CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 513

Biodiesel blends with VLSFO - Brazil´s field tests in vessels

Fuels - Alternative & New Fuels

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ABSTRACT

Improving of the energy and operational efficiency of vessels and the introduction of marine fuels with a lower carbon footprint are among the set of measures and actions that will contribute to achieving the International Maritime Organization (IMO) net-zero greenhouse gas (GHG) emissions by 2050. When it comes to the main alternative fuels, liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), biodiesel (FAME), methanol, hydrogen, and ammonia are potential alternative maritime fuels that have been studied. However, due to the need for short-term measures to be adopted, the use of renewable streams blended with bunker fuel and/or marine diesel, as drop-in fuels, requires little or no technical modifications to fuel storage, engine, or fuel supply system.

Petrobras' commitment to the transition to a low-carbon future is reflected in the maritime sector with the development of a renewable content bunker fuel. In the first stage of the project, during laboratory tests carried out at the Research and Development Center (Cenpes) facilities, after selecting the maritime fuel and biodiesel samples, no impacts were observed in complying with the main properties of the bunker fuel specification, according to ISO 8217:2017, nor in the complementary evaluations of combustion quality and mixture stability tests, indicating approval for a field vessel testing. The selected bunker fuels and biodiesel samples were previously tested before refueling the ships to assure compliance with the established test requirements.

The present work aims to discuss the main results obtained in pioneering tests carried out in Brazil using blends of bunker fuel with renewable content, specifically biodiesel, in different proportions and compositions, on ships with routes along the Brazilian coast. With the successful field tests, Petrobras is contributing to society's demand for fuels with lower GHG emissions, seeking short-term solutions that aim to reduce environmental impact and meet the decarbonization goals in the maritime sector.

1 INTRODUCTION

In July 2023, during the MEPC 80, the 2023 IMO Strategy on Reduction of Greenhouse Gas (GHG) Emissions from Ships has been adopted. This strategy envisages a reduction in carbon intensity (CO_2 emissions per transport work) and GHG emissions, both for the international shipping.[1] Figure 1 summarizes the levels of ambition aiming the net zero emissions by or around 2050.

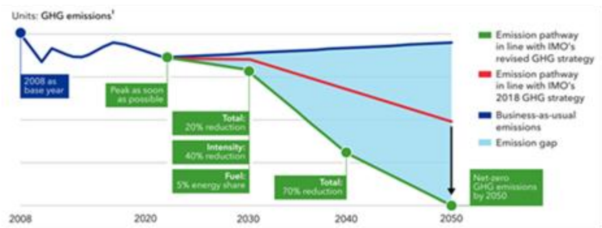


Figure 1. Revised initial strategy goals and ambitions from IMO (adapted from DNV-GL, 2023).

Figure 1 illustrates that by 2030, intermediate ambition targets as an average across international shipping emissions have been set, aiming for a minimum 20 % reduction in greenhouse gas (GHG) emissions, with an aspirational goal of 30 %. Additionally, there is a target to achieve at least a 40 % reduction in carbon intensity. Furthermore, the adoption of zero or near-zero GHG emission technologies, fuels, and/or energy sources is targeted to represent at least 5 %, with an aspirational goal of 10 %, of the energy used by international shipping by 2030.[1,2]

Improvement of the energy and operational efficiency of vessels plus the introduction of marine fuels with a lower carbon footprint are among the set of measures and actions that will contribute to achieving such ambitious targets. When it comes to the main alternative fuels, liquefied natural gas (LNG), hydrotreated vegetable oil (HVO), biodiesel (FAME), methanol, hydrogen, and ammonia are potential alternative maritime fuels that have been studied. However, due to the need for short-term measures to be adopted, the use of renewable streams blended with bunker fuel and/or marine diesel, as drop-in fuels, requires little or no technical modifications to fuel storage, engine, or fuel supply system.

In 2022, reflecting Petrobras' commitment to transitioning towards a low-carbon future in the maritime sector, an R&D project was initiated at Petrobras' Research, Development and Innovation Center (Cenpes) to develop a bunker fuel incorporating renewable content. The initial stage of the research project included several phases: selection of marine fuel and biofuel samples, characterization of these samples, establishment of blending percentages, preparation of formulations, laboratory analyses in accordance with the international specification ISO 8217[3], and additional tests to assess the combustion and ignition quality and stability of the formulations.

The positive results obtained in this stage facilitated the planning of field tests, which were conducted in three distinct phases. Each phase involved the evaluation of different criteria, will be detailed later in this article. As additional information for the project, compatibility tests of materials and bench engine tests are currently underway. These tests aim to compare the performance data with the results obtained in the previous stages.

The present work aims to discuss the key results obtained from pioneering tests carried out in Brazil, using blends of bunker fuel with renewable content, specifically biodiesel, in different proportions and compositions, on ships operating along the Brazilian coast. With the successful field tests, Petrobras is contributing to society's demand for fuels with lower GHG emissions, providing short-term solutions to reduce environmental impact and meet decarbonization goals in the maritime sector.

2 SELECTION OF THE STREAMS

To assess the potential application of renewable fuels, the RMG-380 specification from the international standard ISO 8217 was utilized as a reference for the bunker fuel referred in this study and known as VLSFO (Very Low Sulfur Fuel Oil), given its status as the most commercially traded marine fuel in Brazil. For this research project, biodiesel was selected as the renewable fuel for formulations due to its physicochemical properties, which enable its use as a drop-in fuel in the maritime sector. This means no modifications to existing storage, handling and use systems are required. Furthermore, biodiesel's wide availability further supports its selection.

Another important aspect considered in this project was the established and well-known properties of both VLSFO and biodiesel, which comply with the specifications of ISO 8217, EN14214[4], and Brazilian standards[5]. This compliance facilitated a reduction in the number of laboratory tests required for the evaluation of the formulations. As renewable fuels, soybean biodiesel and tallow biodiesel were selected for evaluation, as they are the most representative of Brazilian production. The initial evaluation results of the VLSFO formulations with biodiesel are presented in Tables 1 to 3.[6]

Table 1. Initial characteristics evaluation for VLSFO and biodiesel blends.

Characteristic	VLSFO A	VLSFO A + 20 %m/m soybean biodiesel	VLSFO B
Kinematic viscosity at 50°C, max, mm²/s	28,31	15,17	222,0
Density at 20°C, max., kg/m³	915,4	907,7	936,5
Acid number, max., mg KOH/g	0,27	0,24	0,34
Potential total sediment (TSP), max., %m/m	0,01	0,02	0,01
Carbon residue – Micro method. max., %m/m	4,06	3,34	6,91
Pour point, max., ºC	-9	-9	9
Water content, max., %v/v	< 0,1	< 0,1	< 0,1

Table 2. Initial ignition quality evaluation for VLSFO + biodiesel blends (IP 541).

Blends	ID, ms	MCD, ms	ECN
VLSFO A	4,14	4,46	> 40 (42,8)
VLSFO A + 20 %m/m soybean biodiesel	4,41	4,69	40,0
VLSFO B	4,19	4,67	> 40 (40,3)
VLSFO B + 20 %m/m tallow biodiesel	3,60	3,93	> 40 (49,8)

Table 3. Initial combustion quality evaluation for VLSFO + biodiesel blends (IP 541).

Blends	EMC, ms	MCP, ms	PMR, ms	Max. ROHR, bar/ms
VLSFO A	9,43	4,98	4,84	4,44
VLSFO A + 20 %m/m soybean biodiesel	8,98	4,28	5,00	6,10
VLSFO B	9,99	5,33	4,96	5,12
VLSFO B + 20 %m/m tallow biodiesel	9,49	5,56	4,47	3,27

As can be seen in Table 1, the incorporation of soybean biodiesel and tallow biodiesel into VLSFO did not adversely affect compliance with the main properties outlined in ISO 8217. The pour point of the formulation containing tallow biodiesel was higher than that of VLSFO, due to the intrinsic characteristics of the fuel, while still meeting the limits set by ISO 8217 for VLSFO.

Tables 2 and 3 present the ignition and combustion data of the formulations analyzed using the Fuel Combustion Analyzer (FCA).[7,8] The data and graphs obtained from the FCA provide comprehensive information on ignition and combustion quality. Figures 2 and 3 illustrate the main graphical outputs from the equipment: the variation of combustion pressure within the FCA chamber (bar) and the rate of heat release (ROHR) over time (bar/ms).

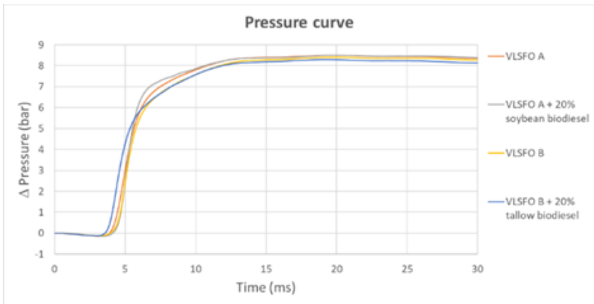


Figure 2. Pressure curve derived from FCA

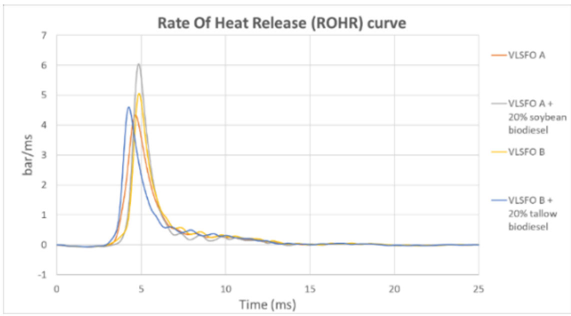


Figure 3. ROHR curve derived from FCA

In the case of the pressure curve, a shorter duration of pressure increase indicates a poor ignition delay of the mixture, thus better ignition quality. Similarly, for the ROHR curve, a leftward displacement of the curve signifies better combustion quality.

The criteria for comparing and classifying the different mixtures were based on the following: the higher the maximum ROHR (Rate of Heat Release) value and the lower the PMR (Position of Maximum ROHR), the better the combustion quality. The PMR is defined as the time interval, in milliseconds, between the needle movement (injection of the sample) and the peak rate of pressure change per unit of time. In other words, it serves as a measure of the work done by the fuel.[6]

The analysis of the combined results for ignition quality and combustion of the mixtures suggests trouble-free performance for the formulations tested in the laboratory. The mixture containing 20% v/v tallow biodiesel with VLSFO demonstrated the best ignition quality compared to pure VLSFO and the other formulations. In terms of combustion characteristics, the mixture with 20% v/v soybean biodiesel exhibited superior quality. It is important to note that not all mixtures prepared from VLSFO can be considered statistically equivalent, as the values obtained can be distinctly identified as either superior or inferior to those of pure VLSFO.

3 FIELD TESTS

While it is acknowledged that field tests with marine biofuels are not new, limited data have been shared or made public. The following challenges, which can be encountered during field tests, are crucial for comprehensive testing and evaluation to ensure that marine biofuel blends can become a viable and sustainable alternative to traditional marine fuels:

- Fuel compatibility considering that marine engines are typically designed for conventional fuels, it is crucial to ensure that biofuels are compatible with these engines without causing damage or requiring extensive modifications;
- Biofuels or biofuel blends should not compromise the performance and efficiency of traditional marine fuels. This includes maintaining engine power, fuel consumption rates, and operational reliability;
- Biofuels or biofuels blends can have different storage requirements and stability issues compared to conventional fuels. They may be more susceptible to microbial growth, oxidation, and phase separation, which can impact their usability over time;
- While biofuels are generally considered more environmentally friendly, their production and use can still have environmental impacts. Field tests need to assess the full lifecycle emissions and potential ecological effects;
- The cost of producing and distributing biofuels can be higher than that of conventional fuels. Ensuring economic viability is essential for their widespread adoption in the marine industry;
- Marine biofuels must adhere to various international regulations and standards. Ensuring compliance with these regulations can be complex and time-consuming.

Following the positive outcomes of the preliminary laboratory tests, planning commenced for the execution of field tests using bunker formulations with biodiesel. The primary objectives of these tests were to assess the logistical challenges associated with the incorporation of biodiesel into bunker fuel, considering varying supply conditions and different biodiesel sources used in the formulations.[9] Additionally, the tests aimed to ensure that the use of this formulation as marine fuel would not adversely impact ship operations. Between 2022 and 2024, three field tests were carried out to explore the different planned complexities.

3.1 Port selection

The selection of the terminal was based on the following key considerations:

- The capacity to receive biodiesel for blending via road transportation and alignment for fuel storage;
- Availability of a small-scale storage for formulation and storage until ship refueling, without negatively impacting the terminal's regular operations.

Due to its geographic location and compliance with these criteria, the Rio Grande Terminal (TERIG) in Rio Grande do Sul was identified as the most suitable site for facilitating the test. TERIG has 11 tanks designated for the storage of fuel oil and bunker fuel, allowing for the allocation of 2 tanks with adequate capacity for preparing the planned test formulation. Another decisive factor in the selection was the existence of an operational system that permits the receipt of biodiesel via road transportation for blending.[9]

3.2 Formulation of VLSFO + biodiesel blends

To calculate and prepare each biodiesel blend formulation, the volumes of the tank ballast used for blending and the amount of product contained in the port lines (tank feed, transfer to the pier) were considered to determine the necessary amount of biodiesel to be added. The contents and sources of each biodiesel used in each field test are presented in Table 4.[9,10,11]

Table 4. FAME feedstock and content for each field test.

Test	#1	#2	#3
FAME content (%v/v)	10 %	24 %	24 %
Feedstock	100 % soybean	70 % soybean, 30 % tallow	tallow - ISCC EU RED[1]

[1] obtained by mass balance

The amount of biodiesel added to the bunker was determined by measuring the volumes used, considering the ballast and other product remnants, and subsequently compared with the results obtained through laboratory testing.

The formulation tank was stirred for approximately 4 hours, a duration verified as sufficient for achieving mixture homogeneity. After this period, aliquots of the formulation were taken to evaluate compliance according to ISO 8217:2017, except for the presence of biodiesel, which was not permitted in VLSFO specification at that time.

3.3 Field tests detailed

In the process of obtaining authorizations for conducting the field test, consultations were held with the ship's classification society, the Brazilian maritime authority (Brazilian Navy), and the National Agency of Petroleum, Natural Gas and Biofuels (ANP). All parties agreed to and authorized the field test.

The first field test was conducted using an LPG tanker from Petrobras's internal fleet (Transpetro). The following criteria were defined for the selection of the vessel:[9]

- Test a blend of 10 % soybean biodiesel with the bunker fuel;
- Perform refueling through a direct connection to the pier, avoiding the use of barges to prevent impacting the refueling operations of other ships due to barge unavailability;
- Operate in cabotage operations, allowing for quick intervention in case of any operational issues during the use of the formulation;
- Ensure the vessel's dimensions and draft are compatible with the TERIG pier limits dimensions;
- Utilize backup tanks with VLSFO without biodiesel addition in case of any issues with the test formulation;
- Pre-clean the tanks reserved for receiving the mixture to avoid sludge presence that could be dragged into filters and separators;
- Have or install a telemetry system to record data from the main engine, including load, RPM, and operating pressures of each cylinder, throughout the test;
- Carry out a detailed inspection of the engine cylinders (cylinder condition) following the manufacturer's procedure (MAN Energy Solutions) to document the engine's condition before and after the test.

For this initial test, it was agreed to use the formulation exclusively in the main engine (MAN 5S35ME-B9), given the novelty of this type of operation in Brazil. The evaluation focused on consumption data, power output, and distance traveled during the field test, as well as monitoring any issues in the fuel filters and separation systems.

As a preparatory measure, the ship's tanks were pre-cleaned to receive the formulation, preventing sludge from being dragged through the treatment and engine feed system. The following operational parameters of the ship were monitored:

- Location, speed, and distance traveled by the ship (AIS – Automatic Identification System);
- Telemetry (load, RPM, and engine pressures): monitoring the fuel operation within the engine's operational limits;

- Qualitative assessment by the crew regarding impacts on the centrifuge and the engine's microfilters;

- cylinder condition: metrological inspection from the access door of the wash air box conducted by a specialized company, following MAN's recommendations. Analysis to be performed before and after the field test.

- Analysis of the residual cylinder oil (metals to assess wear).

The test was conducted between December 2022 and February 2023, lasting 40 days and covering a route of approximately 14,592 km along the Brazilian coast. The amount of test fuel supplied was 280 tons.

When it comes to the second field test, the main aspects that differentiate it from the first test can be summarized as follows:[10]

- Tested a blend of the bunker fuel with 24 % biodiesel (70 % soybean, 30 % tallow);

- A fuel tanker, from a third-party shipowner working for Petrobras, was selected for this field test;

- The tanks selected for receiving the blend were emptied without cleaning at the end;

- Testing was conducted on the main engine (6G50ME-C9.5), auxiliary engines (MAN STX L23/30H-Mk2), and boilers (Aalborg OL18 and AQ-16);

- The amount of test fuel supplied was 516 tons.

The second test was carried out between June and August 2023, lasting 68 days and covering a route of approximately 8,673 km along the Brazilian coast.

The main points that differentiate the third field test, from the previous two tests were:[11]

- Tested a blend of 24 % biodiesel (certified by ISCC EU RED as tallow) with the bunker fuel;

- A container ship, from a third-party shipowner working for other companies, was selected for this field test;

- Refueling was carried out by barge.

- The amount of test fuel supplied was 800 tons.

The third test was carried out between December 2023 and January 2024, lasting 28 days, and covering a route of approximately 9118 km along the Brazilian coast.

Table 5 summarizes the main information from the three field tests conducted so far (2022-2024).[12,13,14,15]

Table 5. Field test main information summarized.

Test	#1	#2	#3
Vessel	LPG Tanker	Fuel Tanker	Container Ship
Quantity supplied (t)	280	516	800
FAME content (%v/v)	10 %	24 %	24 %
Feedstock	100 % soybean	70 % soybean, 30 % tallow	tallow - ISCC EU RED[1]
Supply	Dec/2022	Jun/2023	Dec/2023
End of consumption	Feb/2023	Aug/2023	Jan/2024

[1] obtained by mass balance

4 RESULTS

It is important to emphasize that all the results discussed in this article pertain specifically to the fuels, formulations, vessels, and their respective equipment under the navigation conditions encountered during the conducted field tests. These results should not be extrapolated or considered applicable to similar tests or referenced for any conditions other than those described here without a critical analysis of the differences between the cases. However, the results were significant for increasing the complexity of the tests and collecting variables for future internal studies.

All prepared formulations were sent to be tested in an external laboratory for compliance with the ISO 8217:2017 specification, except for the presence of biodiesel. The results obtained for each formulation are presented in Table 6.

As can be seen in Table 6, [9,10,11] the three formulations comply with the limits of the ISO 8217:2017 specification for the evaluated characteristics. It is worth noting the very low value of total sediment potential found, indicating that the addition of biodiesel did not lead to increased sediment formation in the fuel, which is a primary concern with such blends.

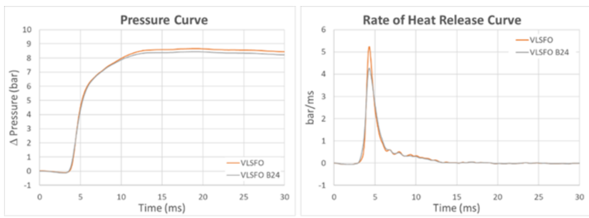
Table 6. Laboratory test results.

Property	Formulation 1st field test	Formulation 2nd field test	Formulation 3rd field test
Water content, %v/v	0,20	0,10	0,05
Density @15°C, kg/m³	925,7	909,5	925,4
Sulfur, %m/m	0,382	0,295	0,320
H_2S (Procedure B), mg/kg	0,58	1,82	<0,40
Flash point (PMCC), ºC	104,0	94,0	104,0
Pour point, ºC	-6	3	9
Ash, %m/m	0,005	0,013	0,010
Kinematic viscosity at 50°C, cSt (mm²/s)	51,37	26,25	27,33
Acid number, mg KOH/kg	0,2	0,9	1,0
Total Sediment Potential – Thermal aging, %m/m	0,01	0,01	0,01
Ramsbottom residue, %m/m	2,67	2,59	3,41
Calcium, mg/kg	<3	<0,05	14
Aluminum + Silicon, mg/kg	<15	<15	<15
Sodium, mg/kg	4	5	6
Vanadium, mg/kg	6	4	8
Zinc, mg/kg	<1	[1]	4
CCAI	812	806	822

[1] not determined as the Calcium content is lower than 0,05 mg/kg.

An important point for future optimization studies is that the formulations were prepared from two products (biodiesel and VLSFO) specified according to international and national standards. There is significant potential for improvement in bunker formulation by the refiner, particularly when it can be prepared in-house, utilizing locally available streams. Additionally, when formulations are prepared at the refiner's own terminals, they can be adjusted to meet the specifications agreed upon at that terminal, thereby avoiding the give-away of properties.

For example, the analysis presented in Figure 4 for the ignition and combustion characteristics of the blend containing 24 % biodiesel indicated that its ignition and combustion tend to occur more quickly than those of pure VLSFO. This behavior was anticipated, given that the specified biodiesel exhibits better ignition and combustion qualities compared to automotive diesel and, by inference, bunker fuel.



Fuel	Ignition		Combustion		Estimated Cetane
	ID, ms	MCD, ms	EMC, ms	MCP, ms	Number (ECN)
VLSFO	3,84	4,13	9,50	5,36	>40
VLSFO + 24 % biodiesel	3,75	4,04	9,11	5,07	>40

Figure 4. VLSFO vs VLSFO + 24 % biodiesel ignition and combustion quality comparison (IP 541).

The field tests on the vessels did not reveal any abnormalities in the behavior of the evaluated engines and boilers, nor in the operation of the filters and separators. Only in one instance was observed a discrete increase in sludge formation in the separator, which did not compromise its integrity, operation, or the quality of the cylinder oil. It is important to emphasize that the tests were planned and conducted to identify the main challenges related to logistical variables, formulation preparation, and, most importantly, the potential impacts on vessel operations.

The engine's operational parameters, including pressures and combustion characteristics within the cylinders, as well as cylinder stability, remained within expected ranges, comparable to operations using bunker fuel without biodiesel. Notably, in the second field test, it was possible to directly compare the performance at the same load of 100 % bunker fuel, marine diesel, and bunker fuel with 24 % biodiesel under same loading conditions, demonstrating similar behavior among them, as illustrated in Figure 5. The data were collected through measurements from the main engine control instrumentation at a 30 % load condition.

Engine

Time Stamp	Engine Speed [rpm]	p(scav) [bar]	Estimated Effective Power [MW]	Estimated Load [%]
6/16/2023 1:24:43 PM	52.4	0.60	2.1	30

VLSFO

Cylinder

Cylinder Number	p(i) [bar]	p(comp) [bar]	p(max) [bar]	p(comp)/p(scav) [abs/abs]
1	8.4	84.7	125.7	53.6
2	8.3	84.7	123.8	53.6
3	8.3	84.4	122.9	53.5
4	8.2	84.0	122.3	53.2
5	8.5	84.8	125.8	53.7
6	8.2	84.6	125.0	53.6
Mean	8.3	84.5	124.3	53.5

Engine

Time Stamp	Engine Speed [rpm]	p(scav) [bar]	Estimated Effective Power [MW]	Estimated Load [%]
6/19/2023 11:32:54 AM	53.0	0.62	2.1	31

Distillate marine fuel

Cylinder

Cylinder Number	p(i) [bar]	p(comp) [bar]	p(max) [bar]	p(comp)/p(scav) [abs/abs]
1	8.5	86.5	127.3	54.0
2	8.4	86.6	126.8	54.0
3	8.4	86.3	125.7	53.9
4	8.4	86.0	124.8	53.7
5	8.6	86.7	127.7	54.1
6	8.5	86.4	127.0	53.9
Mean	8.4	86.4	126.5	53.9

Engine

Time Stamp	Engine Speed [rpm]	p(scav) [bar]	Estimated Effective Power [MW]	Estimated Load [%]
7/10/2023 8:07:26 AM	53.0	0.62	2.1	31

VLSFO + 24 % biodiesel

Cylinder

Cylinder Number	p(i) [bar]	p(comp) [bar]	p(max) [bar]	p(comp)/p(scav) [abs/abs]
1	8.1	86.9	126.7	54.4
2	8.2	86.7	126.1	54.3
3	8.1	86.4	126.3	54.1
4	8.3	86.4	124.6	54.1
5	8.5	86.4	126.8	54.1
6	8.5	86.4	126.7	54.1
Mean	8.3	86.5	126.2	54.2

Figure 5. Performance of a particular data for a 4-stroke engine using VLSFO, distillate marine fuel and VLSFO + 24 % biodiesel at 30 % load.

In all tests, visual inspections of the interiors of the cylinders and pistons of the main engine were performed, which did not indicate any negative impact from the use of the blend, demonstrating compliance of the tested fuel. This is a result that can be attributed to the quality of the renewable component used and the duration of the field test. The cylinder oil was analyzed post-tests to assess degradation, evaluating the Total Base Number (TBN) and the presence of iron (Fe) as indicators of cylinder wear. The wear levels observed in the three field tests were considered satisfactory and acceptable for the engine bore size of each cylinder. Figure 6 graphically presents the evaluation, concluding that the wear acceptance level is satisfactory and "within a safety area."

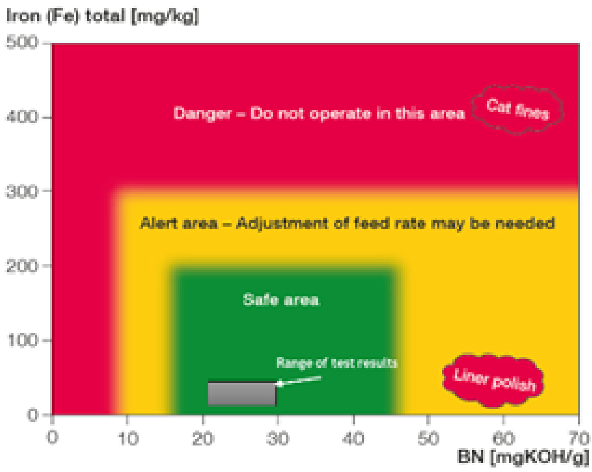


Figure 6. Graphical evaluation of TBN and Iron (Fe) content as an indicator of wearing of the cylinders.

To assess the impact on engine performance, the operational load was varied from low speed to full load, ensuring the ships' travel speed remained consistent with the charterer's contract. It is important to highlight that variables such as sea currents, waves, wind, and the vessel's loading condition (whether full or empty) are challenging to predict during test planning and can significantly impact adversely the results.

Additionally, the potential for decarbonization of each formulation used in the field tests was estimated by considering the complete life cycle using the RenovaCalc database, a tool for calculating the carbon intensity of biofuels used in Brazil. The estimated values for CO_2 emission savings for each test are presented in Table 7. It can be observed that there is an increase in emission savings from the first test, which is related to the increase in biodiesel content and the variation of the raw material used.

Table 7. Estimated CO_2 emissions reductions from each field test.

Vessel	LPG Tanker	Fuel Tanker	Container Ship
Quantity supplied (t)	280	516	800
FAME content (%v/v)	10 %	24 %	24 %
Feedstock	100 % soybean	70 % soybean, 30 % tallow	tallow - ISCC EU RED[1]
CO_2 emission savings[2]	7 %	17 %	19 %

[1] obtained by mass balance
[2] estimated based on RenovaCalc data – full cycle analysis

5 FINAL REMARKS

The maritime sector's journey towards decarbonization is both challenging and essential as it is usually considered as a hard-to-abate sector. With the ambitious targets set by the IMO, the industry must navigate regulatory complexities, technological integration, infrastructure development, and economic viability.

Collaborative efforts among stakeholders, increased investment in R&D, and supportive government policies are crucial to overcoming these hurdles in the search for identifying the lowest cost options for society and the best use of available natural resources making energy more accessible.

Choice and investment in alternatives fuels will consider, among other important metrics, the logistics infrastructure, the existing fleet and the lifetime of the fleet. The adoption of the blending of marine fuels with biofuels, such as biodiesel, will play a relevant role in the short-term (until 2030) offering a practical short-term solution with potential to save carbon emissions immediately, considering the full life cycle analysis, and thus meet the IMO decarbonization targets, especially for the existing fleet.

Considering the analyzed formulations of VLSFO, laboratory tests with the addition of soybean biodiesel or tallow biodiesel at the studied percentage (20 % m/m) showed no impact on meeting the main specification items of ISO 8217. The values found for total potential sediment, one of the tests indicative of the stability and compatibility of VLSFOs, do not suggest any issues in meeting this property. The results of the laboratory evaluation provided greater confidence for the planning and execution of field tests.

All planned field tests with bunker blends containing 10 % and 24 % biodiesel were successfully completed, indicating the feasibility of using bunker blends with biodiesel in the different tested proportions (10 % and 24 %) in commercial vessels. These tests validated the formulation process, with different raw materials and fueling methods tested.

Regarding the operation of the ship's engine and the fuel pre-treatment systems (separators and filters), there were no atypical occurrences in the three tests conducted. The operational parameters of the engine, including pressures and combustion characteristics inside the cylinders, as well as stability among the cylinders, remained within expected ranges, similar to operation with regular VLSFO. This indicates that the use of biodiesel did not negatively affect the performance of the equipment.

The results of the analyses of fuel and cylinder oil samples, as well as the inspections conducted before and after the tests, indicated that the use of the blend with biodiesel had no negative impact on the product specification requirements nor on the cylinders and pistons of the main engine. The analysis of the cylinder oil from the piston drain showed acceptable levels of wear and residual TBN.

It is worth noting that for these tests, it was not necessary to evaluate the emission of nitrogen oxides (NOx) from the ship, as per IMO Circular MEPC.1/Circ.795/Rev.6[16], blends containing up to 30% v/v of biofuels can be used without the need for a technical reassessment by the engine.

Another important aspect for a comprehensive assessment, which is currently underway in this study, is a more detailed evaluation of the potential for microbiological contamination and the impact on elastomers when blending mineral marine fuels with biofuels. As a continuation of this work, the performance and emissions of selected formulations of marine fuels with biodiesel will be evaluated under controlled conditions in test cycles according to the applicable ISO standard, using a marine engine test bench.

With the success of the tests, Petrobras continues its commitment to meeting society's demand for fuels with lower greenhouse gas emissions by seeking short-term solutions aimed at reducing environmental impact and achieving decarbonization targets in the maritime sector. Furthermore, it is important to highlight that the results obtained also led to a special authorization from ANP for the commercialization of bunker blends with 24 % biodiesel in Brazilian territory by Petrobras, until the specification of national marine fuels is revised to align with the most current version of ISO 8217 (2024).[17]

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIS: Automatic Identification System

ANP: Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (National Agency of Petroleum, Natural Gas and Biofuels)

ASTM: American Society for Testing and Materials

CCAI: Calculated Carbon Aromaticity Index

CIMAC: Congrès International des Moteurs à Combustion Interne

ECN: Estimated Cetane Number

EMC: End of Main Combustion

EN: European Standards

FAME: Fatty Acid Methyl Ester

FCA: Fuel Combustion Analyzer

GHG: Greenhouse Gas

H_2S: Hydrogen Sulfide

HVO: Hydrotreated Vegetable Oil

ID: Ignition Delay

IMO: International Maritime Organization

ISCC: International Sustainability & Carbon Certification

IMO: International Organization for Standardization

LNG: Liquefied Natural Gas

LPG: Liquefied Petroleum Gas

MCD: Main Combustion Delay

MEPC: Maritime Environment Protection Committee

NOx: Nitrogen Oxide

PMR: Position of Maximum ROHR

R&D: Research and Development

RED: Renewable Energy Directive

RenovaCalc: Brazilian tool for calculation of the carbon intensity for biofuels.

ROHR: Rate of Heat Release

RPM: Revolutions Per Minute

TBN: Total Base Number

VLSFO: Very Low Sulfur Fuel Oil

7 ACKNOWLEDGMENTS

The authors want to express their thanks to all colleagues participating in the research work, presented here.

Especially, the authors want to thank all the colleagues that have been working from several areas from Petrobras (R, D & I Center, Trading, Refining, Planning, Logistics and Terminals) for their effort to plan, test, schedule, produce and supply the formulations to be used in the field tests.

8 REFERENCES

[1] http://www.imo.org

[2] Energy Transition Outlook 2023 - DNV, 2023

[3] ISO 8217 - Petroleum products - Fuels (class F) - Specifications of marine fuels, 5th edition, 2017

[4] EN 14214:2012+A2:2019 - Liquid petroleum products. Fatty acid methyl esters (FAME) for use in diesel engines and heating applications. Requirements and test methods,

[5] ANP, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Resolução ANP Nº903 de 18.11.2022

[6] Bunker com conteúdo renovável – Resultados laboratoriais (Relatório Parcial). Petrobras: Relatório Técnico Petrobras, 2022.

[7] IP 541: Determination of ignition and combustion characteristics of residual fuels - Constant volume combustion chamber method, Energy Institute, 2006.

[8] N.N. 2011. Fuel Quality Guide – Ignition and Combustion. CIMAC Recommendations.

[9] Teste de Campo de bunker com biodiesel (Relatório Parcial). Petrobras: Relatório Técnico Petrobras, 2023.

[10] Teste de Campo de bunker com biodiesel (Relatório Parcial). Petrobras: Relatório Técnico Petrobras, 2023.

[11] Teste de Campo de bunker com biodiesel (Relatório Parcial). Petrobras: Relatório Técnico Petrobras, 2024.

[12] Roadmap for the Transition of the Maritime Segment – Alternative Fuels - Seminário BNDES-FGV Transição Energética no Mar, Rio de Janeiro, Brasil, 2024.

[13] Maritime Fuels with Renewable Content - ABS Forum, Rio de Janeiro, Brasil, 2024.

[14] Transição no segmento marítimo – Uma visão sobre os combustíveis - 3º Congresso da Rede Brasileira de Bioquerosene e Hidrocarbonetos Sustentáveis para Aviação, Foz do Iguaçu, Brasil, 2024.

[15] Testes de campo com misturas de bunker com biodiesel - SOBENA, Rio de Janeiro, Brasil, 2024.

[16] Unified Interpretations to MARPOL Annex VI - IMO Circular MEPC.1/Circ.795/Rev.6, 2022.

[17] ANP, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Autorização ANP Nº402 de 12.07.2024.

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