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Key areas of decarbonisation in the maritime industry

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Abstract. The study aimed to assess the environmental impacts of alternative fuels in the maritime sector, particularly their potential for global warming, ocean acidification, eutrophication and marine toxicity. To this end, a comparative analysis of different fuels was conducted, including liquefied natural gas, green methanol products, ammonia, biofuels and traditional heavy fuel oil. The results showed that liquefied natural gas, despite its lower CO_2 emissions, had a high climate impact due to methane leaks, with a global warming potential of 0.18 to 0.22 kg CO_2-eq/MJ. Green biofuels, particularly methanol, had the lowest global warming potential (0.016-0.020 kg CO_2-eq/MJ), but their direct CO_2 emissions during combustion remained high. Ammonia, as a carbon-free fuel, reduced CO_2 emissions but produced significant amounts of nitrous oxide (N_2O), which has a significant impact on the climate balance. The ocean acidification potential for heavy fuel oil was 0.18 kg SO_2-eq/MJ, and for ammonia, 0.10 kg SO_2 eq/MJ. Eutrophication analysis showed that ammonia and nitrous oxide emissions significantly increase nitrogen levels in marine ecosystems, which can cause algae growth. The toxicity of different fuels showed that ammonia has the greatest potential to harm marine organisms, even at low concentrations. The practical significance of the results is determined by the need for a comprehensive assessment of the environmental impact of the transition to alternative fuels in shipping, which can be used by maritime transport authorities, environmental agencies, seaports, and companies involved in the development and implementation of technologies for decarbonising shipping and reducing the environmental impact of maritime activities

Keywords: alternative fuels; environmental impact; global warming; acidification potential; ammonia; methanol

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Introduction

Maritime transport is one of the main sources of global greenhouse gas emissions, which significantly affects the planet's climate stability. It contributes not only to increased CO_2 concentrations in the atmosphere, but also to the release of other harmful substances such as nitrogen oxides (NO_x), sulphur (SO_x) and particulate matter (PM), which negatively affect air quality and marine ecosystems. In addition, water pollution and ocean acidification are among the main factors disrupting biogeochemical cycles, particularly the carbon and nitrogen cycles, which threaten marine life. This necessitates the urgent adaptation of the maritime industry to new environmental standards, in particular the decarbonisation of the maritime sector. Under these conditions, a review of the literature was used to compare the results of different research approaches and derive consistent guidelines for practice.

D.M. Reshetkov & N.L. Pavlova (2022a) reviewed key initiatives to reduce greenhouse gas emissions in seaports. The study noted the significance of renewable energy sources and alternative fuels in reducing the environmental impact of maritime transport. The study examined initiatives involving the installation of technologies to reduce CO_2 emissions and the transition to more sustainable energy sources. In another paper, D.M. Reshetkov & N.L. Pavlova (2022b) examined global initiatives related to the decarbonisation of maritime transport, in particular the introduction of alternative fuels such as liquefied natural gas (LNG) and biofuels, and their role in reducing greenhouse gas emissions. The study noted that national and international organisations are already working to create a regulatory framework for such initiatives. The significance of digitalisation and automation of processes in the maritime sector for effective decarbonisation was considered by B. Kormych & T. Averochkina (2024). The study noted that the use of digital technologies can be used for the effective management of seaports and the reduction of CO_2 emissions, which is a substantial step in the decarbonisation process.

A systematic review of technological and operational measures in shipping aimed at achieving the International Maritime Organisation's 2050 targets was conducted by G. Mallouppas & E.A. Yfantis (2021). The study examined in detail alternative fuel technologies, such as methanol and ammonia, as well as innovative technologies, including rotary sails and wind-assisted propulsion, to reduce CO_2 emissions and other pollutants. E. Kostidi & D. Lyridis (2024) emphasised ports as substantial elements of maritime decarbonisation. The study conducted a bibliometric review that identified promising areas for reducing emissions in ports, such as the use of renewable energy sources and technologies to optimise energy consumption. An overview of the role of alternative fuels in the maritime industry, highlighting opportunities and technological limitations (e.g., methane leaks in LNG), was provided by V.A. dos Santos *et al.* (2022). The study emphasised the potential of biofuels and ammonia as fuels in shipping, as well as their ability to reduce greenhouse gas emissions compared to traditional fuels.

R. Bhattacharyya *et al.* (2023) examined the role of nuclear energy in the decarbonisation of the maritime industry. The study analysed the possibility of using nuclear energy to reduce CO_2 emissions in maritime transport and outlined the prospects and challenges for its integration into modern ships. Studying port decarbonisation strategies, A. Raihan *et al.* (2025) noted that one of the main trends is the use of low-carbon technologies, including hybrid systems and wind assistance, to reduce CO_2 emissions in port areas. The study noted the relevance of the integration of these technologies with modern port management systems. T. Ma *et al.* (2025) analysed modern research trends in decarbonisation of the maritime industry, focusing on emerging technologies such as the use of hydrogen fuels, biofuels and electrification of maritime transport. The scientists also proposed a structural analysis of decarbonisation trends, in particular, the use of various types of alternative fuels. A bibliometric study by

G. Xiao *et al.* (2025), which covered the use of digital technologies in shipping for decarbonisation, revealed a significant increase in publications on digital twins, blockchain systems and the Internet of Things (IoT). The study noted that despite the high interest in digital tools, their impact on actual CO_2 emissions remains rather limited.

Decarbonisation of the maritime sector is an integral part of combating climate change and achieving sustainable development. A review of research and initiatives has shown that decarbonising maritime transport requires a comprehensive approach that includes the use of alternative fuels, the introduction of innovative technologies such as wind-assisted propulsion and hybrid systems, and the application of digital technologies for energy management and emissions reduction. These initiatives have the potential to reduce the negative impact of maritime transport on the climate, ocean acidification and marine ecosystems, as well as to improve the maritime industry's resilience to environmental challenges.

The study aimed to analyse the main directions of decarbonisation of maritime transport using alternative fuels and innovative technologies, in particular their impact on ecosystems and climate change. To achieve this goal, the following tasks were set: to analyse the environmental effects of using various alternative fuels on global warming, ocean acidity and biogeochemical cycles; to investigate the toxic effects of new fuels on marine organisms, in particular fish, shrimp and phytoplankton; to assess the risks associated with the environmental and climate impacts of new technologies in maritime transport.

Materials and Methods

A study of the environmental impact of using alternative fuels in the global maritime industry was conducted for the period 2000-2025 using several environmental assessment methods to determine the impact of different types of fuel on the environment and marine ecosystems. To achieve this goal, Life Cycle Assessment (LCA) and Ecological Risk Assessment (ERA) methods were used, as well as methods that assess the impact on marine ecosystems. All methods were aimed at a comparative analysis of the environmental characteristics of fuels such as liquefied natural gas (LNG), methanol, ammonia, biofuels and traditional heavy fuel oil.

To assess the environmental impact of alternative fuels, the LCA method was used, which made it possible to determine the overall environmental impact of fuel at all stages of its life cycle, from raw material extraction to fuel use on board a ship. For each type of fuel, the boundaries of the system were defined, covering the stages of extraction, transportation, storage, consumption and emissions associated with its combustion. One MJ of energy obtained from fuel combustion was chosen as the unit of operation. The inventory collected data on greenhouse gas emissions such as CO_2, CH_4, NO_x, SO_x, NH_3, as well as particulate matter (PM). Primary data on emissions from liquefied natural gas and traditional fuels were obtained from SEA\LNG Limited & Society for Gas as a Marine Fuel Limited (2019), N. Pavlenko *et al.* (2020). The analysis of emissions from green methanol and ammonia was based on data from H. Güleroğlu & Z. Yumurtacı (2025) and O. Guyon *et al.* (2025). Additional information on the pollutant profile is provided by studies by J. Hansson *et al.* (2019), R. Laursen *et al.* (2022), and V. Dulière *et al.* (2020). These data assessed the impact of different types of fuel on environmental categories such as global warming (GWP100), ocean acidification, eutrophication, toxicity to biota, and climate change. The environmental impact assessment was conducted using specialised SimaPro software, which was used to model the fuel life cycle and calculate the total impact on the environment.

The acidification potential of the ocean was assessed based on modelling the transformation and atmospheric deposition of the main acid-forming compounds, sulphur oxides (SO_x) and nitrogen oxides (NO_x). For each type of fuel, the contribution to acidification was calculated based on SO_x emissions (for heavy fuel oil and other carbon fuels) and NO_x emissions (for ammonia and fuels with high combustion temperatures). The quantitative assessment of acidification potential was expressed in SO_2 equivalents per unit of energy (kg SO_2-eq/MJ) according to standard LCA protocols (Hansson *et al*., 2019; Campbell *et al*., 2021). The direct impact on seawater pH from the discharge of alkaline effluents from exhaust gas treatment systems (scrubbers) was assessed separately, using monitoring and modelling data on the chemical composition of effluents (Stripple & Zhang, 2019).

The ERA method was used to analyse the toxicity of fuel and its combustion products, such as nitrous oxide (N_2O) for ammonia and methanol, and methane for LNG. ERA involved identifying hazards arising from fuel use and determining the impact of toxic substances on marine ecosystems, particularly plankton, fish and benthic organisms. The pathways of exposure were determined through emissions to the atmosphere, which enter the ocean and biota through the deposition of toxic compounds. The ERA also included determining the probability of environmental impacts such as changes in ocean pH, toxicity to organisms and disruption of biodiversity. As a result, pollution levels for different types of fuel were calculated, and the potential threat to marine ecosystems was assessed.

Various methods were used to assess the impact of alternative fuels on marine ecosystems, including monitoring changes in water pH, toxic effects on marine organisms (plankton, fish, benthic organisms), and assessment of the impact on biodiversity. pH change was assessed based on ocean acidification potential, which was determined through SO_x emissions for heavy fuel oil and NO_x emissions for ammonia (Campbell *et al*., 2021). The impact of emission cleaning technologies, in particular scrubbers, on the marine environment was analysed separately, with data obtained from the source (Stripple & Zhang, 2019). For each fuel type, the analysis examined how emissions of these pollutants alter ocean acidity and how this affects marine ecosystems. The toxic effects on marine organisms were also assessed using LC_{50} (lethal concentration for 50% of organisms) and EC_{50} (concentration at which 50% of organisms experience development or growth) indicators. The effects on fish, shrimp, oysters and other marine organisms were assessed, as well as the consequences for phytoplankton (Miller *et al*., 1990). In addition, secondary pollutants such as nitrates formed as a result of ammonia combustion, which have a chronic impact on marine ecosystems, in particular on algae growth and biodiversity decline, were studied (Wang *et al*., 2022).

Standard statistical analysis was used to process the data obtained, in particular t-tests to compare the average values between different types of fuel and their environmental impacts. The level of statistical significance was assessed using p-values, where the significance level α was set at 0.05. To analyse variations and compare environmental effects depending on fuel type, appropriate statistical methods were used to accurately assess the difference in impacts and identify the most environmentally efficient fuels for the maritime industry.

Results

Global warming potential (GWP100) of different types of fuel

An analysis of the global warming potential of alternative marine fuels revealed significant differences between fuels due to the specific nature of their emissions throughout their entire life cycle. For LNG, the study determined that despite lower direct carbon dioxide emissions during combustion compared to traditional fuel oil, the climate advantage was largely offset by methane leaks. The global warming potential over a 100-year horizon (GWP100) for LNG ranged from 0.18 to 0.22 kg CO_2-eq/MJ. This range was due to the high global warming potential of methane, which is 28-36 times higher than that of CO_2, and varied depending on the level of leaks during production, transportation and use (SEA\LNG Limited & Society for Gas as a Marine Fuel Limited, 2019; Pavlenko *et al*., 2020).

The "Green" methanol, obtained from renewable raw materials, showed significantly lower values. Its GWP100 was estimated to range from 0.016 to 0.020 kg CO_2-eq/MJ for methanol produced from renewable energy sources such as wind or solar energy. However, direct CO_2 emissions from fuel combustion in marine engines remained high, indicating the need for compensation through a closed carbon cycle to achieve climate neutrality (Güleroğlu & Yumurtacı, 2025; Guyon *et al.*, 2025).

Ammonia, being a carbon-free fuel, was characterised by zero direct CO_2 emissions. However, the study identified a key problem related to incomplete combustion, which led to the formation of nitrous oxide (N_2O). Since the global warming potential of N_2O exceeds that of CO_2 by 265-298 times, even minor emissions have a significant impact on the overall balance. In the absence of optimised engines and exhaust gas cleaning systems, the total GWP100 for ammonia could reach 0.16-0.20 kg CO_2-eq/MJ. As for biodiesel (HVO) and other biofuels, their net CO_2 balance was close to zero, as confirmed by life cycle analysis data. However, GWP100 values showed a significant range from 0.02 to 0.30 kg CO_2-eq/MJ (Guyon *et al.*, 2025). This variability was directly related to the type of feedstock used for production and the effects of indirect land use changes, which could significantly increase the overall greenhouse footprint (Fig. 1).

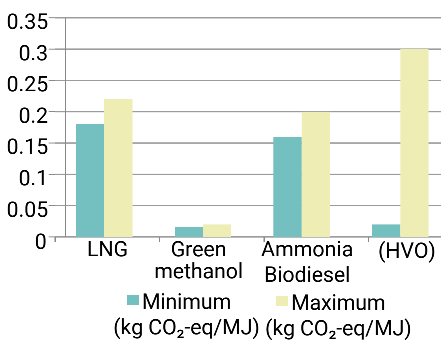

Figure 1. *Comparison of average GWP100 values for different alternative marine fuels*

Source: compiled by the author based on N. Pavlenko *et al.* (2020), O. Guyon *et al.* (2025), H. Güleroğlu & Z. Yumurtacı (2025)

Thus, the analysis of global warming potential (GWP100) for promising types of marine fuel revealed significant heterogeneity in their climate impact. Despite the rejection of carbon, all alternative fuels showed significant compromises. For LNG, methane leaks were the main factor; for ammonia, it was nitrous oxide formation; and for biofuels, it was high dependence on the raw material base and the consequences of land use changes. Even "green" methanol, which had the lowest scores, required further consideration of direct CO_2 emissions. The results confirmed that switching to any of the fuels considered is not an unconditional solution for mitigating the climate impact of shipping and requires a comprehensive assessment of all greenhouse gases throughout the entire life cycle.

Acidification potential of the ocean and eutrophication potential

A detailed analysis of the potential for ocean acidification revealed complex interactions between various pollutants produced by different types of fuel and technologies. For traditional heavy fuel oil with high sulphur content, the main mechanism of acidification was emissions of sulphur oxides (SO_x). As a result of photochemical reactions in the atmosphere, SO_x was oxidised to sulphur trioxide (SO_3), which, interacting with atmospheric moisture, formed sulphuric acid aerosols (H_2SO_4). Further atmospheric leaching of these aerosols by rainfall led to the entry of hydrogen ions (H^+) and sulphate ions (SO_4^{2-}) into the surface layers of the ocean, lowering their pH. The quantitative assessment of the acidification potential for heavy fuel oil was 0.18 kg SO_2-eq/MJ, confirming its significant contribution to global acidification (Hansson *et al.*, 2019).

When using carbon-free fuels, in particular ammonia, the profile of pollutants changed significantly. Although SO_x emissions were completely absent, the main driver of acidification was nitrogen oxide (NO_x) emissions, which were formed during high-temperature combustion in internal combustion engines. In the atmosphere,

NO_x oxidised to nitrogen dioxide (NO_2), which reacted with hydroxyl radicals (OH•) to form nitric acid (HNO_3). This acid, settling on the ocean surface, dissociated with the release of H^+ ions and nitrate ions (NO_3^-). Calculations showed that the acidification potential for ammonia reached 0.10 kg SO_2-eq/MJ, which rendered it comparable in impact to low-sulphur fuels, but with a different chemical mechanism (Laursen *et al*., 2022).

The impact of scrubber technology (exhaust gas cleaning systems) was studied separately. The study determined that when an open scrubber system was used to remove SO_x from flue gases, pollutants were transferred from the gas phase to the water phase. The discharge of these alkaline effluents, containing sulphites, sulphates and heavy metals, directly into the marine environment caused sharp local changes in pH. In contrast to the global phenomenon of acidification from atmospheric deposition, this effect was localised, creating areas of chemical stress in port waters and shipping lanes where massive discharges of wastewater occurred. The concentration of pollutants in effluents could exceed background values by tens of times (Dulière *et al*., 2020) (Table 1).

Table 1. *Comparative indicators of acidification potential and main chemical mechanisms of impact*

Influence source	Primary chemical agent	Reaction product	Acidification potential (kg SO_2-eq/MJ)
Heavy fuel oil	SO_x	H_2SO_4	0.18
Ammonia	NO_x	HNO_3	0.10
Scrubbers (drains)	Sulphites/Sulphates	Alkaline effluents (local pH increase)	Not measured in SO_2-eq. (direct chemical pollution)

Source: compiled by the author based on H. Stripple & Y. Zhang (2019), V. Dulière *et al.* (2020), M. Campbell *et al.* (2021)

The assessment showed that the potential for ocean acidification from maritime activities was shaped by several interrelated pathways. Traditional fuel oil remained the main source of acidification through SO_x emissions, while the transition to ammonia shifted this impact to NO_x emissions with similar harmful effects. At the same time, scrubber technology used to reduce atmospheric emissions created an additional burden on the marine environment through the direct discharge of chemically active effluents. Thus, various options for decarbonising ship energy did not eliminate the problem of acidification, but only transformed its manifestations, creating both global and localised threats to marine ecosystems.

A detailed analysis of the eutrophication potential of marine activities revealed complex dynamics of nutrient inputs into marine ecosystems, particularly using new types of fuel. The most significant source of nitrogen pollution was found to be direct emissions of ammonia (NH_3) when used as a primary fuel. Unreacted ammonia entered the atmosphere, where it underwent transformation and transport over long distances. Further dry and wet deposition of nitrogen compounds on the ocean surface led to excessive input of bioavailable nitrogen into the marine environment. A quantitative assessment within the life cycle analysis showed that the eutrophication potential for ammonia was 0.065 kg PO_4-eq/MJ, which exceeded similar indicators for traditional carbon fuels. An additional contribution to eutrophication processes was made by gaseous emissions of nitrous oxide (N_2O), which was formed as a by-product of ammonia combustion in ship engines. After entering the atmosphere, N_2O underwent photochemical transformations to form nitrate compounds, which subsequently settled on the ocean surface. This process posed a particular threat to open water areas where the natural nutrient content was a limiting factor for phytoplankton growth. Extrapolation of the data showed that even at a concentration of N_2O in emissions of 0.3% of the total volume, its contribution to the overall eutrophication potential could reach 15-20% (Miller *et al.*, 1990).

A systematic study of the impact of ship discharges revealed their role as a significant source of local pollution. Analysis of ballast water composition showed the presence of nitrogen compounds in concentrations of 2.5-4.8 mg/l and phosphorus in concentrations of 0.3-0.7 mg/l. In areas with intensive shipping, this led to an increase in nitrate concentrations in coastal waters by 25-40% compared to background values (Miller *et al.*, 1990). The impact was particularly noticeable in the waters of large ports, where the accumulation of nutrients from effluents stimulated the growth of microscopic algae, in particular representatives of the genera *Alexandrium* and *Pseudo-nitzschia* (Table 2).

Table 2. *Comparative characteristics of eutrophication sources from marine activities*

Influence source	Influence mechanism	Primary components	Eutrophication potential	Spatial scale of impact
Ammonia (NH_3) emissions	Atmospheric precipitation	Nitrogen compounds	0.065 kg PO_4-eq/MJ	Regional (up to 500 km)
Nitrous oxide (N_2O) emissions	Atmospheric transformation and precipitation	Nitrate compounds	0.010-0.015 kg PO_4-eq/MJ	Global
Ballast water	Direct source	N, P, organic compounds	3.2-5.8 kg PO_4-eq./equivalent ballast water	Local (ports and coastline)
Domestic waste	Direct source	N, P, organic matter	0.8-1.2 kg PO_4-eq/day per vessel	Local (ports and coastline)

Source: compiled by the author based on D.C. Miller *et al.* (1990)

A study of the eutrophication potential of marine activities revealed the complex nature of the impact of various sources of nitrogen pollution. The use of ammonia as an alternative fuel created stable channels for the entry of bioavailable nitrogen into marine ecosystems through atmospheric deposition. At the same time, nitrogen oxide emissions and direct discharge of ship waste created an additional burden on coastal and ocean ecosystems. The results showed that the transition to nitrogen-containing fuels without adequate emission treatment and waste disposal systems could lead to a significant increase in eutrophication processes, especially in regions with intensive shipping.

Marine toxicity potential and comparative analysis of the environmental footprint of innovative technologies

Research into the marine toxicity potential of alternative fuels and related emissions has revealed varying levels of threat to marine organisms. Experimental data on the acute toxicity of methanol to aquatic organisms showed LD_{50} values for fish species of 2,500-5,000 mg/L over a 96-hour exposure period. For invertebrates, particularly shrimp of the genus *Artemia*, the LC_{50} value was 7,800-12,000 mg/L. Calculations showed that a spill of 100 tonnes of methanol in the enclosed waters of the port could create local concentrations exceeding 1,500 mg/L, posing a threat to benthic organisms. Ammonia showed significantly higher toxicity compared to methanol. For most fish species, lethal LC_{50} concentrations ranged from 0.2 to 2.5 mg/L after 96 hours of exposure. Sensitive invertebrates, such as crab and oyster larvae, showed lethal effects at concentrations as low as 0.5-1.2 mg/L. Modelling of a large-scale ammonia spill of 500 tonnes showed that under conditions of limited water circulation, toxic concentrations could persist in a 5-metre-thick layer of water for 24-48 hours, creating a zone of complete marine organism mortality over an area of up to 5 km^2. Atmospheric deposition of nitrate compounds formed as a result of NO_x emissions had toxic effects of a different type. Chronic exposure to nitrates at concentrations of 25-40 mg/l caused developmental disorders in fish larvae and a decrease in phytoplankton diversity. Experiments have shown that nitrate concentrations above 50 mg/l inhibit the growth of macroalgae and coral polyps. In areas with intensive shipping, an increase in background nitrate concentrations to 15-20 mg/l was observed, which could cause sublethal effects in sensitive species (Wang *et al.*, 2022) (Table 3).

Table 3. *Toxicity parameters of various pollutants for marine organisms*

Contaminant	Test organism	Toxicity value	Value	Exposure duration
Methanol	Fish (*Oncorhynchus mykiss*)	LC_{50}	4.500 mg/l	96 hours
Methanol	Shrimp (*Artemia salina*)	LC_{50}	9.500 mg/l	48 hours
Ammonia	Fish (*Cyprinodon variegatus*)	LC_{50}	0.8 mg/l	96 hours
Ammonia	Oyster larvae (*Crassostrea gigas*)	LC_{50}	1.1 mg/l	48 hours
Nitrates	Fish larvae (*Danio rerio*)	EC_{50} (development disorders)	45 mg/l	72 hours
Nitrates	Phytoplankton (*Skeletonema costatum*)	EC_{50} (growth impairment)	60 mg/l	96 hours

Source: compiled by the author based on Y. Wang *et al.* (2022)

The assessment of marine toxicity potential revealed significant differences in the level of threat posed by different types of fuel and associated pollutants. Ammonia proved to be the most toxic, with a direct lethal effect on marine organisms even at low concentrations. Methanol showed moderate toxicity but posed a threat in large-scale spills. Atmospheric deposition of nitrates had a chronic effect, manifested in impaired development of marine organisms and changes in the structure of plankton communities. The results showed that the transition to alternative fuels required consideration not only of their greenhouse characteristics, but also of the potential consequences for marine ecosystems in the event of accidents and long-term operational impacts.

Research into the environmental effectiveness of innovative technologies has demonstrated significant potential for reducing anthropogenic pressure on marine ecosystems. The implementation of aerodynamic and hydrodynamic improvements, in particular Flettner rotors and anti-fouling systems (ALS), has resulted in fuel consumption reductions of 8-15%, depending on the type of vessel and operating conditions. On transatlantic routes, an average reduction in CO_2 emissions of 12% was recorded, which amounted to approximately 1,500 tonnes per year for a standard-sized vessel. SO_x emissions were reduced proportionally by 10-14% and NO_x emissions by 8-11%, which directly affected ocean acidification potential indicators. In addition, there was a 9-13% reduction in particulate matter (PM) emissions, which is relevant for maintenance of air quality in coastal areas. Hybrid energy systems demonstrated high efficiency in areas with special environmental requirements. When using rechargeable batteries for manoeuvring within ports and coastal areas, there was a sharp reduction in NO_x emissions by 94-98% compared to traditional diesel engine operation. Particulate matter emissions (PM2.5 and PM10) were reduced by 89-95%, significantly improving air quality in port cities. Analysis of data from large container ships showed that the use of hybrid systems for 1,200 hours per year prevented emissions of approximately 5.8 tonnes of NO_x and 0.9 tonnes of particulate matter per ship. In addition, a reduction in underwater noise levels of 12-15 dB was recorded, which reduced acoustic stress for marine life (Carjova *et al.*, 2025) (Table 4). An analysis of the environmental footprint of innovative technologies has demonstrated their significant effectiveness in reducing anthropogenic impact on the marine environment. Aerodynamic and hydrodynamic improvements have led to an overall reduction in all categories of emissions through reduced fuel consumption, while hybrid energy systems have demonstrated maximum effectiveness in the most vulnerable coastal areas. The results indicate that combining these technologies with low-carbon fuels can provide a synergistic effect in the decarbonisation of the maritime industry, minimising several types of environmental impact simultaneously.

Table 4. *Comparative effectiveness of innovative technologies in reducing emissions*

Technology	CO_2 emission reduction (%)	NO_x emission reduction (%)	SO_x emission reduction (%)	PM emission reduction (%)	Most efficient area
Flettner rotors	10-15	8-12	10-14	9-13	Open sea, areas with stable winds
ALS systems	8-12	7-10	8-12	8-11	High-speed sailing conditions
Hybrid systems	100 (in power supply mode)	94-98	95-99	89-95	Port waters, coastal areas

Source: compiled by the author based on K. Carjova *et al.* (2025)

Discussion

The results of the study confirmed the heterogeneity of the potential of various alternative fuels in reducing greenhouse gas emissions, which requires a comprehensive approach to their use in maritime transport. In particular, the use of liquefied natural gas has demonstrated advantages in reducing CO_2 emissions compared to traditional fuel oil, but the significant role of methane leaks, which greatly increase the potential for global warming, requires additional measures to minimise this risk. This aspect is consistent with the findings of V. Koilo (2024), who emphasised the need to ensure technological excellence in reducing methane emissions when using LNG to achieve effective decarbonisation of the maritime industry.

Analysis of "green" methanol obtained from renewable energy sources has shown a significantly lower impact on global warming, as confirmed by studies such as those by V.J. Jimenez *et al.* (2022), highlighting the advantages of renewable energy sources in the context of reducing emissions in maritime transport and improving the energy efficiency of ships. However, as noted in the study, the high dependence on CO_2 emissions from methanol combustion requires further attention to compensation through a closed carbon cycle, which is critical to achieving climate neutrality. As for ammonia, despite its near-zero CO_2 emissions, the presence of nitrous oxide (N_2O) as a combustion by-product significantly affects its climate potential. This observation is consistent with the study by E. Ejder *et al.* (2024), highlighting the need to develop technologies that reduce N_2O emissions in ammonia engines for effective decarbonisation of maritime transport. The researchers emphasised that ensuring proper control of incomplete combustion and improving the efficiency of dual-fuel engines is a step towards reducing the negative environmental impact of ammonia. Biofuels, in particular Hydrotreated Vegetable Oil (HVO), have the least impact on the climate, but significant variations in GWP100 from 0.02 to 0.30 kg CO_2-eq/MJ indicate that efficiency depends on the type of raw material. This correlates with the findings of a study by M. Lind *et al.* (2023), which noted the importance of developing standards for assessing the life cycle of biofuels to reduce their negative impact on the climate and marine ecosystems. The study highlighted that the incorporation of all stages of the biofuel life cycle would reduce their negative impact.

Decarbonising the maritime sector is a complex and multifaceted process that requires the integration of innovative technologies and strategies to reduce emissions at all stages, from fuel production to its consumption in shipping. Studies such as that by J.M.M. Prados *et al.* (2024) highlight the significance of strategies aimed at reducing CO_2 emissions and supporting a stable transition to a sustainable maritime industry by 2050. The results of the study on the potential of various alternative fuels for decarbonising the maritime industry support current scientific views on the need to develop and apply the latest technologies in the maritime sector. The study by D.R. Cunha *et al.* (2025) highlights the key challenges for decarbonising ports and the maritime industry, noting the significance of integrating renewable energy sources and alternative fuels into maritime transport to achieve sustainable development. The authors also highlighted the need to develop appropriate infrastructure and legislative support for the successful implementation of these initiatives.

Y. Wang & L.A. Wright (2021) examined the economic, technological and political challenges associated with the introduction of alternative fuels in the maritime sector. In particular, the study noted that the use of fuels such as methanol, ammonia and hydrogen has environmental potential but requires significant investment in technology and infrastructure. This is consistent with the findings of the current study, which states that when switching to alternative fuels, both positive and negative environmental impacts must be considered, including toxic effects and global warming potential. The use of hydrogen technologies for energy conservation in the maritime sector, which is one of the promising strategies for decarbonisation, has been studied by R. Jayabal (2025). The study also emphasised the significance of developing the appropriate infrastructure for hydrogen technologies, which reduces CO_2 emissions and contributes to the sustainable development of the industry. According to this, hydrogen is a key element of future efforts to combat climate change in the maritime sector, which is consistent with the results of a study that highlights the importance of hydrogen fuels in reducing global warming. The study by A.I. Ibokette *et al.* (2024) examines the regulatory and operational challenges of implementing zero-emission technologies in the US maritime industry. In particular, it highlights the need for improved legal regulations and government support to ensure effective decarbonisation. These results are consistent with conclusions regarding the need to improve regulatory aspects for the integration of new technologies and fuels into maritime transport, which will ensure a more efficient decarbonisation process.

The significance of achieving sustainable development goals, in particular Goal 13 (climate action), through decarbonisation of the maritime sector, was discussed by P.C. Ezinna *et al.* (2021). The study emphasised the need to integrate environmental standards and modern technologies that will help reduce emissions and improve the environmental status of marine ecosystems. This is consistent with the findings of this study, which highlights the need to develop low-carbon technologies for maritime transport. Z.Y. Song *et al.* (2025) explored the concept of "green maritime logistics corridors" and their potential for decarbonising maritime transport. This new solution involves optimising shipping through the introduction of green technologies and the sharing of environmental practices. Based on the results of this study, it is possible to confirm the importance of developing such initiatives to reduce emissions and create sustainable logistics routes. Solutions for decarbonising international shipping, in particular, policy recommendations and technological solutions that can reduce CO_2 emissions, are discussed in the study by Z. Wan *et al.* (2018). The study emphasised that effective decarbonisation of maritime transport requires the introduction of innovative technologies and active cooperation with international organisations to create standards and mechanisms for financing such initiatives. This is consistent with the findings of the presented study, which indicate that decarbonisation of maritime transport requires not only technical changes but also changes in the regulatory framework to ensure an effective transition to alternative fuels and reduce emissions.

The study by A. Romano & Z. Yang (2021) provided an overview of the state of decarbonisation in shipping for the period 2000-2020, noting progress in the use of alternative fuels such as LNG, biofuels and ammonia. The researchers also emphasise the significance of integrating decarbonisation strategies with other aspects of the maritime economy, such as economic efficiency and safety. This correlates with the results of this study, which shows that the transition to alternative fuels must be ensured not only technologically, but also economically, in terms of reducing the cost of transport services. Initiatives to improve the energy efficiency of ships and reduce CO_2 emissions were considered in a study by M. Issa *et al.* (2022). The researchers emphasised the importance of technologies that reduce the energy consumption of ships, such as energy recovery systems and efficient energy management systems. The results of the presented study confirm that to achieve a significant reduction in emissions, it is necessary to use both new types of fuel and efficient energy systems. An analysis of the potential for reducing greenhouse gas emissions using antifouling coatings in maritime transport was conducted by A. Farkas *et al.* (2021). The researchers noted that these technologies can reduce water resistance, leading to lower fuel consumption and, accordingly, lower CO_2 emissions. This supports the findings of this study, which emphasises the need to integrate various technological innovations, such as the use of new coatings and rotary sails, to achieve comprehensive decarbonisation.

In summary, it is possible to state that decarbonisation of the maritime sector requires a comprehensive approach that encompasses both the introduction of new technologies and the improvement of the regulatory framework and infrastructure. The transition to alternative fuels such as methanol, ammonia and hydrogen, as well as the integration of green technologies and digital solutions, are necessary steps to reduce emissions and improve the environmental health of marine ecosystems.

Conclusions

Research into the environmental impacts of alternative fuels in the maritime sector has shown that different fuels have significant impacts on the environment, including global warming, ocean acidification, eutrophication and toxicity to marine ecosystems. An analysis of the global warming potential (GWP100) for different types of fuel revealed significant variability: for LNG, GWP100 ranged from 0.18 to 0.22 kg CO_2-eq/MJ, which was due to methane leaks, which have a global warming potential 28-36 times higher than CO_2. At the same time, green methanol obtained from renewable energy sources had significantly lower GWP100 values, ranging from 0.016 to 0.020 kg CO_2-eq/MJ, but direct CO_2 emissions from its combustion remained high. Ammonia, as a carbon-free fuel, showed virtually zero direct CO_2 emissions, but produced significant amounts of nitrous oxide (N_2O), which increased its global warming potential to 0.16-0.20 kg CO_2 eq/MJ.

Regarding ocean acidification, the acidification potential for heavy fuel oil was 0.18 kg SO_2-eq/MJ, which was due to sulphur oxide (SO_x) emissions. For ammonia, this figure was lower at 0.10 kg SO_2-eq/MJ, but the acidification problem was offset by NO_x emissions, which formed nitric acid (HNO_3). Eutrophication analysis showed that ammonia emissions caused excessive bioavailable nitrogen entering marine ecosystems. The eutrophication potential for ammonia was 0.065 kg PO_4-eq/MJ, which exceeded similar indicators for traditional carbon fuels. In terms of toxicity, ammonia was found to be the most toxic to marine organisms, with an LC_{50} for fish of 0.8 mg/L and for oyster larvae of 1.1 mg/L. Methanol, in spills of 100 tonnes, could create local concentrations exceeding 1,500 mg/l, posing a threat to benthic organisms. Innovative technologies such as the Flettner rotor and hybrid energy systems have shown significant environmental benefits, including a 12% reduction in CO_2 emissions, a 94-98% reduction in NO_x emissions in port waters, and an 89-95% reduction in particulate matter emissions. This highlights the significance of the latest technologies in the reduction of the environmental footprint of shipping.

The results obtained showed that switching to alternative fuels in maritime transport is not an unconditional solution for mitigating environmental impacts but requires a comprehensive assessment of all fuel life cycle factors. Further research should address the optimisation of technologies for cleaning emissions of ammonia and nitric oxide, as well as reducing methane leaks when using LNG. Incorporating all aspects of the impact of alternative fuels will help to develop strategies for the effective decarbonisation of the maritime industry.

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Conflict of Interest

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Основні напрямки декарбонізації морської галузі

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Анотація. Метою дослідження було оцінити екологічні наслідки використання альтернативних видів палива в морській галузі, зокрема їхній потенціал щодо глобального потепління, підкислення океанів, евтрофікації та морської токсичності. Для цього було проведено порівняльний аналіз різних видів палива, включаючи зріджений природний газ, зелену метанолову продукцію, аміак, біопалива та традиційний важкий мазут. Результати показали, що зріджений природний газ, незважаючи на знижені викиди CO_2, мав високий кліматичний вплив через витоки метану, з потенціалом глобального потепління від 0,18 до 0,22 кг CO_2-екв./МДж. Зелені біопалива, зокрема метанол, мали найнижчий потенціал глобального потепління (0,016-0,020 кг CO_2-екв./МДж), але їхні прямі викиди CO_2 під час спалювання залишалися високими. Амміак, як безвуглецеве паливо, знижував викиди CO_2, однак утворював значні кількості закису азоту (N_2O), що суттєво впливає на кліматичний баланс. Потенціал підкислення океану для важкого мазуту становив 0,18 кг SO_2-екв./МДж, а для аміаку – 0,10 кг SO_2-екв./МДж. Аналіз евтрофікації показав, що викиди аміаку та закису азоту значно підвищують рівень азоту в морських екосистемах, що може викликати розвиток водоростей. Токсичність різних палив продемонструвала, що аміак має найбільший потенціал для шкоди морським організмам, навіть за низьких концентрацій. Практична значимість результатів полягає в необхідності комплексної оцінки екологічних наслідків при переході до альтернативних палив у судноплавстві, що може бути використано органами управління морським транспортом, екологічними агентствами, морськими портами, а також компаніями, які займаються розробкою і впровадженням технологій для декарбонізації судноплавства та зниження екологічного впливу морської діяльності

Ключові слова: альтернативні види палива; екологічний вплив; глобальне потепління; потенціал підкислення; аміак; метанол