.	5	Agree blend grade (e.g., B10, B20, B30) under ISO 8217 / ASTM D7467 Verify traceability of feedstock and sustainability certificates (e.g., ISCC, RSB) Require certificate of analysis (density, viscosity, flash point, oxidation stability, water)	2	Crew will not be able to detect low flash point until fire hazard emerges	5	50
S.2.	Antioxidant or cold-flow additive omitted	4	Use antioxidant	2	Visual check and sampling	2	16
S.3.	Stratification and water bottoms form, giving non-homogeneous fuel.	4	Store the blend in clean, dedicated tanks that are kept dry and fitted with a nitrogen blanket to minimize moisture ingress and oxidation. Circulate or recirculate the cargo slowly at scheduled intervals and maintain temperature above the blend's cloud-point to keep components uniformly mixed. Operate a first-in/first-out policy and limit shore-tank residence time (e.g.,	2	Carry out top-, middle- and bottom-level sampling before loading and weekly thereafter; measure water content by Karl-Fischer or centrifuge and compare density across the column. Install interface sensors or water-bottom probes that alarm when free-water height exceeds a set threshold.	3	24

			< 30 days). Drain tank low-points on a routine schedule and ensure water-draw valves are serviceable.				
S.4.	Oxidative degradation raises acid number and viscosity.	5	Dose an OEM-approved antioxidant at blending and limit cargo residence to ≤ 30 days under nitrogen blanket.	3	Take fortnightly samples for peroxide value/ acid-number testing; initiate corrective action when values exceed ISO 8217 limits.	2	30
S.5.	Elastomer seals in manifold swell or crack.	3	Replace nitrile or natural-rubber gaskets with FKM (Viton) or fluorosilicone seals certified for B20+ service.	4	Conduct a post-bunkering manifold tightness test and visual inspection; any weeping indicates seal degradation requiring immediate replacement.	1	12
S.6.	Static charge not dissipated before transfer.	4	Checklist for bonding and grounding	2	Use a portable electrostatic voltmeter at the manifold; halt transfer if the reading exceeds 1 kV relative to earth.	1	8
S.7.	Flammability / vapour explosion and static electricity; Static sparking ignites Cat-3/Cat-4 vapours.	4	Lower the oxygen content in cargo tank below 5% during cargo operation via inerting	2	Deploy fixed hydrocarbon detectors at the manifold and in ullage space; alarms at 10 % LEL trigger automatic ESD shutdown.	5	40
S.8.	Peroxide/acid build-up corrodes carbon-steel tank base.	5	Add antioxidant package and keep cargo temperature ≤ 40 °C; drain water bottoms weekly to limit catalytic ions.	2	Use peroxide test strips or titration on weekly drain samples; values above threshold prompt antioxidant top-up and enhanced monitoring.	2	20
S.9.	Microbial growth and sludge clog suction strainers.	5	Dose a broad-spectrum biocide at loading and ensure routine water-bottom removal to deny microbes a habitat.	3	Log differential pressure across suction strainers; a sudden rise (> 20 kPa above baseline) signals bio-sludge accumulation requiring cleaning and biocide re-dosing.	3	30
S.10	Fine filters block, starving engines; blackout risk.	5	Regular check and change for filters, reduce the service time for filters	2	Visual inspection and notice for all filters associated	2	20
S.11	Booster pump cavitates.	4	Maintain adequate net-positive suction head (NPSH) by pre-heating the blend to its OEM-specified viscosity (typically 40–50 °C) and ensuring suction strainers are clean and tank levels remain above the minimum suction height.	3	Fit a suction-side pressure transmitter and vibration sensor linked to the alarm system; a drop in inlet pressure or a sudden increase in vibration amplitude triggers an immediate alert and automatic pump speed reduction or shutdown.	1	12
S.12	Incompatibility with fuel system material (seals, gasket).	5	Specify and install FAME-resistant materials (e.g., Viton/FKM or fluorosilicone) for all seals and gaskets	2	Inspect removed seals during each planned-maintenance interval and record any swelling, cracking, or	1	10

			in contact with blends above B10.		softening; trigger replacement if dimensional change exceeds OEM limits.		
S.13	Static-electricity ignition• Charge build-up when switching between low-conductivity diesel pockets and high-conductivity biodiesel	5	Enforce slow-start ($< 1\ \text{m s}^{-1}$) and bottom-filling procedures during the first five minutes of loading to allow charge relaxation and ensure continuous bonding/grounding.	2	Deploy an inline conductivity probe at the manifold with alarm set to $< 50\ \text{pS m}^{-1}$; suspend transfer if the reading falls below the threshold.	2	20
S.14	Injector-tip deposits cause sticking / fire-back.	4	Dose a calcium-free detergent additive (OEM-approved) whenever biodiesel fraction exceeds B20 to inhibit polymer and salt formation on injector needles.	3	Monitor injector return-flow balance and exhaust gas temperature spread; a sudden imbalance or ≥ 20 °C deviation flags deposit build-up requiring inspection.	3	36
S.15	Legacy asphaltenes and fresh biodiesel sludge remain; later mobilise and foul fuel system.	5	Perform a full hot-water/chemical tank wash followed by wall-wash sampling (n-heptane test) and reject wash if visible sludge remains.	1	Install differential-pressure transmitters across suction strainers; an unexpected ΔP rise (> 20 kPa above baseline) alerts crew to mobilised sludge.	2	10
S.16	Hot-work ignition during tank entry.	4	Implement a two-stage gas-freeing protocol with forced air ventilation until $O_2 > 20$ % v/v and hydrocarbons < 1 % LEL throughout tank levels.	2	Use a continuously-running, intrinsically safe multi-gas meter worn by each entrant; suspend work immediately if HC rises above 1 % LEL or O_2 drops below 19.5 %.	2	16

Potential failure modes in cargo operations of biodiesel blends

Table 35 maps eight sequential blocks in the carriage of biodiesel blends with conventional marine fuel as bulk cargo, from charter specification through tank-stripping after discharge. For each block it lists two dominant safety-critical failure modes; for example, static-spark ignition during loading, peroxide-driven corrosion in voyage, or hot-work ignition during tank entry; and anchors each mode to its underlying mechanism, such as mis-declared flash-point, additive mis-dosing, inert-gas pressure loss or incomplete tank washing. By pairing the task breakdown with causation detail, the table provides a comprehensive inventory of where and how cargo handling can escalate into fire, explosion, or leakage. This structured catalogue becomes the starting point for quantifying risk via severity, occurrence, and detection ratings. In effect, Table 15 functions as the first analytical step of an FMEA tailored to biodiesel-blend cargo operations.

Table 35. Cargo operation breakdown and potential failure mode for biodiesel blends and conventional marine fuel.

#	Process stage (functional block)	Principal safety-related failure modes (FM)	Failure mechanism/ contributing factors
1	Tank suitability & charter specification	**FM 1.1** Blend booked for un-coated or copper-bearing tanks, peroxide-catalysed corrosion & leakage. **FM 1.2** Flash-point, or blend class wrongly declared, leading to incorrect inert-gas or firefighting provision.	▪ Charterer misidentifies cargo; terminal documentation error. ▪ Owner assumes B30 “non-flammable” when Cat 4 limits still apply to vapour space.
2	Terminal storage / pre-load blending & sampling	**FM 2.1** Cargo oxidised or contaminated with water/metals before loading. **FM 2.2** Wrong antioxidant or conductivity improver dose, increasing static-spark risk.	▪ Long residence time, poor nitrogen blanketing at shore tank. ▪ Additive dosing pump mis-calibrated; quality-assurance lapse.

3	Ship-tank preparation (pre-wash, inerting, compatibility check)	**FM 3.1** Residual heavy fuel reacts with biodiesel, polymerising into sludge and raising fire-back risk at heaters. **FM 3.2** Inert-gas system set for diesel cargo (O_2 < 8 %) but not for Cat 3/4 vapour space (O_2 < 5 %), leaving flammable head-space.	▪ Inadequate hot-water wash; manual scraping omitted. ▪ Misinterpretation of ISGOTT table or faulty O_2 sensor.
4	Loading operation (ship–shore transfer)	**FM 4.1** Static discharge ignites vapour cloud at manifold.	▪ High initial filling velocity through dry hose; conductivity mismatch diesel pockets ↔ biodiesel cargo.
5	At-sea carriage & tank management	**FM 5.1** Peroxide build-up corrodes CS tank base, leading to pin-hole leak into ballast or cofferdam. **FM 5.2** Loss of inert-gas pressure during heavy weather, oxygen ingress, flammable atmosphere.	▪ Warm ambient + dissolved O_2 accelerate oxidation; water bottoms catalyse acids. ▪ IG fan trip, PV valve lift, or sloshing damage to IG line.
6	Heating / circulation prior to discharge	**FM 6.1** Heater coils over-shoot > 80 °C, causing thermal decomposition and vapour release. **FM 6.2** Pump cavitation and seal failure due to high viscosity or sludge, releasing hot cargo in pumproom.	▪ Faulty thermostat; watchkeeper inattentive. ▪ Filter ΔP ignored; suction strainers clogged with polymers.
7	Discharge operation at receiving terminal	**FM 7.1** Over-pressure in discharge line; relief fails, flange gasket blows, spraying hot fuel. **FM 7.2** Static ignition at terminal manifold during topping-off.	▪ Viscosity rise; operator throttles valve too quickly. ▪ Bond/ground clamp not connected; poor earthing continuity.
8	Tank stripping, washing & gas-freeing	**FM 8.1** Legacy asphaltenes + biodiesel sludge left in corners, later mobilise and foul next cargo heater system. **FM 8.2** Hot-work ignition: residual light ends or peroxide vapours ignite during man-entry.	▪ Incomplete hot-water wash; no chemical detergent. ▪ Gas readings taken at hatch but not in lower frame; peroxide hotspot undetected.

■ Prioritisation of risks with cargo operations of biodiesel blends

Table 36 sets out the quantified FMEA results for each safety-critical failure mode identified in the biodiesel-blend cargo chain. For every FM, the table lists the assigned severity, the single most effective prevention control adopted to lower occurrence, the resulting occurrence score, the key detection control used to raise detectability, and the corresponding detection score; multiplying these three ratings yields the risk-priority number (RPN) shown in the final column. The data reveal that static-spark ignition at the loading manifold (FM 4.1) attains the highest RPN, followed closely by hose or loading-arm rupture (FM 4.2) and peroxide-driven corrosion leaks (FM 5.1), signalling that transfer-phase hazards dominate the current risk landscape. Conversely, hot-work ignition after thorough gas-freeing (FM 8.2) registers the lowest RPN, indicating that existing controls are adequate for that scenario. By translating qualitative hazards into numerical priorities, Table 16 provides a clear basis for deciding where further mitigation or resource allocation is most urgently required.

Table 36. Risk priority number for cargo operation potential failure mode- biodiesel blends with conventional marine fuel.

FM ID	Severity (S)	Prevention controls (reduce O)	Occurrence (O)	Detection controls (reduce D)	Detection (D)	RPN
1.1 Tank alloy unsuited, corrosion leak	4	Charter sheet lists approved tank materials; class verification of coating & copper content	2	Pre-load visual inspection; ultrasonic thickness trending; peroxide test strips	3	24

1.2 Flash-point or blend class mis-declared	5	Mandatory ISO 8217 / ASTM D7467 CoA; double-check by cargo surveyor	2	Shipboard closed-cup flash-point test before loading	2	20
2.1 Oxidised / water-contaminated cargo loaded	3	Nitrogen-blanketed shore tanks; ≤ 30-day storage limit; weekly water dip	3	Shore-tank acid-number & water-content sampling; on-board pre-load Karl-Fischer	3	27
2.2 Additive mis-dosage, static hazard	4	Automated dosing skid with flow-proportional control; calibrated pump	2	Inline conductivity probe at manifold; additive-batch log audited	4	32
3.1 Heavy-fuel residue reacts, sludge/fire-back	3	Hot-water wash plus detergent; strict tank-cleaning checklist	2	Visual bottoms inspection, filter ΔP monitoring during voyage	3	18
3.2 Inert-gas not to Cat 3/4 spec	5	IG manual specifies $O_2 < 5$ % for blends; IG analyser calibration	2	Continuous O_2 monitor with alarm; IG log reviewed by chief officer	2	20
4.1 Static-spark ignition at manifold	5	Bond/ground clamps, dry-break velocity $< 1\ \mathrm{m\ s^{-1}}$ start; antistatic additive	3	Portable electrostatic voltmeter; manifold gas detector	3	45
5.1 Peroxide corrosion, tank leak at sea	4	Antioxidant added; cargo temperature < 40 °C; water bottoms drained	2	Fortnightly peroxide & acid sampling via restricted valve	4	32
5.2 Loss of IG pressure, flammable atmosphere	5	Dual IG fans; low-pressure alarm to bridge; PV valves set	2	Head-space O_2 recorder with trend alarm; IG log audit	3	30
6.1 Heater over-shoot > 80 °C, vapour release	4	PID controller and high-temperature cut-out; watch-circle SOP	2	Engine-control-room temperature alarms; vapour detector in deckhouse	3	24
6.2 Pump cavitation, seal failure (hot leak)	3	Viscosity chart; pre-heat to target; suction-strainer checks	3	Pumproom vibration sensor; seal-oil drip tray with level alarm	3	27
7.1 Discharge-line over-pressure, flange blow-out	4	Relief valves sized & tested; staged valve-opening SOP	2	Pressure transmitters with ESD trip; flange hot-spot IR gun	2	16
7.2 Static ignition at shore manifold	5	Grounding cable continuity test; flow-start in “slow fill” mode	2	Fixed gas detectors, IR camera at manifold	3	30
8.1 Sludge left, fouls next cargo heating	2	Complete hot-water & chemical wash; wall-wash sampling	3	Post-wash portable microscope for sludge check; cargo-heating temperature audit	3	18
8.2 Hot-work ignition during tank entry	5	Two-stage gas-free test (upper & lower frame); permit-to-work system	1	Continuous gas monitor on entrant; standby watch with gas meter	2	10

■ Prioritisation of environmental risks with bunkering and cargo operations of biodiesel blends

Table 37 compares the environmental-risk landscape across four operating contexts, biodiesel blends carried as bunker or cargo, in coastal or deep-sea waters, by showing the risk-priority numbers (RPN = S × O × D) for eleven failure modes. The figures reveal that oxygen-depletion in semi-enclosed sensitive marine areas (E-8), fire hazards linked to alcohol-containing blends (E-7), and undetected sub-surface plumes (E-11) produce the highest RPNs, especially when cargo is spilled in coastal area, where severity remains high. In contrast, deep sea bunker scenarios generally score lower, except for persistent surface slicks (E-3) and aromatic bio-accumulation (E-1). Variability in feedstock composition (E-10) carries a consistently "high" rating across all contexts, underscoring the challenge of predicting spill behaviour despite compliance with EN 14214 and ASTM D6751. Collectively, the table clarifies which environmental hazards warrant priority mitigation under different carriage and geographic conditions, thereby informing contingency-plan upgrades and equipment pre-positioning.

Table 37. Risk priority number for environmental failure mode either in bunkering or cargo operation in coastal and deep sea.

No.	Failure mode & main causes (only those listed)	Typical controls now in place	RPN= S*O*D			
			Bunker		Cargo	
			Coastal	Deep sea	Coastal	Deep sea
E-1	Bioaccumulation of diesel aromatics (low-blend spills)	B5–B10 retain polyaromatics; coastal biota density high	3* 3*4 = 36	2*2*5 = 20	4*3*4 = 48	3 * 2 *5 = 30
E-2	Toxicity spike from partially degraded oxidised biodiesel	Peroxides, acids, gum formation reduce biodegradability	3 *2 *4 = 24	2*2*5 = 20	3*2*4 = 24	2 / 2 / 5 = 20
E-3	Persistence of surface slick (B0–B5) hampers response	Lower FAME %, cool water, heavy sea state	4*3*3 = 36	3*3*4 = 36	4*2*3 = 24	3 / 2 / 4 = 24
E-4	Sub-surface plume from dissolved light ends	Deep-sea dilution masks detection; fluorometer coverage	2*2 *5 = 20	3*3*5 = 45	2*2*4 = 16	3 / 3 / 5 = 45
E-5	Reduced dispersant efficiency on oxidised blends	High viscosity, gum formation; cold water	3*3 *3 = 27	3* 3*4 = 36	3*2*3 = 18	3 / 2 / 4 = 24
E-6	Inadequate spill response capability specific to biodiesel properties	Standard oil spill kits designed for hydrocarbons	5*5*1=25	4*4*1=16	5*4*3=60	4*4*3=48
E-7	Fire hazard from certain biodiesel blends	Certified fuel quality standards; Fire suppression systems onboard	5*5*4=100	2*5*4=40	5*5*3=75	5*5*4=100
E-8	Enhanced biodegradation leading to oxygen depletion in semi-enclosed marine environments	Natural attenuation; Limited monitoring	5*5*4=100	2*2*2=8	5*5*5=125	4*5*5=100
E-9	Formation of toxic degradation products during weathering	Not explicitly controlled in current response plans	5*3*4=60	3*3*4=36	5*5*2=50	4*5*2=40
E-10	Variability of biodiesel feedstock composition leading to unpredictable behaviour	Adherence to fuel standards (EN 14214, ASTM D6751)	4*5*4=80	3*3*3=27	4*3*5=60	4*3*5=60
E-11	Sub-surface plume remains undetected	-	4*4*4=64	4*3*4=48	5*4*5=100	5*4*5=100

Annex VI: Regulatory review of biodiesel blends as a marine fuel

This annex provides a comprehensive overview of the regulatory landscape governing biodiesel and biodiesel blends in maritime transport. It examines relevant international, regional (EU), and national frameworks, highlights emerging standards, and identifies critical regulatory gaps related to the carriage, use, safety, and emissions reporting of biodiesel as a marine fuel.

■ IMO standards for the carriage, handling, and use of biodiesel blends and alternative fuels in shipping

○ *Fuel quality requirements and NO_x compliance under MARPOL Annex VI*

MARPOL Annex VI, in Regulation 18.3, establishes requirements concerning fuel oil quality, safety, and NO_x emissions compliance. One of the primary regulatory challenges associated with using biodiesel blends in marine engines has historically been demonstrating continued compliance with the NO_x Technical Code, particularly when switching from conventional fuels to biodiesel blends.

To resolve these uncertainties, the IMO adopted MEPC.1/Circ.795/Rev.6, which provides a unified interpretation clarifying that:

- marine diesel engines using biodiesel blends up to B30 (30% biodiesel, 70% petroleum diesel) do not require additional NO_x emission testing; and
- biodiesel blends exceeding B30, up to pure biodiesel (B100), may also avoid re-certification or retesting for NO_x compliance, provided that no modifications have been made to the engine, fuel injection equipment, or combustion chamber which could influence NO_x emissions.

This clarification has been instrumental in removing regulatory barriers to the operational uptake of biodiesel, aligning with IMO's broader strategy for reducing greenhouse gas (GHG) emissions from ships.

○ *Carriage and handling requirements for biodiesel blends under MARPOL Annex I and Annex II*

The regulation of biodiesel blends for carriage at sea is primarily determined by the proportion of bio-content within the fuel. Under the current IMO framework, the applicable MARPOL Annex changes depending on the blend ratio between petroleum-derived fuels and biofuels such as FAME or HVO.

Biodiesel blends containing up to 25% biofuel content have traditionally been allowed for carriage as oil cargoes under MARPOL Annex I. Blends exceeding this limit (i.e., more than 25% biofuel) have been regulated as chemical cargoes under MARPOL Annex II, subject to the International Bulk Chemical (IBC) Code requirements.

However, a significant regulatory development occurred during the IMO Sub-Committee on Pollution Prevention and Response (PPR 12) held in London from 27 to 31 January 2025. During this session, the Sub-Committee finalized an Interim Circular allowing conventional bunker tankers certified as oil tankers under MARPOL Annex I to carry biofuel blends containing up to 30% biofuel (B30). This development effectively raises the permissible biofuel content for carriage on oil tankers from B25 to B30 without requiring reclassification as chemical tankers.

The Interim Circular finalized at PPR 12 and approved at *MEPC 83* in April 2025 provides operational flexibility for bunker suppliers and ship operators to transport B30 biofuel blends without chemical tanker standards' operational and regulatory complexities.

○ *Additional consideration - handling of FAME cargoes under IBC Code*

PPR 12 also discussed the need for enhanced operational controls when handling FAME cargoes due to their physical properties and potential environmental impacts during tank cleaning operations. Notably, incidents of FAME residues causing pollution in sensitive areas like the North Sea triggered proposals to amend the IBC Code.

A proposal to introduce a mandatory prewash requirement for ships unloading FAME cargoes within designated sea areas (extending from Gibraltar northwards along the Norwegian coast, including the Baltic Sea, UK, and Ireland, as defined under MARPOL Annex II, Regulation 13.9) is under consideration. The ESPH Technical Group is currently reviewing this proposal, which is expected to be further discussed at PPR 13 in 2026.

o *Safety provisions under SOLAS and the ISM Code*

Under the International Convention for the Safety of Life at Sea (SOLAS), Chapter II-2 mandates that all marine fuels must have a minimum flashpoint of 60°C to mitigate fire hazards. This requirement is particularly pertinent for biodiesel blends, such as those containing Fatty Acid Methyl Esters (FAME), which may exhibit lower flashpoints. To address safety concerns associated with low-flashpoint fuels, the IMO adopted amendments to SOLAS Chapter II-2, Regulation 4.2.1, during MSC 106. These amendments, effective from January 1, 2026, aim to prevent the inadvertent use of fuels with flashpoints below the mandated threshold by enhancing documentation and verification processes.

In parallel, the International Safety Management (ISM) Code obliges ship operators to implement a Safety Management System (SMS) that encompasses comprehensive risk assessments, emergency preparedness, and crew training tailored to the specific hazards of alternative fuels, including biodiesel blends. Recognizing the evolving fuel landscape, the Maritime Technologies Forum (MTF) released guidelines in April 2024 to assist operators in adapting their SMS frameworks. These guidelines emphasize the necessity for structured risk management, updated emergency procedures, and targeted crew training to ensure safe operations with alternative fuels.

Furthermore, the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) provides mandatory provisions for ships utilizing fuels with flashpoints below 60°C. While primarily designed for gaseous fuels like LNG, the IGF Code's principles are increasingly relevant for liquid alternative fuels, guiding the safe design, installation, and operation of fuel systems on board.

These regulatory frameworks and guidelines collectively underscore the imperative for ship operators to proactively address the unique safety challenges posed by biodiesel blends and other alternative fuels, ensuring compliance and safeguarding maritime operations.

o *Evolution of IMO guidelines for the carriage of biodiesel as cargo*

IMO has progressively refined its guidelines to ensure the safe carriage and use of biofuel blends in shipping.

Initially, MEPC.1/Circ.761/Rev.1 (2011) provided guidance on biofuel blends mixed with petroleum products, focusing on discharge monitoring and fire safety; however, this was revoked in 2019 to align with more comprehensive regulations.

Subsequently, MEPC.1/Circ.879 (2018) introduced clarity for blends of petroleum fuels with energy-rich alternatives, such as Hydrotreated Vegetable Oil (HVO), establishing a 75% content threshold to determine the applicability of MARPOL Annex I or II.

Further refinement came with MSC-MEPC.2/Circ.17 (2019), which detailed requirements based on the proportion of petroleum oil in the blend: blends with ≥75% petroleum content fall under MARPOL Annex I; those with >1% but <75% under Annex II with IBC Code conditions; and blends with ≤1% petroleum content are treated as pure biofuel under the IBC Code.

In December 2022, IMO adopted Resolution MEPC.362(79), amending MARPOL Annex VI to require the inclusion of fuel oil flashpoint information in the Bunker Delivery Note (BDN), effective May 1, 2024. This will enhance safety measures for biofuels with lower flashpoints.

Additionally, MEPC.1/Circ.905 (2023) provides interim guidance on the use of biofuels under MARPOL Annex VI Regulations 26, 27, and 28. It allows for a lower CO_2 Emission Conversion Factor (Cf) if the biofuel achieves at least a 65% well-to-wake GHG emissions reduction compared to fossil Marine Gas Oil (MGO), supported by recognized Proof of Sustainability certificates. This interim method will remain until the IMO finalizes a comprehensive well-to-wake GHG methodology under forthcoming Life Cycle Assessment (LCA) Guidelines.

Furthermore, in early 2025, IMO's PPR 12 finalized an interim circular permitting conventional bunker ships certified under MARPOL Annex I to carry biofuel blends containing up to 30% biofuel, pending approval at MEPC 83 in April 2025. This measure aims to facilitate decarbonization efforts without extensive vessel retrofitting.

Industry guidelines for biodiesel blends in shipping

The technical management of biodiesel blends in shipping is governed by a range of guidelines, standards, and industry practices to ensure safe handling, fuel quality, and engine compatibility. While biodiesel, particularly FAME offers environmental benefits as a renewable fuel component, its physical and chemical properties require specific management measures in the maritime context.

CIMAC WG7 guidelines for managing distillate fuels with biodiesel (FAME)

CIMAC (International Council on Combustion Engines)[12] Working Group 7 (WG7) has provided industry guidance since 2013 on managing marine distillate fuels containing Fatty Acid Methyl Esters (FAME), commonly referred to as biodiesel. Focused initially on blends containing up to 7% FAME (B7), the operational principles remain applicable to higher FAME concentrations, particularly following the 2024 revision of ISO 8217, which now permits up to 100% FAME in certain marine fuel grades, provided quality specifications are met. ISO 8217:2024 and CIMAC WG7 guidelines (2024) offer updated guidance on fuel testing, quality assurance, handling, and risk mitigation for biodiesel-containing marine fuels (refer Table below).

Title	Description
Fuel testing and quality assurance measures for biodiesel (FAME) blends *Stringent fuel quality control measures are essential both pre- and post-blending to ensure operational reliability when using FAME-containing distillate fuels*	▪ *Verification of FAME Content*: Determined by approved test methods: ○ EN 14078 (preferred for distillates) ○ ASTM D7371 (alternative for distillates) ○ ASTM D7963 or IP 631 (for residual or blended grades) ▪ *Oxidation Stability Testing*: Critical for assessing storage life and degradation potential: ○ EN 15751 (for FAME and FAME blends) ○ ISO 12205 (for petroleum-only blends in DM grades) ▪ *Monitoring Net Heat of Combustion*: Measured using ASTM D240 (Bomb Calorimeter), especially important for fuels with significant FAME content due to lower energy density (typically ~37 MJ/kg for pure FAME vs ~42 MJ/kg for marine gas oil).
Storage and handling best practices for FAME-containing distillate fuels *Operational risk controls*	▪ *Material Compatibility*: Confirm all shipboard materials in contact with fuel (seals, hoses, gaskets, tank coatings) are suitable for biodiesel use, as FAME may soften or degrade incompatible materials. ▪ *Avoiding Long-Term Storage*: Biodiesel blends should be used within recommended storage periods due to vulnerability to: ○ Oxidative degradation ○ Acid formation ○ Microbial growth ○ Water absorption

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[12] CIMAC is the leading global non-profit association promoting the development of ship propulsion, train drive, and power generation. The association comprises National Member Associations and Corporate Members in America, Asia, and Europe. It provides a forum for technical interchange in piston engines, gas turbine systems, non-shaft line propulsion systems, automation and controls, system integration and digitalization solutions. CIMAC's Strategy and Working Groups produce technical publications. CIMAC has been granted consultative status with IMO.

	▪ *Enhanced Fuel Monitoring During Storage*: Regularly tested for: ○ Acid number increase ○ Water content (risk of phase separation) ○ Microbial contamination (sludge formation) ○ Oxidative stability decline ▪ *Tank Protection Measures*: Minimize exposure to heat and water ingress, as these factors accelerate biodiesel degradation. ▪ *Fuel System Maintenance*: Clean filters regularly due to possible sediment release from biodiesel solvency effects and tank cleaning to prevent carry-over of residues or microbial sludge.
Cold flow property management *Biodiesel exhibits inferior cold flow properties compared to petroleum diesel. Therefore, in colder environments, proactive measures are essential*	▪ Use of cold flow improvers (CFI) or additives ▪ Heating arrangements in storage and transfer systems ▪ Avoiding fuel stagnation in exposed piping ▪ Reporting of Cloud Point (CP) and Cold Filter Plugging Point (CFPP) is required for DF grades under ISO 8217:2024
Engine and operational compatibility considerations *Ships using biodiesel blends, especially with FAME content exceeding 7%, should pay particular attention to compatibility*	▪ *Water Tolerance in High-Pressure Fuel Systems*: Excessive water in FAME blends can cause injector damage in high-pressure common rail (HPCR) fuel systems. ▪ *Potential Filter Blockage Risks*: Biodiesel's solvent characteristics may dissolve historical sediments from tank walls, causing initial clogging when first introduced. ▪ *Energy Content Considerations*: Fuel consumption rates may increase depending on FAME content due to its lower specific energy.
Certification and traceability *Essential; not provided by ISO 8217:2024*	Proof of Sustainability (PoS) documentation or supplier declaration should accompany biofuels to confirm feedstock and sustainability credentials.

■ Classification societies (IACS) and biodiesel blend application

The International Association of Classification Societies (IACS) plays a crucial role in aligning engine certification, safety compliance, and operational practices for biodiesel use.

○ *Application of MARPOL Annex VI Regulation 18: Fuel oil availability and quality for biofuel*

MEPC.1/Circ.795/Rev.9 (2024), which provides the current unified interpretations to MARPOL Annex VI, specifies the interpretation of the application of regulation 18.3 for the quality of biofuel and synthetic fuel.

According to regulation 18.3: "Fuel oil for combustion purposes delivered to and used on board ships to which this Annex applies shall meet the following requirements." The interpretation of regulation 18.3 is that a fuel oil which is a blend of not more than 30% by volume of biofuel[13] or synthetic fuel[14] should meet the requirements of regulation 18.3.1, and fuel oil that is a blend of more than 30% by volume of biofuel or synthetic fuel should meet the requirements of regulation 18.3.2.

According to regulation 18.3.2.2, fuel oil derived by methods other than petroleum refining shall not cause an engine to

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[13] For the purposes of this interpretation, a biofuel is a fuel oil which is derived from biomass and hence includes, but is not limited to, processed used cooking oils, fatty-acid-methyl-esters (FAME) or fatty-acid-ethyl-esters (FAEE), straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), glycerol or other biomass to liquid (BTL) type products.

[14] For the purposes of this interpretation, a synthetic fuel is a fuel oil from synthetic or renewable sources similar in composition to petroleum distillate fuels.

exceed the applicable NOx emission limit outlined in regulation 13. The interpretation of this regulation is that a marine diesel engine which can operate on a biofuel or a synthetic fuel or blends containing these fuels without changes to its NOx critical components or settings/operating values outside those as given by that engine's approved Technical File, should be permitted to use such a fuel oil without having to assess as given in the regulation.[15] Where fuel oils are derived from methods other than petroleum refining, or fuel oil which is a blend of more than 30% by volume of biofuel or synthetic fuel and does not fall under this unified interpretation, the ship's IAPP Certificate may continue to be issued where the overall NOx emissions performance has been verified not to cause the specified engine to exceed the applicable NOx emissions limit when burning said fuels using the onboard simplified measurement method following 6.3 of the NOx Technical Code 2008, or the direct measurement and monitoring method in accordance with 6.4 of the NOx Technical Code, or by reference to relevant test-bed testing.

Engine type approval and biodiesel use

Under IACS UR M71, marine engines are type-approved based on DM-grade fuel testing, which indirectly accommodates a wide range of liquid fuels, including biodiesel blends. However, verification through shipboard trials following IACS UR M51 procedures is often recommended for blends exceeding conventional parameters to ensure suitability and operational reliability.

Example from Indian Register of Shipping (IRS) Guidelines: "Use of Biofuels on Ships" (December 2023)

In December 2023, the Indian Register of Shipping (IRS) released comprehensive technical guidelines titled *"Use of Biofuels on Ships,"* providing structured guidance for the safe and effective use of biofuels in the maritime sector. The guidelines cover key aspects of biofuels such as FAME, HVO, and BTL, recognising their applicability as drop-in fuels in marine operations. It outlines specific technical requirements addressing fuel tank arrangements, material compatibility of shipboard systems, and temperature considerations for the storage and handling of biofuels. Operational considerations highlighted include the need for ship-specific biofuel implementation plans, comprehensive risk assessments, and adherence to established fuel specifications. Furthermore, the IRS guidelines provide regulatory compliance procedures for conducting biofuel trials following MARPOL Annex VI Regulations 3.2 and 4, particularly concerning nitrogen oxides (NO_x) emissions measurement and safety protocols. To support safe and efficient onboard use, the guidelines also emphasise the importance of continuous fuel quality monitoring, preventive maintenance practices, and adequate crew training in managing the operational challenges and characteristics specific to biofuels.

International fuel quality standards applicable to biodiesel blends

International standards exist for biodiesel fuels to ensure that the fuel meets certain minimum requirements. The standards ensure that important factors in the fuel production process are satisfied. These include low sulphur content and the absence of glycerine, alcohol, catalyst, and free fatty acids. Basic industrial tests to determine whether the products conform to standards are specified in the standards rules.

ISO standard

The singular ISO standard for biofuels is ISO 8217:2024: Products from petroleum, synthetic and renewable sources – Fuels (class F) – Specifications of marine fuels.

ISO 8217:2024 was prepared in cooperation with ship owners, ship operators, shipping associations, national standards bodies, classification societies, fuel testing services, engine designers, fuel treatment equipment manufacturers, marine fuel suppliers, fuel additive suppliers, and the petroleum industry to meet the requirements for marine fuels supplied worldwide for consumption on board ships.

The increased focus on environmental concerns and legislation to address them is leading to a transition in marine

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[15] For the purposes of this interpretation, parent engine emissions tests undertaken on DM or RM grade fuels to the ISO 8217:2005 standard, as required by paragraph 5.3.2 of the NOx Technical Code, should be valid for all DM or RM grade fuels used in operation, or that the engine may be designed for, or capable of operation on, including those meeting ISO 8217 standards superseding ISO 8217:2005.

fuels. There is a shift away from marine fuels supplied from traditional oil products derived from the processing of petroleum crude, and a shift towards oil products derived from synthetic and renewable, recycled, or alternative sources. ISO 8217:2024 considers the diverse nature of these fuels and incorporates a number of categories of distillate and residual fuels, even though not all categories may be available in every supply location. ISO 8217:2024 facilitates the transition. However, sustainability aspects and accounting are not within the scope.

The fuel categories in ISO 8217:2024 have been classified according to ISO 8216-1 and include the distillate fuel categories DMX, DMA, DMB, DMZ, DFA, DFB, DFZ, and the residual fuel categories RMA, RME, RMG, RMK, and RF.

ISO 8217:2024 specifies the permitted minimum flash point limits following the provisions given in the SOLAS Convention.

ISO 8217:2024 in its entirety defines the general requirements and specifications for fuels used in marine diesel engines and boilers, prior to onboard fuel handling (storage, settling, centrifuging, filtration, heating) before use.

ISO 8217:2024 specifies seven categories of distillate fuels[16], one of which is for diesel engines used for emergency purposes. It also specifies four categories of residual fuels with sulphur content at or below 0.50% by mass, five categories of residual fuels containing FAME, and five categories of residual fuels with sulphur content exceeding 0.50% by mass.

This seventh edition of the internationally recognised standard for marine fuel specification, ISO 8217:2024, is one of the most significant revisions to date, featuring substantial updates to grades and parameters, new bio product terminology, and adding two tables to categorise residual marine fuels. These tables distinguish between fuels with sulphur content up to 0.5% (predominantly VLSFO) and those above 0.5%, as well as a table for bio-residual marine fuels.

In the 2024 edition of ISO 8217, updated clause 5.1 is more inclusive in terms of the fuel composition (renewables and synthetics). Updated Clause 5.2 refers to added substances and chemical species. In Clause 5.3, referenced inorganic acids and organic chlorides, and fuels shall be free of these compounds. New clause 6-10 defines test methods, interpretation of results, and other general requirements. Bunker suppliers must ensure fuel deliveries are free from organic chlorides and other harmful substances. The list of tables and annexes in ISO 8217 is provided in the table below.

List of tables and annexes in ISO 8217:2024

Title	Description
Table 1	Distillates and bio-distillate marine fuels (DM/DF grades) • Up to 100% FAME for DF grades • Reporting of FAME content & Net Heat of Combustion for DF grades • Minimum Cetane Number & Oxidation Stability requirements for DF grades • Removal of winter/summer quality variation for Cloud Point & Cold Filter Plugging Point
Table 2	Residual fuels with sulphur content up to 0.50% by mass (RM low sulphur grades) – New • New grades – 0.10% & 0.50% sulphur • De minimis level of FAME • Expanded stability parameter requirement and reporting • Removal of winter/summer quality variation for Pour Point • Minimum Kinematic Viscosity requirements

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[16] For the purposes of ISO 8217:2024, the term “fuels” comprises of the following:

- hydrocarbons from petroleum crude oil, oil sands and shale oil;
- synthetic hydrocarbons, renewable hydrocarbons or hydrocarbons from recycled sources, with molecular structures that are indistinguishable from petroleum hydrocarbons;
- fatty acid methyl ester (FAME), where permitted as specified in the standard; and
- blends of any of the above, where permitted as specified in the standard.

Table 3	Bio-residual marine fuels (RF grades) – New • New grades – Up to 100% FAME • Reporting of FAME content & Net Heat of Combustion • Expanded stability parameter requirement and reporting • Removal of winter/summer quality variation for Pour Point • Minimum Kinematic Viscosity requirements
Table 4	Residual fuels with sulphur content above 0.50% by mass (RM high sulphur grades) • Reduced number of grades • De minimis level of FAME • Two options for stability parameter accepted for reporting • Removal of winter/summer quality variation for Pour Point • Minimum Kinematic Viscosity requirements
Annex A	Bio-based liquid fuels including FAME – Expanded
Annex B	Composition of marine fuels – Expanded
Annex C	Ignition characteristics of residual marine fuels
Annex D	Hydrogen sulphur
Annex E	Acid Number
Annex F	Cold flow characteristics – New
Annex G	Ash – formerly Annex F
Annex H	Stability of residual fuels – New
Annex I	Unrefined used lubricating oil – formerly Annex G
Annex J	Specific energy – formerly Annex H
Annex K	Characterization of residual marine fuels – New

In practical terms, ISO 8217:2024 update provides clearer parameters and specific requirements. It stipulates that all tables must adhere to “General Requirements – Clauses 5 to 10,” which reduces ambiguity and limits subjective interpretation when delivering to this standard.

○ *The role of EN 14214 and ASTM D6751 with reference to ISO 8217*

EN 14214 “Fatty Acid Methyl Esters (FAME) for use in diesel engines and heating applications — Requirements and test methods” is the standard used in the European Union and is more related to the formulation of the product. This means that tests to determine ester content and glycerides concentration are included as spec parameters.

ASTM D6751 “Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels” is a standard predominantly used in the US and is more performance orientated.

Both standards serve the same purpose by providing sufficient quality guarantees for the FAME to be blended into the marine fuel pool where ASTM D6751 is more defined by operational requirements whereas EN14214 has more quantitative compositional requirements.

It is important to note that the FAME being used as blend component shall conform to a chosen specification, plus the finished product shall also conform to the chosen ISO 8217 grade. It is however impossible to “see” the FAME quality after blending; therefore, the FAME quality must be established through declaration by the supplier prior to blending.

Further, ASTM D6751 for neat biodiesel (B100) prior to blending, includes a voluntary No. 1-B grade, which provides more stringent controls for minor components in raw materials used to make biodiesel than the No. 2-B grade. The finished blended fuel standards are D975 for on/off road diesel up to 5% biodiesel (B5), D7467 for B6-B20 on/off road applications, and D396 for heating oil up to 5% biodiesel. B100 used for D975, D7467, and D396 must meet D6751 (either the No. 1-B or the No. 2-B grade) prior to blending.

Whereas EN 14214 describes the requirements and test methods for FAME before blending with diesel, several standards specify the requirements for fuels containing FAME including the following:

- EN 14214 (2013 + A2:2019): 100% FAME biodiesel;
- EN 590 (2014): for diesel fuel containing FAME up to 7% (%V/V);
- EN 16734 (2016) specifies B10 fuel with FAME content up to 10 %(V/V); and
- EN 16709 (2015) specifies B20 and B30 fuels with FAME content from 14 to 20 %(m/m) for B20 and FAME content from 24 to 30 %(m/m) for B30A range of international standards governs biodiesel quality, providing essential specifications to ensure fuel consistency, engine compatibility, and operational safety.

When biodiesel conforms to EN 14214 or ASTM D6751 standards, it is generally regarded as suitable for use in unmodified marine diesel engines, although operational diligence remains.

European Standards

Transport fuels is an area with high reliance on European standardization. Common and precise methods of sampling and testing, to avoid double sampling and testing in evaluating the quality of a product, are extremely essential when it comes to trading fuels. The development of European Standards is an important element in providing these common methods and ensuring that European consumers and businesses are provided with safe and reliable fuels, while considering the environment (e.g. emissions). European standardization also plays a role in ensuring clear consumer information on the compatibility between new alternative fuels and cars, by setting clear and simple labelling requirements. As such, biofuels are also used as a blend component of regular fuel.

Harmonised standards adopted by the European Standardisation Organisations CEN and CENELEC. CEN/TC 19 on Gaseous and liquid fuels, lubricants and related products of petroleum, synthetic and biological origin has responsibility in the activity sector fuels including solid and gaseous fuels, petroleum, and distillates. The scope of CEN/TC 19 includes standardization of methods of sampling, analysis and testing, terminology and specifications and classifications for petroleum related products, fuels, lubricants and hydraulic fluids, that origin from mineral oil and biomass; including the standardization of gaseous and liquid fuels and biofuels for transport and stationary applications. It excludes bio-methane and natural gas. The standards include those for characterizing the product quality and for related aspects, e.g. a quality monitoring system for automotive fuel.

Select list of European standards related to biofuels listed under CEN/TC 19.

Standard	Scope
EN 14214:2012+A2:2019 (WI=00019562)	Liquid petroleum products - Fatty acid methyl esters (FAME) for use in diesel engines and heating applications - Requirements and test methods
EN 15376:2014 (WI=00019452)	Automotive fuels - Ethanol as a blending component for petrol - Requirements and test methods
EN 15940:2023 (WI=00019610)	Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods
EN 16709:2024 (WI=00019623)	Automotive fuels - High FAME diesel fuel (B20 and B30) - Requirements and test methods
EN 16734:2022 (WI=00019586)	Automotive fuels - Automotive B10 diesel fuel - Requirements and test methods
CEN/TR 16982:2016 (WI=00019506)	Diesel blends and fuels - Cold filterability issues

CEN/TR 17544:2020 (WI=00019565)	Automotive fuels - Report on studies done on cold soak filter blocking tendency (CS-FBT) on FAME as blend component for diesel fuel, and of diesel fuel containing up to 30 % (V/V) of FAME

■ EU regulatory framework supporting biodiesel blends in shipping

The EU has established a comprehensive regulatory framework to promote the adoption of renewable and low-carbon fuels, including biodiesel blends such as FAME and HVO, within the maritime sector. This framework is primarily within the "Fit for 55" legislative package, which aims to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels. Key legislative instruments relevant to biodiesel use in shipping include the Renewable Energy Directive (RED II and the proposed RED III), FuelEU Maritime Regulation, inclusion of maritime transport in the EU Emissions Trading System (EU ETS), Fuel Quality Directive (FQD), and Energy Taxation Directive (ETD).

○ *Renewable Energy Directive (RED II and Proposed RED III)*

Directive (EU) 2018/2001, commonly known as RED II, establishes a common framework for promoting energy from renewable sources within the EU. It sets a binding target of at least 32% renewable energy in the EU's overall energy mix by 2030. For the transport sector, including maritime transport, RED II mandates that a minimum of 14% of the energy consumed in transport should come from renewable sources by 2030. Sustainable biofuels, such as FAME and HVO, are recognized under RED II and can contribute to this target, provided they meet specific sustainability and greenhouse gas emission savings criteria.

The proposed revision, known as RED III, aims to increase the overall renewable energy target to 40% by 2030, reflecting the EU's heightened climate ambitions. This revision is expected to promote further the use of advanced biofuels and other renewable fuels in the maritime sector.

○ *FuelEU maritime regulation*

The FuelEU Maritime Regulation is a legislative proposal under the Fit for 55 package to increase the use of renewable and low-carbon fuels in maritime transport. It limits the greenhouse gas intensity of energy used onboard ships arriving at, within, or departing from EU ports. The regulation will become applicable from 2025, with progressively stricter GHG intensity reduction targets. Certified sustainable biofuels, including biodiesel blends that comply with RED II sustainability criteria, are expected to play a significant role in helping ship operators meet these targets.

○ *Inclusion of maritime transport in the EU Emissions Trading System (EU ETS)*

The amended EU Emissions Trading System (EU ETS) includes maritime transport activities. This inclusion means that ship operators must monitor, report, and verify their CO_2 emissions and surrender allowances for these emissions. Notably, emissions from the combustion of sustainable biofuels that meet RED II criteria are considered to have a zero-emission factor, effectively exempting them from the requirement to surrender allowances under the EU ETS. This provides a financial incentive for ship operators to adopt biodiesel blends.

○ *Fuel Quality Directive (FQD)*

The Fuel Quality Directive (Directive 98/70/EC) sets technical specifications for fuels used in road and non-road mobile machinery, including inland waterway vessels. While its primary focus has been on road transport fuels, the FQD's principles influence fuel quality standards that can extend to marine fuels, particularly regarding reducing GHG emissions and promoting biofuels. The directive mandates a reduction of the lifecycle GHG intensity of transport fuels by 6% by 2020, encouraging the integration of biofuels like FAME and HVO.

○ *Energy Taxation Directive (ETD)*

The Energy Taxation Directive (Directive 2003/96/EC) lays down the framework for taxing energy products within the EU. The proposed revision of the ETD aims to align energy taxation with the EU's climate objectives by restructuring tax rates based on the energy content and environmental performance of fuels. Under the revised ETD, sustainable biofuels are expected to benefit from lower tax rates than conventional fossil fuels, promoting their use in maritime transport.

National practices and innovations supporting biodiesel use in shipping

Singapore

The Maritime and Port Authority of Singapore (MPA) has proactively supported the adoption of biodiesel in maritime operations. In 2022, the MPA increased the permissible biodiesel blend limit in conventional bunker tankers from B25 to B30, eliminating the need for separate approvals for such blends. This policy change is part of Singapore's broader strategy to promote cleaner marine fuels and reduce greenhouse gas emissions in its port waters. The MPA has also introduced standardized requirements for fuel quality, certification, and documentation to ensure the safe and consistent use of biodiesel blends.

United Kingdom

The United Kingdom's Renewable Transport Fuel Obligation (RTFO) mandates that fuel suppliers ensure a certain percentage of their fuel supply comes from renewable sources, including biodiesel. As of 2024, the RTFO target is 12.4% renewable fuel by 2032. The RTFO applies to various transport modes, including maritime, when renewable fuels of non-biological origin are used. Suppliers must provide evidence of sustainability and greenhouse gas savings to receive Renewable Transport Fuel Certificates (RTFCs), which can be traded or used to meet their obligations. This framework encourages biodiesel blends in shipping by providing economic incentives and a structured compliance mechanism.

United States

In the United States, the Environmental Protection Agency (EPA) implements MARPOL Annex VI through regulations codified in 40 CFR Part 1043 under the Act to Prevent Pollution from Ships (APPS). While these regulations primarily address emissions from ships, the U.S. also supports biodiesel use through the Renewable Fuel Standard (RFS) program, which mandates the blending of renewable fuels, including biodiesel, into the transportation fuel supply. Additionally, the American Petroleum Institute (API) has developed Recommended Practice 1640, providing guidelines for the handling, blending, storing, and delivering of light products, including biodiesel (FAME), to ensure quality management during distribution and storage processes.

Canada

Canada's Regulations for the Prevention of Pollution from Ships and for Dangerous Chemicals (SOR/2007-86) align with MARPOL Annex VI requirements, focusing on reducing air pollution and greenhouse gas emissions from vessels. The Canadian government has also implemented renewable fuel regulations requiring a minimum renewable content in diesel fuel, which includes biodiesel. These regulations support the use of biodiesel blends in shipping by ensuring fuel quality standards and promoting lower-emission fuels.

China

China has established Domestic Emission Control Areas (DECAs) to reduce sulphur and particulate matter emissions from ships, initially covering the Pearl River Delta, Yangtze River Delta, and Bohai Rim, and later extending to 12 nautical miles offshore. Biodiesel blends, with their low sulphur content, can support compliance with DECA requirements. However, challenges such as increased NOx emissions from older engines using biofuels and the lack of consistent national evaluation policies may affect the broader adoption of biodiesel in China's maritime sector.

Japan

Japan's "Roadmap to Zero Emission from International Shipping" (2020) aligns with the International Maritime Organization's greenhouse gas reduction strategy. The roadmap outlines two pathways: transitioning from LNG to biomethane and carbon-recycled methane starting from 2025 and expanding the use of hydrogen and ammonia as marine fuels. Biodiesel blends are recognized as part of Japan's future energy consumption strategies, aiming for 40% of the international shipping energy mix to consist of carbon-recycled methane and biofuels by 2050. Regulatory frameworks are evolving to recognize biofuels as carbon-neutral, supporting their integration into maritime operations.

South Korea

South Korea has established Domestic Emission Control Areas (ECAs) around major ports, including Incheon, Pyeongtaek-Dangjin, Yeosu-Gwangyang, Busan, and Ulsan. A fuel sulphur content limit of 0.10% applies to ships at berth or anchored from September 2020 and to ships operating within ECAs from January 2022. Compliance methods include the use of scrubbers, switching to low-sulphur fuels, LNG, or biodiesel blends. The regulatory framework supports the near-shore adoption of biodiesel as a compliant fuel option.

Panama Canal

In Panama, the Panama Canal Authority (ACP) issued Notice to Shipping No. N-1-2020 in January 2020, requiring vessels to use lighter fuels when transiting the canal. Vessels are expected to switch from residual fuels to marine distillate fuels prior to transit. MARPOL Annex VI-compliant LNG and biofuels, including biodiesel blends, are accepted to supplement or replace distillate fuels during canal operations. This measure aims to reduce particulate emissions and improve local air quality.

India

In November 2023, the Directorate General of Shipping issued a Merchant Shipping Notice outlining requirements for the use of biofuels and their blends on Indian ships. Key points include:

- **Fuel Specifications**: Biofuels must meet declared standards and be compatible with existing machinery and equipment. For FAME biofuels, compliance with EN 14214 or ASTM D6751 standards is recommended. HVO biofuels should adhere to the EN 15940 standard.
- **Sustainability Certification**: Biofuels, whether used in pure or blended form, must be certified by recognized international certification schemes, such as the International Sustainability and Carbon Certification (ISCC) or the Roundtable on Sustainable Biomaterials (RSB). A Proof of Sustainability document should accompany the Bunker Delivery Note to verify the reported biofuel consumption.
- **Operational Considerations**: Critical fuel properties, including lubricity, cold flow properties, acid number, and oxidation stability, should align with the limits recommended by equipment manufacturers to ensure safe operation and long-term reliability.

Australia

In Australia, the use of biodiesel is governed by national fuel quality standards. The Australian diesel fuel standard permits up to 5% biodiesel (B5) in diesel fuel sold at the pump. Higher concentrations of conventional biodiesel can cause issues with current diesel engines and fuel systems, so blends above B5 are less common.

While the maritime sector in Australia has not widely adopted biodiesel blends beyond this limit, the country's focus on reducing carbon emissions in transportation may lead to future initiatives promoting higher biodiesel blend usage in shipping.

GESAMP[17] Hazard Evaluation of Biofuels

The Revised GESAMP Hazard Evaluation Procedure provides an updated set of criteria for evaluating the hazards of chemical substances that may enter the marine environment through operational discharge, accidental spillage, or loss

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[17] GESAMP is an advisory body consisting of specialized experts nominated by the Sponsoring Agencies (IMO, FAO, UNESCO-IOC, WMO, IAEA, UN, UNEP, UNIDO, UNDP). Its principal task is to provide scientific advice concerning the prevention, reduction and control of the degradation of the marine environment to the Sponsoring Agencies.

overboard from ships.[18]

Hazards to human health and the marine environment are considered, and the information is collated in the form of a “hazard profile,” a comprehensive but easily readable fingerprint of each substance's hazard characteristics.

The hazard profiles of substances carried by ships are prepared by the Evaluation of the Hazards of Harmful Substances Carried by Ships (EHS) Working Group of GESAMP and published at regular intervals as a “composite list” available from the International Maritime Organization (IMO).

GESAMP Hazard evaluation endpoints

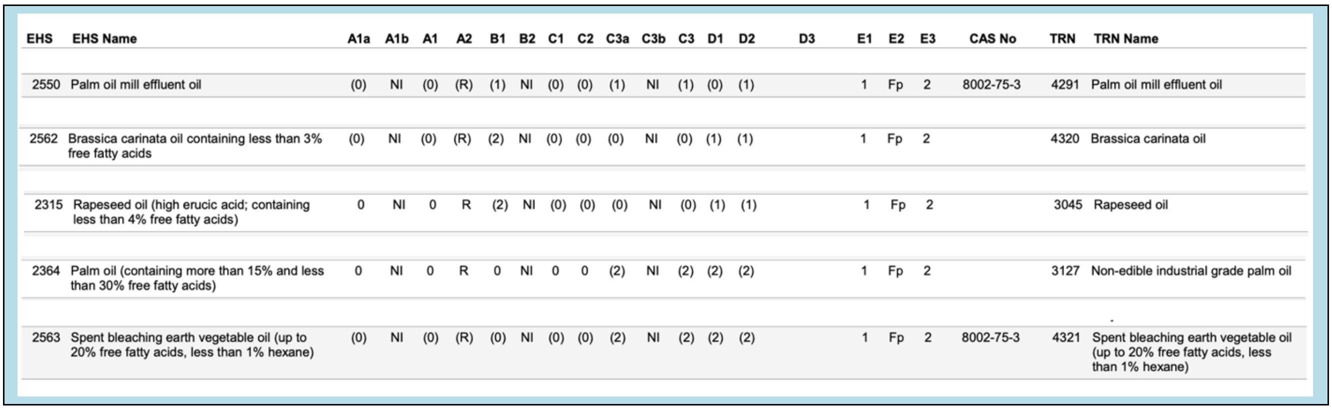
A: Bioaccumulation and Biodegradation	A1: Bioaccumulation
	A2: Biodegradation
B: Aquatic Toxicity	B1: Acute aquatic toxicity
	B2: Chronic aquatic toxicity
C: Acute Mammalian Toxicity by ingestion, skin contact, and inhalation	C1: Acute oral toxicity
	C2: Acute dermal toxicity (skin contact)
	C3: Acute inhalation toxicity
D: Irritation, Corrosion and Long-term Health Effects	D1: Skin irritation/corrosion
	D2: Eye irritation
	D3: Long-term health effects
E: Interference with other uses of the sea	E1: Tainting of seafood
	E2: Behaviour of chemicals in the marine environment
	E3: Interference with the use of coastal amenities

o *Vegetable oils used as feedstock for biofuel production*

The hazard profile of several vegetable oils used as feedstock for biofuel production has been evaluated by the GESAMP/EHS Group (PPR.1-Circ.12). GESAMP Hazard Profiles are assigned with respect to the following biofuels:

- Brassica carinata oil containing less than 3% free fatty acids (EHS 2562);
- Rapeseed oil (high erucic acid; containing less than 4% free fatty acids) (EHS 2315);
- Spent bleaching earth vegetable oil (up to 20% free fatty acids, less than 1% hexane) (EHS 2563); and
- Palm oil containing more than 15% and less than 30% free fatty acids (EHS 2364).

An extract of PPR.1-Circ.14, Annex 4 - GESAMP/EHS Composite List, GESAMP Hazard Profiles of evaluated biofuels.



EHS	EHS Name	A1a	A1b	A1	A2	B1	B2	C1	C2	C3a	C3b	C3	D1	D2	D3	E1	E2	E3	CAS No	TRN	TRN Name
2550	Palm oil mill effluent oil	(0)	NI	(0)	(R)	(1)	NI	(0)	(0)	(1)	NI	(1)	(0)	(1)		1	Fp	2	8002-75-3	4291	Palm oil mill effluent oil
2562	Brassica carinata oil containing less than 3% free fatty acids	(0)	NI	(0)	(R)	(2)	NI	(0)	(0)	(0)	NI	(0)	(1)	(1)		1	Fp	2		4320	Brassica carinata oil
2315	Rapeseed oil (high erucic acid; containing less than 4% free fatty acids)	0	NI	0	R	(2)	NI	(0)	(0)	(0)	NI	(0)	(1)	(1)		1	Fp	2		3045	Rapeseed oil
2364	Palm oil (containing more than 15% and less than 30% free fatty acids)	0	NI	0	R	0	NI	0	0	(2)	NI	(2)	(2)	(2)		1	Fp	2		3127	Non-edible industrial grade palm oil
2563	Spent bleaching earth vegetable oil (up to 20% free fatty acids, less than 1% hexane)	(0)	NI	(0)	(R)	(0)	NI	(0)	(0)	(2)	NI	(2)	(2)	(2)		1	Fp	2	8002-75-3	4321	Spent bleaching earth vegetable oil (up to 20% free fatty acids, less than 1% hexane)

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[18] GESAMP (2014, 2nd ed.). *Revised GESAMP Hazard Evaluation Procedure for Chemical Substances Carried by Ships* (IMO/FAO/UNESCO-IOC/WMO/ IAEA/UN/UNEP/UNIDO/UNDP) Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection, Rep. Stud. GESAMP No. 64. IMO, London.

GESAMP/EHS Group at EHS 60[19] recalled that considering recent submissions of products used mainly as feedstock for biofuel production, EHS 59 had:

- briefly considered whether it would be appropriate to develop generic entries covering groups of similar vegetable oil products, should there be an increase in the requests to evaluate vegetable oil products because of the expected growth in demand for biofuels and the associated shipment of feedstock oils to produce biofuels;
- recalled that in 2003, the Chair of GESAMP/EHS at the time had informed ESPH 9 that GESAMP would, in the future, only evaluate additional vegetable oils based on data provided;[20] and
- agreed to defer further discussions regarding whether grouping vegetable oils in the Composite List was appropriate or not until its next session.

Having noted that there had not been a noticeable increase in requests to evaluate vegetable oils used as feedstock for biofuel production, the GESAMP/EHS Group agreed that there was no need to consider the issue further until many submissions of this nature were received or until another body requested it.

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[19] PPR.1-Circ.13

[20] MEPC 71/11, paragraph 7.1.4

Annex VII: Regulatory gap analysis for biodiesel blends as a marine bunker fuel

Gaps in existing IMO regulations (MARPOL Annex I & II)

The MARPOL Convention provides comprehensive pollution prevention rules for oil (Annex I) and noxious liquid substances (Annex II), including cargo and fuel handling provisions. However, biodiesel blends used as marine fuel occupy a regulatory grey area under MARPOL. The ambiguity lies in whether biodiesel blends, particularly those beyond B30, should be treated under oil spill response protocols (Annex I) or chemical spill protocols (Annex II), especially during accidental releases.

This uncertainty could delay or complicate emergency response actions as responders may not know which procedures, equipment, or dispersants to deploy.

Behaviour of biodiesel blends in marine spills, a key technical gap

Currently, no unified international standards or datasets are available for predicting the behaviour of biodiesel blends in marine spill scenarios. Biodiesel exhibits distinct environmental properties compared to conventional petroleum fuels, including:

- higher biodegradability;
- lower persistence in the marine environment;
- reduced toxicity in many cases;
- increased susceptibility to microbial degradation;
- potential for oxygen depletion in confined waters due to biodegradation; and
- different spreading, emulsification, and weathering characteristics.

The absence of predictive models for biodiesel spill fate and behaviour, including weathering rates, dissolution, or biodegradation dynamics, severely limits the effectiveness of response planning and environmental impact assessments.

Spill response techniques, lack of testing for biodiesel effectiveness

Existing spill response strategies (booms, skimming, dispersants, and sorbents) are primarily optimized for petroleum hydrocarbons. However, the effectiveness of these techniques against biodiesel blend spills is largely untested and unverified.

Technique	Potential Limitations with Biodiesel
Booms and skimmers	Lower viscosity and higher solubility of biodiesel may reduce containment efficiency.
Dispersants	Designed for petroleum oils; efficacy for biodiesel blends uncertain. Some biodiesel components may not disperse similarly.
Sorbents	Sorption capacity for biodiesel is unknown; materials may need adaptation for polar biodiesel components.

This highlights the urgent need for testing, validation, and possibly developing spill response technologies specifically suitable for biodiesel blends.

■ Gaps in international spill preparedness frameworks

Key international spill preparedness and response standards — such as the IMO OPRC Convention, associated Guidelines, and regional contingency plans — have been developed almost exclusively for petroleum hydrocarbons. These frameworks do not currently provide any specific procedures or operational guidance for biodiesel blend spills.

Biodiesel spills may require differentiated response strategies due to:

- rapid biodegradation (requiring oxygen management);
- water solubility of components (requiring adapted containment or recovery); and
- emulsification and behaviour differing from oil slicks.

Without such guidance, there is a risk of inappropriate, delayed, or ineffective spill response.

■ Gaps in technical standards (ISO & ASTM)

While international fuel standards such as ISO 8217, ASTM D6751, and ASTM D7467 specify fuel quality parameters for biodiesel blends, these standards do not address spill response considerations. There are no global standards or methodologies for:

- monitoring biodiesel spills;
- containment and recovery procedures;
- environmental impact measurement;
- biodegradation assessment; and
- oxygen demand modelling during spills.

This lack of technical standards presents a regulatory vacuum in responding to biodiesel-related marine incidents.

■ Operational preparedness gaps (oil spill response organizations & national plans)

Oil Spill Response Organizations (OSROs) and national contingency plans are currently structured around petroleum spill scenarios. Very few, if any, OSROs possess equipment, sorbents, or specific operational plans optimized for biodiesel spill scenarios.

This creates potential operational vulnerabilities, including:

- equipment incompatibility;
- absence of biofuel-specific sorbents;
- lack of biodegradation monitoring tools; and
- no dedicated biodiesel spill response protocols.

■ Training and awareness deficiencies

IMO Model Courses, regional spill response workshops, and industry training programs have not yet incorporated biodiesel-specific spill response content. This creates a significant readiness gap among response personnel, operators, and regulators.

Regulatory instruments reviewed in respect of biodiesel blends as marine fuel

Instrument	Relevance
MARPOL (International Convention for the Prevention of Pollution from Ships)	Key convention regulating pollution, especially: • Annex I – Oil • Annex II – Noxious Liquid Substances • Annex VI – Air pollution and energy efficiency (includes fuel quality, NOx, and SOx).
SOLAS (International Convention for the Safety of Life at Sea)	Addresses fuel flash point, fire safety, storage systems, and emergency procedures.
OPRC (1990)	Establishes requirements for pollution response preparedness; applicable to non-conventional fuels under national regimes.
London Convention and Protocol	Covers dumping at sea, including substances introduced through fuel used onboard ship.
OPRC-HNS Protocol (2000)	Extends OPRC to hazardous and noxious substances (HNS), potentially including biofuel spills depending on composition.
IBC Code	Relevant if high-content biodiesel blends (>B30) are carried as cargo rather than fuel. Includes prewash and tank cleaning rules.
ISM Code	Requires ship-specific risk assessments, contingency plans, and documentation for fuel use (e.g., Safety Data Sheets for biofuels).
IGF Code	Not directly applicable to biodiesel but relevant for fuels with lower flashpoints; future revisions may consider renewable fuels.

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