



# Study on Emission Characteristics of Biofuel Application in Low-Speed Marine Engines

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**Abstract.** This study investigates the emission characteristics of B24 low-sulfur biofuel (24% FAME + 76% LSFO) compared to marine low-sulfur fuel oil in low-speed marine diesel engines. Emissions of carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), total hydrocarbons (HC), and black carbon (BC) were evaluated under different load conditions in propulsion test modes. The results demonstrate that B24 fuel offers significant advantages in reducing CO<sub>2</sub>, CO, HC, and BC emissions, particularly under low to medium load conditions, although its NO<sub>x</sub> emissions were slightly higher than conventional fuel. A comprehensive life cycle analysis reveals that B24 fuel, derived from renewable resources with a lower carbon footprint, exhibits greater environmental friendliness and emission reduction potential, providing a viable solution for green transformation in marine propulsion systems.

**Keywords:** biofuel; characteristics; analysis; Marine diesel engines

## 1 Introduction

Global climate change and environmental pollution are becoming increasingly severe. In particular, the widespread use of traditional fossil fuels in energy consumption and emission structures is one of the main causes of global warming and air pollution [1]. The shipping industry, as a critical component of the global transportation system, burns vast amounts of heavy fuel oil and diesel annually, producing significant quantities of carbon dioxide (CO<sub>2</sub>), sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), and particulate matter (PM) [2]. These emissions not only exacerbate climate change but also severely impact marine ecosystems and the air quality of coastal cities.

To address global warming, the International Maritime Organization (IMO) introduced the Sulphur Cap 2020 policy in 2020, limiting the sulfur content of marine fuel to no more than 0.5%. This policy has significantly increased the demand for alternative energy in the shipping industry, particularly stimulating interest in low-sulfur, low-carbon biofuels [3]. As a renewable and clean alternative fuel, biofuel oil has become a potential solution for marine propulsion systems due to its environmental advantages and broad application prospects.

Low-speed marine diesel engines, known for their efficiency and durability, are widely used in maritime vessels. However, environmental concerns associated with traditional fossil fuels have driven the exploration of novel biofuels suitable for low-speed diesel engines. The primary sources of biofuels include renewable resources such as plant oils, animal fats, and waste cooking oils. These materials can be processed into biodiesel (e.g., fatty acid methyl esters, FAME) or hydrotreated into hydrotreated vegetable oil (HVO). The carbon dioxide produced during their combustion can be reabsorbed through photosynthesis, achieving carbon neutrality and effectively reducing greenhouse gas emissions over their full lifecycle [4]. Moreover, biofuels have extremely low sulfur content, resulting in much lower sulfur oxide emissions during combustion compared to traditional fossil fuels. This can significantly mitigate the impacts of ship emissions on marine acidification and air pollution [5].

Therefore, studying the emission characteristics of biofuels in low-speed marine diesel engines is of great importance for promoting the green transformation of the shipping industry.

## 2 Experimental Plan

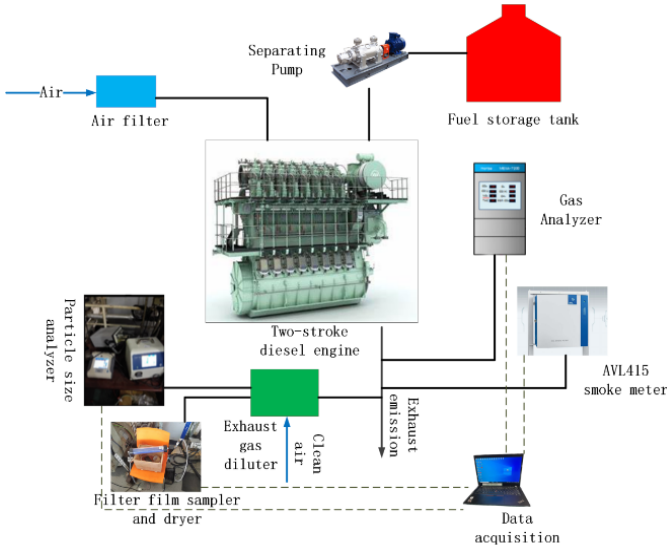
The experiment was conducted at the Automation Engine Room Laboratory of Shanghai Maritime University using a MAN B&W 6S35ME-B9 low-speed diesel engine (the main technical parameters of the engine are shown in Table 1) as the test target. Bench tests were performed under five different load conditions in propulsion test mode: 25%, 50%, 55%, 90%, and 100%. The fuels tested were a blend of 24% FAME and 76% LSFO (B24 low-sulfur biofuel) and marine low-sulfur fuel oil. Emissions of NO<sub>x</sub>, CO<sub>2</sub>, CO, THC (total hydrocarbons), and black carbon were measured and compared between the two fuels. The total test duration exceeded 200 hours, with 94 hours dedicated to testing each biofuel. The engine parameters under different load conditions in propulsion test mode are listed in Table 2. The experimental workflow is illustrated in Figure 1.

**Table 1.** Main technical parameters of the 6S35ME-B9 diesel engine.

Parameter	Value
Engine type	Two-stroke, 6-cylinder
Cylinder bore (mm)	350
Stroke (mm)	1, 550
Rated speed (rpm)	142
Rated power (kW)	3, 570
Nominal power (kW)	3, 250

**Table 2.** Five test load conditions in propulsion test mode.

Load condition (%)	Speed (rpm)	Power (kW)	Torque (kN·m)
25%	89	895	98
50%	112	1,785	160
75%	129	2,677	206
90%	138	3,213	234
100%	142	3,570	248



**Fig. 1.** Experimental workflow.

After the engine load stabilizes, all measurement devices should record data within the same time frame, with each test condition maintained for no less than 30 minutes. NO<sub>x</sub>, CO<sub>2</sub>, CO, and THC emissions were measured by using a HORIBA PG 350 gas analyzer, while black carbon was measured with an AVL 415SE smoke meter. The experimental equipment and facilities met the requirements for evaluation tests. The fuels used for comparison included a blend of 24% FAME and 76% LSFO (B24 low-sulfur biofuel) and marine low-sulfur fuel oil. The test fuels were supplied by Shanghai Zhongran Marine Fuel Co., Ltd.

### 3 Emission Test Results

At the 50th session of the Marine Environment Protection Committee (MEPC), the International Maritime Organization (IMO) adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, marking a new chapter in the decarbonization of international shipping. This strategy specifies the intensity of emission reductions required for international shipping, emphasizing improvements in the energy efficiency of new

ships, reductions in carbon intensity, and the adoption of zero- or near-zero GHG emission technologies, fuels, and/or energy sources, to achieve net-zero GHG emissions around 2050. Furthermore, the strategy outlines two milestone checkpoints in 2030 and 2040 to assess the phased progress of GHG emission reductions in international shipping.

Emission testing quantitatively evaluates the CO<sub>2</sub> emissions and overall GHG emissions of B24 low-sulfur biofuel. To analyze the impact of B24 low-sulfur biofuel on the emission performance of low-speed marine diesel engines, a comparative analysis was conducted by using marine low-sulfur fuel oil as a baseline under propulsion test mode.

Since the study focuses on large ship engines, emission test indicators are measured by using power-based emission factors. Power-based emission testing calculates emissions based on the engine's power output, meaning the amount of emissions is directly related to the engine's output power (e.g., kilowatts). This method is commonly used to assess engine emissions under different load conditions, particularly for measuring emissions from high-power engines.

### 3.1 CO<sub>2</sub> Power-Based Emission Factor Test Results

Figure 2 illustrates the CO<sub>2</sub> emissions of B24 low-sulfur biofuel and marine low-sulfur fuel oil under varying engine load conditions, revealing a consistent trend of decreasing emissions as the engine load increases. At 25% load, marine low-sulfur fuel oil emits slightly more CO<sub>2</sub> than B24 low-sulfur biofuel, indicating a marginal difference in performance at lower loads. However, as the load increases to 50%, 75%, and 100%, the CO<sub>2</sub> emissions of marine low-sulfur fuel oil become either lower than or comparable to those of B24 low-sulfur biofuel. At high engine loads, specifically 100%, the emissions of the two fuels are nearly identical, demonstrating that the performance gap diminishes as the engine operates at higher capacities.

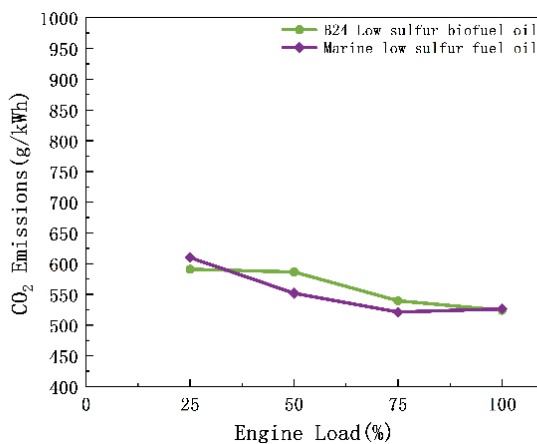


Fig. 2. CO<sub>2</sub> power-based emission factor test results.

This trend underscores the potential of marine low-sulfur fuel oil to perform on par with B24 low-sulfur biofuel in terms of CO<sub>2</sub> emissions under high-load conditions. Furthermore, the observed similarities in emission performance at higher loads suggest that both fuels can be viable alternatives for reducing carbon emissions in marine applications, especially when engines operate near maximum efficiency. These findings highlight the importance of load-dependent emission assessments to fully evaluate the environmental benefits of alternative fuels in the marine and industrial sectors.

### 3.2 NO<sub>x</sub> Power-Based Emission Factor Test Results

Figure 3 illustrates the nitrogen oxide (NO<sub>x</sub>) emissions of B24 low-sulfur biofuel and marine low-sulfur fuel oil across varying engine load conditions, demonstrating noticeable variations in emission patterns between the two fuels. At 25% load, B24 low-sulfur biofuel emits approximately 18 g/kWh of NO<sub>x</sub>, which is slightly higher than the 17 g/kWh emitted by marine low-sulfur fuel oil. This indicates a marginally better performance of marine low-sulfur fuel oil at low-load conditions. As the engine load increases to 50%, both fuels experience a significant reduction in NO<sub>x</sub> emissions. Marine low-sulfur fuel oil drops to approximately 14 g/kWh, outperforming B24 low-sulfur biofuel, which emits around 15 g/kWh. This stage highlights the ability of both fuels to reduce emissions significantly at mid-range loads, with marine low-sulfur fuel oil demonstrating superior performance.

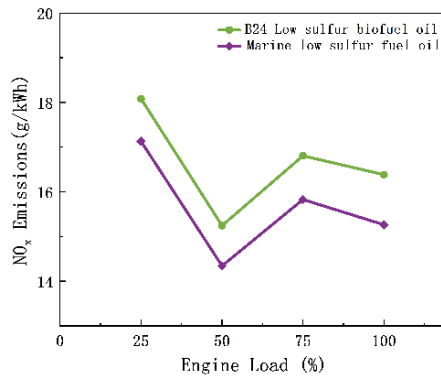


Fig. 3. NO<sub>x</sub> power-based emission factor test results.

At 75% load, the NO<sub>x</sub> emissions of both fuels rise again, with B24 low-sulfur biofuel reaching 18 g/kWh, noticeably higher than marine low-sulfur fuel oil, which emits 16 g/kWh. This trend suggests that the emission advantages of marine low-sulfur fuel oil are maintained even as engine loads increase. Finally, at 100% load, the NO<sub>x</sub> emissions slightly decrease compared to 75% load, but B24 low-sulfur biofuel remains at around 17 g/kWh, still higher than marine low-sulfur fuel oil, which emits approximately 15 g/kWh. These consistent differences across load conditions underscore that marine low-sulfur fuel oil tends to generate less NO<sub>x</sub> emissions than B24 low-sulfur biofuel, particularly under medium and high-load conditions.

Overall, the results highlight that while both fuels exhibit emission reductions at specific load ranges, marine low-sulfur fuel oil maintains a clear advantage in controlling nitrogen oxide emissions. This makes it a more environmentally favorable option, especially in applications where engines operate at higher loads. Furthermore, these findings emphasize the importance of evaluating fuel performance under varying operational conditions to better understand their environmental impacts and identify the most suitable options for reducing air pollution in the marine and industrial sectors.

### 3.3 HC Power-Based Emission Factor Test Results

Figure 4 illustrates the hydrocarbon (HC) emissions of B24 low-sulfur biofuel and marine low-sulfur fuel oil under varying engine load conditions, revealing clear differences in their emission profiles. Across all load conditions, the HC emissions of B24 low-sulfur biofuel are consistently lower than those of marine low-sulfur fuel oil, showcasing its superior emission control performance. This difference is particularly evident at low to medium engine loads (25%-50%), where the HC emissions of B24 low-sulfur biofuel approach nearly zero. This demonstrates the biofuel's remarkable ability to minimize hydrocarbon emissions at these load levels. In contrast, the HC emissions of marine low-sulfur fuel oil remain relatively higher, ranging between 0.1 and 0.2 g/kWh, indicating less effective emission control.

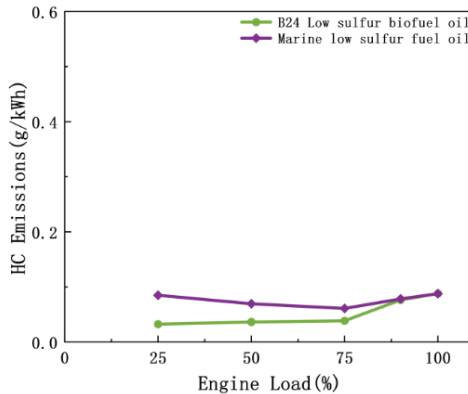


Fig. 4. HC power-based emission factor test results.

The significantly lower emissions of B24 low-sulfur biofuel may be attributed to its more complete combustion characteristics, which enable a reduction in unburned hydrocarbons. This advantage highlights its potential as a cleaner and more environmentally friendly fuel alternative. Furthermore, the consistent reduction in HC emissions observed with B24 low-sulfur biofuel under all load conditions underscores its viability in promoting sustainable energy practices, especially in applications where stringent emission standards are required. These findings emphasize the importance of selecting fuels with advanced combustion properties to mitigate environmental pollution and support global efforts toward cleaner energy solutions.

### 3.4 CO Power-Based Emission Factor Test Results

Figure 5 illustrates the carbon monoxide (CO) emissions of B24 low-sulfur biofuel and marine low-sulfur fuel oil under different engine load conditions, highlighting a consistent difference in their emission performance. Across all engine loads, the CO emissions of B24 low-sulfur biofuel are consistently lower than those of marine low-sulfur fuel oil, underscoring its superior capability in reducing CO emissions. For marine low-sulfur fuel oil, the CO emissions gradually decrease as the engine load increases, reflecting improved combustion efficiency at higher loads. However, a slight increase is observed at 100% load, which suggests a potential limitation in its emission reduction performance under maximum engine capacity.

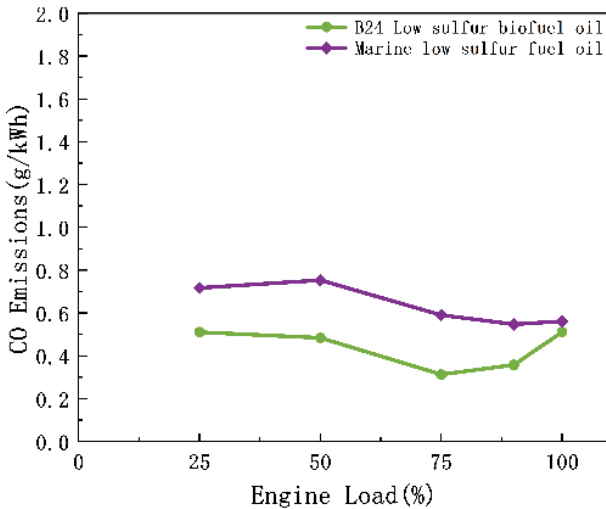


Fig. 5. CO power-based emission factor test results.

In contrast, the CO emissions of B24 low-sulfur biofuel reach their lowest level at medium load (75%), demonstrating optimal performance in emission control and combustion efficiency at this stage. However, similar to marine low-sulfur fuel oil, a slight increase in CO emissions is also observed at 100% load. This trend indicates that while both fuels show slight limitations in emission control at maximum loads, B24 low-sulfur biofuel consistently performs better across all load ranges.

The significantly lower CO emissions of B24 low-sulfur biofuel can be attributed to its more efficient and complete combustion process, which reduces the production of carbon monoxide. This highlights its potential as a cleaner and more environmentally friendly alternative, especially for applications requiring stringent emission standards. Furthermore, the performance of B24 low-sulfur biofuel across different load conditions emphasizes its suitability for scenarios with higher demands for emission reduction and environmental protection. These findings reinforce the importance of selecting advanced fuels to achieve more sustainable and environmentally conscious energy solutions.

### 3.5 Black Carbon Power-Based Emission Factor Test Results

Figure 6 illustrates the black carbon (BC) emissions of B24 low-sulfur biofuel and marine low-sulfur fuel oil across varying engine load conditions, revealing a general trend of decreasing emissions as engine load increases. At low load (25%), the BC emissions of B24 low-sulfur biofuel are higher than those of marine low-sulfur fuel oil, likely due to incomplete combustion at lower temperatures or suboptimal conditions. As the engine load increases to medium levels (50%-75%), the BC emissions of both fuels reach their lowest levels and are nearly identical, reflecting improved combustion efficiency under these conditions. However, at high load (100%), both fuels exhibit a slight increase in BC emissions, with B24 low-sulfur biofuel maintaining slightly better performance in emission reduction compared to marine low-sulfur fuel oil.

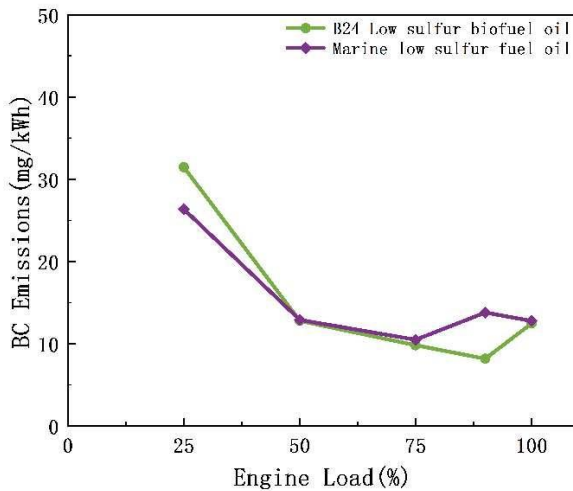


Fig. 6. BC power-based emission factor test results.

The superior performance of B24 low-sulfur biofuel at medium to high loads underscores its potential as an effective fuel for minimizing black carbon emissions in demanding operational scenarios. This could be attributed to its more complete combustion process under higher temperatures and pressures, which helps reduce particulate matter formation. Despite this advantage, the relatively higher BC emissions at low loads indicate that further optimization of B24 low-sulfur biofuel is necessary to enhance its combustion efficiency and emission control in low-load conditions.

Overall, these findings highlight the importance of tailoring fuel properties and combustion strategies to specific operational conditions. While B24 low-sulfur biofuel demonstrates significant potential for black carbon reduction, especially at high loads, addressing its performance limitations at lower loads would further enhance its environmental benefits and applicability in a wider range of scenarios. This reinforces the need for ongoing research and development to optimize the use of alternative fuels in reducing black carbon emissions and mitigating environmental impacts.

## 4 Conclusion

From a life cycle perspective, there are significant differences in the greenhouse gas (GHG) emission reduction potential between B24 low-sulfur biofuel and marine low-sulfur fuel oil. Life cycle analysis (LCA) takes into account the carbon footprint of each stage of the fuel's life cycle, from raw material production, manufacturing, and transportation to use and disposal. B24 low-sulfur biofuel is produced from biomass resources such as plant oils and waste cooking oils. During the growth of these raw materials, a large amount of CO<sub>2</sub> is absorbed through photosynthesis, which can partially offset the CO<sub>2</sub> emissions during the combustion process in the life cycle assessment. In contrast, marine low-sulfur fuel oil is derived from fossil fuels, and its extraction and refining processes are associated with higher carbon emissions, reducing its effectiveness in GHG emission reduction.

In the fuel manufacturing and transportation stages, although B24 low-sulfur biofuel may require more processing steps, its overall carbon emissions are lower due to the reliance on renewable energy during production. In comparison, the refining and transportation of marine low-sulfur fuel oil consume large amounts of energy, further increasing carbon emissions. In the usage stage, the bench tests show that B24 low-sulfur biofuel offers certain emission reduction advantages in terms of CO<sub>2</sub>, CO, HC, and black carbon, especially at low to medium loads. However, its NO<sub>x</sub> emissions are slightly higher, which may contribute to local air pollution, though this has a relatively small impact on global GHG emissions.

In the disposal stage, the residue from B24 low-sulfur biofuel is more easily biodegradable and, under certain conditions, can be recycled or converted into bio-based products, reducing environmental pollution. In contrast, the residue from marine low-sulfur fuel oil usually requires special treatment, resulting in additional carbon emissions. Therefore, from a life cycle perspective, B24 low-sulfur biofuel has greater potential for GHG emission reduction and environmental friendliness, making it a more sustainable fuel option.

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