Asian Journal of Applied Science and Technology (AJAST)
Volume 10, Issue 4, Pages 12-32, Oct-Dec 2026

The Atmospheric and Marine Footprint of Global Shipping: Assessing Ozone Layer Protection, Environmental Impacts, and Engineering Solutions for Sustainable Pathways

Rama A. Alnemari[1], Shahad H. Maghnam[1], Atheer I. Ayoub[1], Mona A. Alhoumidi[1], Rahaf M. Alosaimi[1], Juri F. Althobaiti[1] & Dalia Saber[1*]

[1]*Mechanical Engineering Department (Industrial Engineering Program), College of Engineering, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia. Corresponding Author (Dalia Saber) Email: dselsayed@tu.edu.sa**

DOI: Under Assignment

Copyright © 2026 Rama A. Alnemari et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Article Received: 15 August 2026 *Article Accepted: 22 October 2026* *Article Published: 26 October 2026*

ABSTRACT

The ozone layer is one of the most critical components of the Earth's atmosphere, protecting life from harmful ultraviolet radiation. However, industrial activities and global transportation sectors, particularly maritime transport, have contributed to its depletion. Maritime transport is considered a backbone of world trade, carrying over 80% of goods globally. Despite its importance, this sector generates significant environmental impacts through emissions, the use of ozone-depleting substances, oil spills, and harmful chemicals used in ship maintenance. These activities directly and indirectly affect the ozone layer and contribute to broader environmental challenges. Maritime transport is one of the fundamental pillars of the global economy, handling over 80% of the volume of international trade. However, alongside this vital importance come significant environmental impacts that threaten ecosystems and public health. This paper examines four key aspects of the environmental impacts of maritime transport: emissions of ozone-depleting substances and gaseous pollutants, harmful chemicals used in ship maintenance, in addition to oil spills and their indirect effects on the marine environment and the atmosphere. By analyzing these aspects, the paper aims to provide a comprehensive overview of the challenges facing the maritime industry and the ways to address them.

Keywords: Ozone Layer; Maritime Transport; Ozone-Depleting Substances; Sustainability Trends; Operational Life; Environmental Impacts; Gaseous Pollutants; Harmful Chemicals; Emissions; Oil Spills.

1.0. Introduction

Maritime transport is the backbone of global trade, responsible for carrying over 80% of the world's goods by volume [1,2]. While it is considered one of the most energy-efficient modes of commercial transport, the shipping industry significantly contributes to environmental degradation, including air pollution, greenhouse gas emissions, and ozone layer depletion. Among these, the impact on the ozone layer although comparatively less discussed has emerged as a critical area of concern due to the use of ozone-depleting substances (ODS) in ship operations, particularly in refrigeration and fire suppression systems [3].

The ozone layer serves as a protective shield, absorbing the majority of the sun's harmful ultraviolet (UV-B) radiation. Its depletion has been linked to increased rates of skin cancer, cataracts, and adverse effects on ecosystems [4,5]. Although international agreements like the Montreal Protocol have been effective in phasing out the production and consumption of many ODS, challenges remain in sectors where enforcement is limited or where legacy systems continue to operate such as in maritime transport [4].

This research paper explores the intersection of maritime transport and ozone layer protection by examining the environmental impacts of shipping-related ODS emissions, the engineering solutions available to mitigate these impacts, and the sustainable pathways forward. It investigates the current status of ODS usage in maritime activities, including hydrochlorofluorocarbons (HCFCs) and halons, and evaluates technical alternatives such as low-global-warming-potential (GWP) refrigerants and inert gas fire suppression systems. Furthermore, the paper discusses policy frameworks, compliance mechanisms, and industry best practices aimed at aligning the maritime sector with global ozone recovery goals.

By integrating environmental science, mechanical engineering, and sustainability policy, this study aims to contribute to a deeper understanding of how the maritime industry can evolve to support not only climate mitigation but also the long-term protection of the stratospheric ozone layer.

1.1. Objectives

This paper examines four key aspects of the environmental impacts of maritime transport:

1. Emissions of ozone-depleting substances and gaseous pollutants,
2. Emissions of carbon dioxide (CO_2), sulfur oxides (SOx), and nitrogen oxides (NOx),
3. Harmful chemicals used in ship maintenance,
4. Oil spills and their indirect effects on the marine environment and the atmosphere.

By analyzing these aspects, the paper aims to provide a comprehensive overview of the challenges facing the maritime industry and the ways to address them.

2.0. Proposed Model and Methodology

2.1. Maritime Transport and Its Environmental Impacts

Maritime transport is one of the fundamental pillars of the global economy, handling over 80% of the volume of international trade. However, alongside this vital importance come significant environmental impacts that threaten ecosystems and public health. This paper examines four key aspects of the environmental impacts of maritime transport: emissions of ozone-depleting substances and gaseous pollutants, harmful chemicals used in ship maintenance, in addition to oil spills and their indirect effects on the marine environment and the atmosphere. By analyzing these aspects, the paper aims to provide a comprehensive overview of the challenges facing the maritime industry and the ways to address them [4].

2.1.1. Ozone-depleting substances (ODS) used in ships and their sources

The discovery of the stratospheric ozone layer's depletion, culminating in the identification of the Antarctic ozone hole, unveiled one of the most significant environmental challenges of the 20th century. Scientific consensus established that halogenated aliphatic hydrocarbons, collectively known as Ozone-Depleting Substances (ODS), were the primary non-recommended ones [6]. These compounds, notably chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), were prized for their chemical stability, non-toxicity, and excellent thermodynamic properties, leading to their widespread adoption as refrigerants, foam blowing agents, and solvents. The maritime industry, a pillar of global trade, became a significant repository and emission source for ODS, extensively utilizing them in cargo refrigeration and shipboard air-conditioning systems. A critical environmental challenge persists in the form of "ODS banks" the vast quantities of these substances sequestered within existing equipment and products [7]. Onboard vessels, these banks reside within the circuits of refrigeration plants and insulating foams, posing a continuous threat of gradual leakage, catastrophic release, or improper venting during maintenance. Despite the landmark Montreal Protocol (1987) mandating a global phase-out, the enduring presence

of ODS in existing ship systems underscores the necessity for robust management strategies, including recovery, recycling, and environmentally sound destruction, to mitigate their ongoing impact [4].

The initial response to the ODS phase-out was the adoption of transitional and long-term synthetic substitutes. Hydrochlorofluorocarbons (HCFCs) were introduced as interim replacements due to their lower Ozone Depletion Potential (ODP) compared to CFCs. However, as they still contained ozone-depleting chlorine, their production and consumption were also scheduled for elimination. This led to the large-scale adoption of Hydrofluorocarbons (HFCs) as the primary long-term substitutes. With an ODP of zero, HFCs effectively solved the problem of stratospheric ozone depletion and became the standard in new refrigeration and air-conditioning systems. Nevertheless, this solution introduced a formidable new challenge.

While HFCs do not harm the ozone layer, they are potent greenhouse gases with high Global Warming Potential (GWP). Empirical data underscores the severity of this issue; for instance, HFC emissions from their use as ODS replacements in Taiwan surged from 373 kilotons of carbon dioxide equivalent (CO_2eq) in 2011 to 1,555 kilotons of CO_2eq in 2022. This trend illustrates a critical environmental trade-off: the solution to the ozone crisis inadvertently exacerbated climate change [8].

The recognition of HFCs as powerful drivers of global warming precipitated a pivotal development in international environmental policy: the Kigali Amendment to the Montreal Protocol in 2016. This amendment represents a paradigm shift, integrating climate change mitigation directly into the ozone protection regime by mandating a global phasedown of HFC production and consumption. For industries reliant on refrigeration, including the maritime sector, this signals the end of the era of high-GWP HFCs. The current technological landscape is now defined by the development and deployment of fourth-generation refrigerants with low or negligible GWP. This evolution has bifurcated into two primary pathways. The first is the development of synthetic ultra-low GWP alternatives, such as Hydrofluoroolefins (HFOs), which have GWP values often near 1. The second pathway involves a resurgence of natural refrigerants, including ammonia (R-717), hydrocarbons, and carbon dioxide (R-744), which offer ODP of zero and negligible GWP, positioning them as truly sustainable, future-proof solutions. The maritime industry's environmental journey continues as it transitions from HFCs to sustainable alternatives under the Kigali Amendment. This shift toward low-GWP refrigerants like HFOs and natural refrigerants represents a critical step in the sector's sustainability path. Successfully managing this transition while maintaining operational efficiency remains essential for the industry's future, balancing environmental responsibility with its vital role in global commerce [9,10].

2.1.2. Emissions of carbon dioxide (CO_2), sulfur oxides (SOx), and nitrogen oxides (NOx)

Maritime transportation, the backbone of global trade, casts a long shadow on environmental and human health through its significant emissions of carbon dioxide (CO_2), sulfur oxides (SOx), and nitrogen oxides (NOx). While indispensable for the world economy, the combustion of low-grade marine fuels in ship engines releases a complex cocktail of pollutants into the atmosphere. These emissions are not merely a peripheral concern but a major contributor to global anthropogenic pollution, with profound implications for climate change, air quality, and public health. The specific environmental impacts of these key pollutants are systematically detailed in Table 1[11].

Table 1. Gaseous Pollutants from Ships and Associated Environmental Impact [11].

Consequences	**Pollutants**		
	SO_x	NO_x	CO_2
Greenhouse effect			X
Ozone-stratospheric			
Ozone-ground level		X	
Acid rain	X	X	
Linked-up with:			
Fuel combustion	X	X	X
Cargo handling			
Ships equipment			
Incinerators	X	X	X

This critical examination delves into the scale, sources, and multifaceted impacts of these emissions, while also exploring the evolving landscape of international regulations and technological solutions aimed at mitigating this pressing global challenge. The scale of emissions from the shipping sector is substantial. It accounts for approximately 3.3% of global CO_2 emissions and is responsible for a disproportionate 10–15% of global anthropogenic SOx and NOx emissions. This disparity stems from the reliance on heavy fuel oil (HFO), a residual refinery product with an exceptionally high sulfur content averaging 27,000 parts per million. The combustion of this fuel results in the release of millions of tonnes of pollutants annually, including particulate matter (PM), which poses severe risks to respiratory and cardiovascular health. Geographically, the impact is concentrated, with around 70% of these emissions occurring within 400 kilometers of coastlines, directly exposing populous coastal communities to degraded air quality. The environmental consequences extend beyond smog formation, contributing to ocean acidification and the acidification of rain. Different vessel classes, particularly container ships, bulk carriers, and oil tankers, are identified as the largest contributors to this problem. In response, the International Maritime Organization (IMO) has established a regulatory framework under MARPOL Annex VI. This includes the progressive tightening of global sulfur caps and the creation of stricter Emission Control Areas (ECAs). Furthermore, the IMO has introduced energy efficiency measures like the Energy Efficiency Design Index (EEDI) to address CO_2 emissions. Mitigation strategies are diverse, ranging from technological solutions such as exhaust gas cleaning systems (scrubbers) and selective catalytic reduction (SCR) units, to operational measures like slow steaming and the use of alternative fuels like liquefied natural gas (LNG) [1,12,13].

2.1.3. Chemical substances used in ship maintenance that may contain harmful materials

The management of hazardous and noxious substances (HNS) in the marine environment represents a critical challenge that spans the entire lifecycle of maritime vessels, from operational use to final recycling Table (2). The international framework governing these substances, developed through systematic evaluation of thousands of chemicals by bodies like the GESAMP EHS Working Group and implemented through MARPOL Convention, establishes rigorous hazard profiling methodologies. These profiles classify substances based on quantitative criteria for aquatic toxicity, bioaccumulation potential, and biodegradation, directly informing regulatory measures

for operational vessels. However, when ships reach their end-of-life in recycling facilities, these carefully managed chemicals become a concentrated inventory of risk that requires specialized handling and disposal protocols.

The hazard categories defined under MARPOL Annexes II and III including substances with bioconcentration factors exceeding 500 or those exhibiting "extremely toxic" aquatic toxicity below 0.01 mg/L are precisely the materials that ship recycling facilities must confront. Polychlorinated Biphenyls (PCBs), historically used in cable insulation, transformers, and capacitors, exemplify high-priority concerns due to their carcinogenicity, bioaccumulative nature, and severe impacts on immune, nervous, and endocrine systems. Similarly, organotin compounds like Tributyltin (TBT) from anti-fouling paints demonstrate the persistent challenge of substances that contaminate marine ecosystems and enter the food chain. The transition from operational regulation to end-of-life management reveals additional complexities, as heavy metals such as lead and mercury—prevalent in paints, coatings, and electrical equipment require controlled handling to prevent neurological damage, kidney failure, and cardiovascular issues [14].

The recycling process itself generates unique hazardous scenarios that extend beyond the original regulatory scope. Hydrocarbon wastes including waste oils, fuels, and lubricants from engines and hydraulic systems present significant contamination risks to soil and groundwater, while their volatile fractions contribute to atmospheric pollution. Bilge water accumulates complex mixtures of oil, heavy metals, and inorganic salts, often requiring pretreatment before discharge. Furthermore, dismantling activities transform stable materials into hazardous forms: thermal cutting of solid foam insulation releases toxic smoke, mechanical processing of glass fiber generates inhalable particles with pathological effects similar to asbestos, and improper handling of Polyvinyl Chloride (PVC) risks generating highly toxic dioxins and furans through uncontrolled combustion. The integration of scientific assessment with practical recycling methodologies demonstrates the evolution of a comprehensive management approach. Advanced ship recycling yards now implement procedures that address the full spectrum of hazardous substances, from initial identification through final disposal. This includes pre-cleaning operations, controlled dismantling environments, personal protective equipment protocols, and partnerships with certified treatment facilities. The continuous refinement of both international regulations and facility-level practices underscores the maritime industry's ongoing commitment to reconciling industrial activity with environmental stewardship and occupational safety throughout the vessel lifecycle [15].

Table 2. Comprehensive Hazardous Substance Management Framework [14].

Substance Category	**Hazard Profile**	**Operational Management**	**Recycling & Disposal Protocols**
PCBs	Bioaccumulative (BCF >500), carcinogenic, chronic toxicity	Contained use in electrical systems	Cold mechanical dismantling; high-temperature incineration (1200°C+); specialized landfill
TBT, TPT	Aquatic toxicity, bioaccumulation, food chain contamination	Hull coating applications	Controlled removal of contaminated sections; chemical treatment

Lead, Mercury	Neurological toxicity, bioaccumulation, renal damage	Contained in paints and electrical components	Dust suppression; soil remediation; specialized waste facilities
Oil, Fuel, Sludge	Aquatic toxicity, soil contamination, volatile emissions	Storage and transfer protocols	Vapor control; tank cleaning; bioremediation; recycling
Bilge Water	Chemical mixtures, heavy metal content, ecological impact	Treatment systems onboard	Pretreatment; chromium testing; phase separation
PVC, Solid Foam	Toxic combustion products, persistent waste	Structural and insulation applications	Ventilation systems; solvent alternatives; thermal treatment

2.1.4. Oil spills and their indirect impact on both the atmospheric and marine environment

Marine oil spills represent catastrophic events whose consequences ripple far beyond the initial point of release, creating a complex web of environmental degradation and societal disruption. While international frameworks, such as the GESAMP hazard evaluation system, provide a structured methodology for assessing the inherent properties of harmful substances, the real-world impacts of a spill are shaped by a dynamic interplay of biophysical and socioeconomic factors. This analysis synthesizes insights from the foundational work of GESAMP with comprehensive empirical studies of previous oil spill disasters to elucidate the multifaceted and often protracted consequences of these incidents. It argues that a full understanding of an oil spill's impact requires moving beyond acute toxicity to account for indirect pathways affecting marine ecosystems, atmospheric quality, human health, and economic stability [16].

The immediate and direct impacts of an oil spill, as conceptualized in hazard profiles, are often physical in nature. Substances classified as persistent floaters ('Fp') or sinkers ('S') under the GESAMP framework can smother coastal habitats and wildlife, leading to immediate mortality and long-term habitat loss. However, the spill's characteristics and context dramatically modulate its severity. The location is a critical determinant; a nearshore spill proximate to human populations and sensitive ecosystems can incur cleanup costs up to 100 times greater than an offshore event and inflict more severe economic damage. Furthermore, the type of oil transported introduces distinct hazards. The carriage of non-conventional products like diluted bitumen presents novel risks, as the volatile organic compounds (VOCs) used as diluents can rapidly evaporate, creating acute public health crises through air pollution in nearby urban areas, a phenomenon starkly illustrated by the 2010 Kalamazoo River pipeline rupture [17].

The disaster response itself can introduce secondary hazards, complicating the recovery process. The application of chemical dispersants, a common countermeasure, has been shown to increase the bioavailability of toxic hydrocarbons in the water column. Empirical evidence suggests that the combination of oil and dispersant can be more toxic to marine organisms than oil alone, potentially inhibiting natural degradation processes and prolonging ecological injury for decades. These biophysical shocks subsequently trigger profound socioeconomic repercussions. Commercial fisheries and aquaculture suffer direct losses from harvesting closures and, critically, from a loss of market demand due to consumer fears of tainted seafood, even in areas untouched by the spill.

Similarly, the tourism industry experiences severe brand damage, with visitor spending in affected regions declining by over a third, as documented after the Exxon Valdez disaster.

The human dimension of oil spills reveals some of the most profound and lasting impacts. Beyond physical health effects from exposure to oil and dispersants, communities consistently experience significant psychological distress. Technological disasters like oil spills induce greater and more prolonged mental health impacts than natural disasters, leading to documented increases in post-traumatic stress, substance abuse, and social disruption, particularly in communities reliant on the affected marine resources for their livelihood and cultural identity.

In conclusion, an oil spill is not a singular event but a trigger for a cascade of interconnected crises that permeate ecological and human systems. The GESAMP hazard evaluation procedure offers a valuable lens for anticipating certain physical and toxicological threats, but the empirical record demonstrates that the most significant consequences often emerge from indirect pathways. These include the exacerbation of damage by response measures, the severe economic losses driven by market and reputational factors, and the deep, corrosive social and psychological impacts on affected communities. Therefore, effective risk reduction, preparedness planning, and policy development must adopt an integrated, systems-based approach that acknowledges and addresses this full spectrum of direct and indirect impacts to build truly resilient coastal societies.

The environmental impacts of maritime transport represent a multi-faceted challenge that requires integrated and committed solutions. From emissions of ozone-depleting substances and gaseous pollutants to hazardous chemicals and oil spills, the need to strengthen international regulations and adopt eco-friendly technologies is evident. The maritime industry must accelerate the pace of transition towards sustainable alternatives, such as low-global warming potential refrigerants and clean fuels, while enhancing safety measures and waste management. Only through these measures can a balance be achieved between the demands of global trade and the preservation of the environment for future generations [16,17].

3.0. Methods

3.1. Industrial Engineering's Function in Logistics and Sea Transportation

Logistics of Industrial Shipping Applying analytical techniques and systems thinking to the maritime industry is the main goal of engineering. Planning, creating, and overseeing transportation networks is its primary duty in order to ensure the sustainable and effective movement of goods. This field of engineering is essential for guaranteeing prompt product delivery, maximizing the efficiency of supply chains that travel across the ocean, and above all reducing the negative environmental effects of international trade [18].

By actively applying data science and optimization for expensive, high-impact assets like ports and ships, this role goes beyond simple coordination in the context of international sea transportation. According to Kim and Lee [19], the outcomes are crucial for improving overall effectiveness, reducing operational costs (such as fuel consumption), and streamlining processes all of which directly support sustainability mandates and adherence to standards set by organizations like the IMO. Experts in this field can pinpoint problem areas and put plans into action to improve supply chain performance by utilizing technology and data-driven insights. In addition to

increasing the profits of multinational trade firms, this proactive approach contributes to the industry's overall sustainability and environmental responsibility [20].

3.1.1. Optimization and Efficiency: Core Engineering Functions

Efficiency and Optimization: Fundamental Engineering Tasks

The primary duty of industrial engineers in maritime transportation is to maximize throughput while reducing costs by making all shipping operations as productive and resource-efficient as possible [19].

Route and Network Planning: This comprises determining the most effective routes, schedules, and locations for ports, distribution centers, and transshipment points using optimization techniques and operations research models. A well-designed network increases overall supply chain efficiency while reducing transit time and expenses. It has been demonstrated that optimization techniques based on AI and reinforcement learning can cut fuel consumption on long-distance routes by up to 11% [19].

Load and Performance Optimization: To optimize the physical volume and weight of cargo loaded into ships and containers, engineers employ precise load-planning techniques, such as trim management and stowage. By maximizing the use of available vessel space, this vital function lowers the cost per unit shipped. By identifying optimal speed profiles and operational efficiencies through performance analysis based on propulsion data, energy consumption and emissions can be directly reduced [20].

3.1.2. Integration and Synchronization of the Supply Chain

Logistics engineering minimizes operational bottlenecks that result in waste and emissions by ensuring that a vessel's movement is coordinated with the entire onshore supply chain [21-23].

Reducing Port Dwell Time: Industrial engineers plan terminal layouts and scheduling systems to manage the movement of goods by truck, rail, and ship. Emissions from berthing or anchorage are greatly reduced by cutting down on dwell time, or the amount of time a ship is idle at port. Reducing traffic and increasing turnaround efficiency are made possible by considering the ship and port as a single, integrated system [24].

Information Flow and Visibility: Real-time tracking of cargo and vessel status is made possible by contemporary technologies like blockchain, RFID, and Internet of Things sensors. Managers can avoid expensive delays and environmental inefficiencies by using enhanced visibility to inform data-driven decisions about inventory management, port calls, and rerouting [21].

3.1.3. Resilience and Risk Management

In order to ensure safety, operational continuity, and a lower risk to the environment and finances, industrial engineers also create resilient systems that can withstand and recover from disruptions [25].

Contingency networks and disruption planning:

Companies can effectively respond to severe weather, port strikes, and canal blockages by stress-testing their logistical networks and creating pre-planned alternatives. Rerouting expenses and excessive fuel consumption are reduced when redundancy and flexibility are incorporated into the system [25].

Systems Safety and Security:

Security engineering creates defenses against theft, piracy, and cyberattacks, guaranteeing the continued operation of operational and navigational systems. A strong safety framework lowers the chance of accidents, safeguards people and property, and increases the general resilience of maritime operations [18].

4.0. Results and Discussion

4.1. Sustainability Trends in Maritime Transport

As the backbone of the global economy, the maritime industry facilitates approximately 90% of international trade by volume. However, this expansive seaborne transportation network generates substantial greenhouse gas (GHG) emissions that contribute to climate change. A typical ship releases a variety of pollutants into the atmosphere and water body, including CO_2, NOx, SOx, and particulate matter (Figure 1).

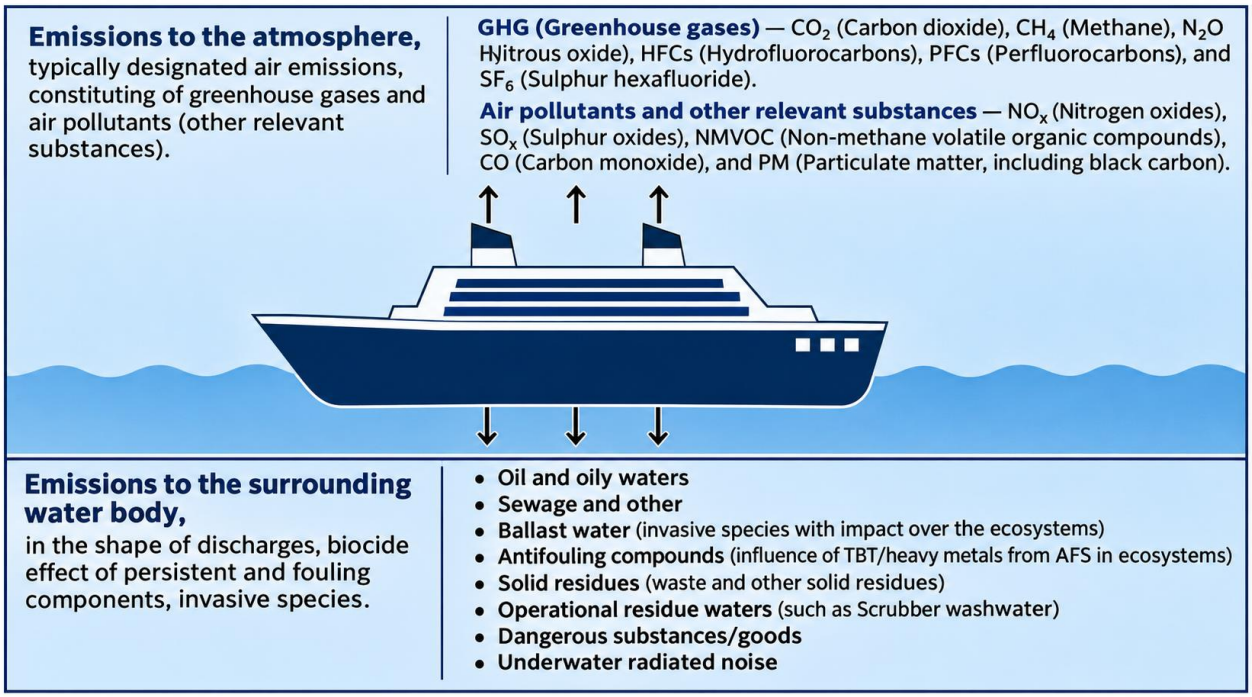


Figure 1. Pollutant emissions to the atmosphere and water body from a generic ship [27].

According to the IMO Fourth GHG Study, maritime transport's share of global GHG emissions increased from 2.76% in 2012 to 2.89% in 2018, with projections indicating a potential 44.4% escalation above 2018 levels by 2050 without intervention. At the global scale, these emission trends across the shipping industry are illustrated in Figure 2 [26,27].

These emissions not only degrade air quality in coastal regions but also impact atmospheric composition, with implications for ozone layer stability and overall environmental health. The environmental significance of maritime transport became particularly evident during the COVID-19 lockdowns.

A study at Alexandria Port, Egypt, revealed measurable improvements in air quality and ozone stability as maritime activity declined. In 2020, ozone (O_3) concentrations decreased by about 15%, accompanied by decreases in NO_2 and SO_2 of roughly 30%, and record lows in aerosol indicators (AAI = –1.2, AOD = 214 mol/m²).

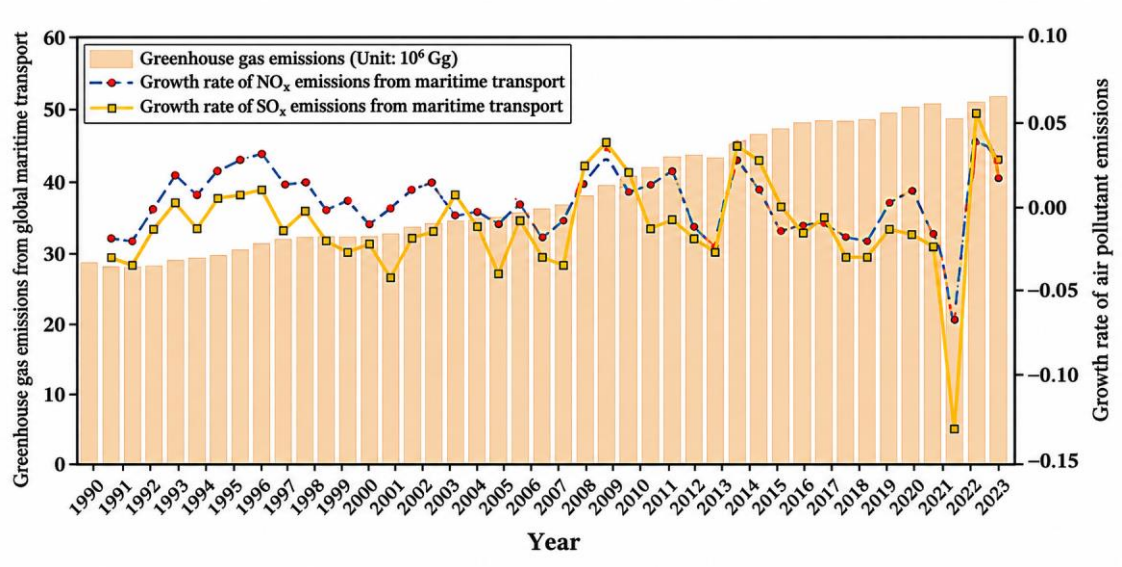


Figure 2. Emission Trends from Global Maritime Transport [27].

Figure 3 demonstrates how reduced shipping emissions during the lockdown temporarily enhanced atmospheric conditions, indicating the potential of emission control and cleaner fuel policies to support ozone layer protection under normal operations. Achieving meaningful reductions in maritime emissions requires practical, system-level changes within industry. This study therefore focuses on three complementary approaches to promote sustainability in maritime transport: designing more efficient logistics systems to reduce emissions, conducting life-cycle analyses of ships from design to dismantling, and managing maritime supply chains in a way that minimizes environmental impact [28].

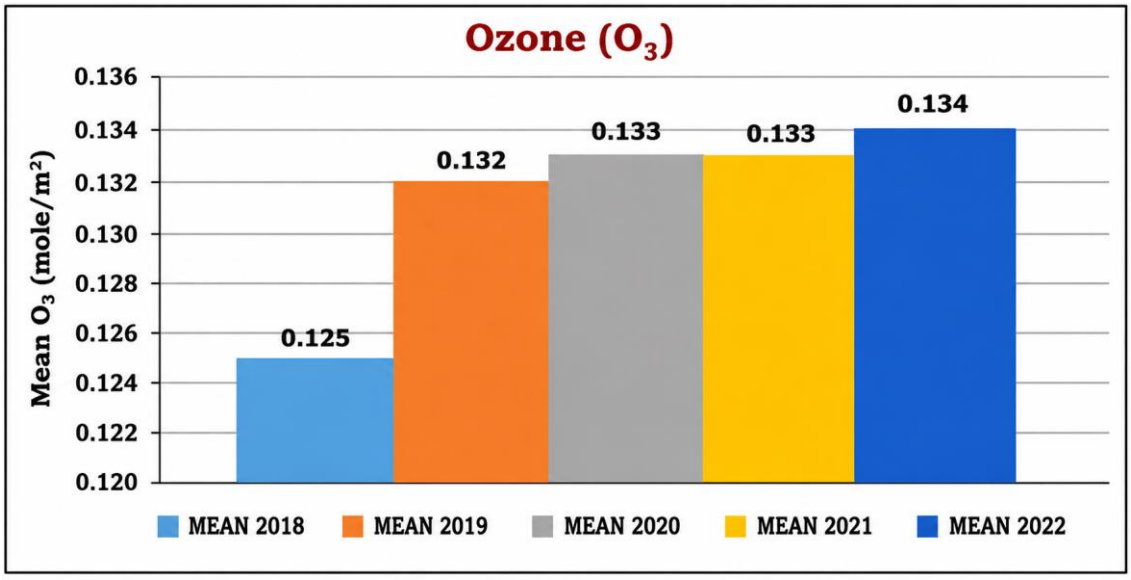


Figure 3. The Mean Values of the O_3 (Mole/M²) In the Alexandria Maritime Port Over the Study Period [28].

4.1.1. Designing efficient logistics systems to reduce emissions

Reducing emissions in maritime transport is closely tied to the efficiency of ship operations and logistics systems. Because fuel consumption accounts for nearly 50% of total operational costs, any improvement in energy efficiency directly contributes to both economic and environmental sustainability. In this context, designing

efficient logistics systems means not only improving individual vessel performance but also optimizing routes, port coordination, and fleet management at a systemic level [29].

A holistic view of logistics efficiency recognizes that emission reduction measures must span the entire maritime transport chain including ship operations, port activities, and hinterland connections. As Lee, Kwon, and Ruan [30] highlight, sustainability in maritime logistics increasingly depends on governance, system integration, and performance management across these interconnected sectors. Optimizing port-hinterland flows, for instance, minimizes redundant movements, reduces waiting times, and decreases overall fuel use and emissions.

From a technical and operational standpoint, several strategies are being implemented within the industry:

- Speed Optimization (Slow Steaming): Operating ships at lower speeds significantly decreases fuel consumption, CO_2 emissions, and operating costs. However, this must be balanced against delivery schedules, prompting the use of the term "speed optimization" rather than simply "slow steaming."

Route Optimization and Voyage Planning: Advanced weather routing systems and digital forecasting tools enable ships to avoid adverse conditions and leverage favorable currents, reducing voyage time and energy use. Accurate weather prediction is essential for maintaining schedule reliability.

- Fleet and Port Coordination: Improved coordination between ship operators and port authorities ensures ships arrive when berths are available, minimizing anchorage time, port congestion, and unnecessary fuel consumption.

- Digitalization and Monitoring: The use of digital twins, real-time tracking, and predictive analytics supports better decision-making and performance monitoring, optimizing vessel operations and logistics efficiency throughout the supply chain.

- Improved Maintenance and Operations: Regular hull cleaning, propeller polishing, and optimizing ballast and trim can enhance energy efficiency and prolong engine life, resulting in lower GHG emissions over time [31].

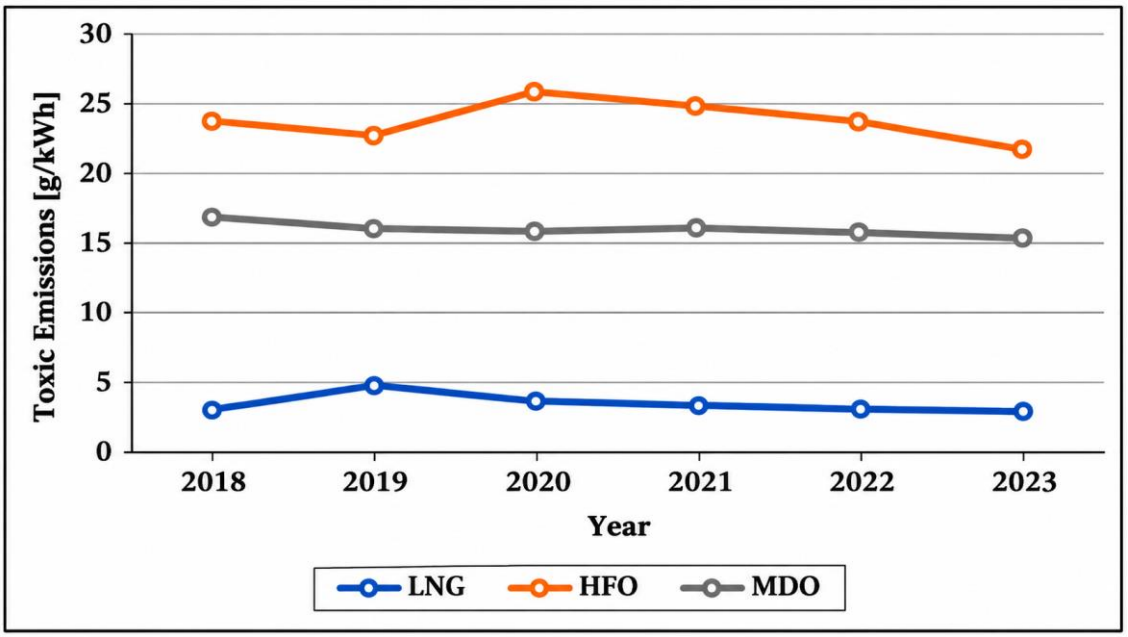


Figure 4. Emissions of toxic compounds by marine fuels, 2018–2023 [32].

The Baltic Sea region illustrates how emission reduction can be achieved in maritime transport. As a Sulphur Emission Control Area (SECA), the region has encouraged the adoption of liquefied natural gas (LNG) instead of heavy fuel oil (HFO) or marine diesel oil (MDO). This shift has significantly lowered CO_2, SO_x, and NO_x emissions, contributing to the decarbonization of maritime operations. Figure 4 shows that LNG consistently produces the lowest toxic emissions compared to HFO and MDO, highlighting its potential as a cleaner marine fuel [32].

Reducing emissions in maritime transport involves more than fuel selection; it requires system-level management of routes, schedules, and fleet operations, combined with energy- efficient technologies and operational practices. Effective governance, performance monitoring, and coordination across the maritime supply chain are essential for realizing emission reductions. By integrating fuel transition strategies, operational optimization, and digital monitoring, the maritime sector can achieve measurable reductions in greenhouse gas and pollutant emissions while maintaining economic efficiency, representing a key step toward sustainable maritime transport [33].

4.1.2. Life Cycle Analysis of Ships: From Design to Dismantling

The environmental performance of a ship cannot be measured solely by its fuel consumption or operational emissions. Instead, a complete evaluation requires examining every stage of its existence from material extraction and design to operation, maintenance, and end-of-life dismantling. This approach, known as Life Cycle Analysis (LCA), has become a cornerstone of sustainable maritime engineering. By assessing the full environmental footprint, LCA helps identify where interventions can most effectively reduce greenhouse gas (GHG) emissions, hazardous discharges, and substances that may indirectly affect ozone balance and air quality [34].

1. Design and Construction

The design phase represents the foundation of a vessel's environmental sustainability. Every material, component, and system chosen at this stage determines the potential environmental risks later in the ship's life. Historically, ship construction included substances such as asbestos insulation, PCB-based sealants, tributyltin coatings, and ozone-depleting refrigerants (CFCs, halons, and HCFCs). Modern environmental design principles aim to eliminate such materials entirely through material substitution and design-for-disassembly, which facilitate safe recycling and reuse at the end of service. International conventions, including the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes, emphasize preventing hazardous waste generation through smarter design. Under this framework, the preferred term "ship dismantling" highlights a process focused on safe removal and controlled waste management rather than uncontrolled scrapping. In parallel, shipyards are increasingly adopting the Inventory of Hazardous Materials (IHM) a comprehensive record identifying all hazardous substances onboard. Maintaining this inventory from the design stage ensures traceability, enabling safer operation and responsible dismantling later in the vessel's life cycle [35].

2. Operational Life

During its operational phase, a ship's environmental footprint arises primarily from propulsion emissions, onboard energy use, and system maintenance. While ozone-depleting substances are now largely banned in new vessels,

older ships may still rely on legacy refrigerants and coatings that release harmful compounds if not properly managed. Operational practices such as fuel optimization, hull and propeller maintenance, and refrigerant recovery significantly reduce both greenhouse and ozone-related emissions. Life cycle modeling studies (Yuksel et al and Seithe et al.) [36,37] demonstrate that optimizing voyage routes, improving hull hydrodynamics, and introducing hybrid or alternative-fuel propulsion systems can lower life-cycle GHG emissions by up to 40%. The integration of digital monitoring systems tracking energy use, refrigerant leaks, and waste discharges supports preventive maintenance and early intervention, further extending the vessel's efficiency and compliance lifespan.

3. Dismantling and Recycling

The final phase dismantling carries the highest environmental risk if performed unsafely. The distinction between ship recycling (as adopted by the IMO) and ship dismantling (as defined by the Basel Convention) lies mainly in the management of hazardous outputs. Sustainable dismantling requires enclosed working zones, containment systems, and waste segregation to prevent toxic releases into the atmosphere and marine environment. Empirical studies of major recycling hubs such as Alang (India) and Chittagong (Bangladesh) reveal persistent challenges in hazardous material management, where open burning and uncontained cutting release asbestos fibers, PCB residues, and volatile organic compounds. In contrast, EU-based facilities compliant with the EU Ship Recycling Regulation (EU SRR) apply engineered platforms, air-filtration systems, and certified waste treatment protocols proving that end-of-life emissions can be nearly eliminated when lifecycle principles guide the process. Integrating life-cycle principles into maritime transport enables sustainable improvement from design to disposal.

Environmentally conscious material selection reduces future hazards, efficient operation minimizes emissions, and controlled dismantling prevents secondary pollution. Together, these practices form a continuous system that not only supports maritime decarbonization but also contributes directly to ozone layer protection. The life-cycle perspective therefore embodies a comprehensive approach to environmental stewardship ensuring that the benefits of maritime progress do not come at the expense of the planet's atmospheric and marine balance. Managing Maritime Supply Chains to Minimize Environmental Impact The maritime supply chain integrates ships, ports, and hinterland logistics into a single global system that underpins international trade. Given its scale and complexity, even minor inefficiencies can lead to significant environmental costs. Effective management of these interconnected operations is therefore essential to minimizing emissions, improving energy efficiency, and protecting atmospheric quality, including the ozone layer [26, 27,35,38].

4.1.3. Managing Maritime Supply Chains to Minimize Environmental Impact

The maritime supply chain integrates ships, ports, and hinterland logistics into a single global system that underpins international trade. Given its scale and complexity, even minor inefficiencies can lead to significant environmental costs. Effective management of these interconnected operations is therefore essential to minimizing emissions, improving energy efficiency, and protecting atmospheric quality, including the ozone layer [39,40].

Integrating Sustainability into Supply Chain Management

Modern sustainability strategies emphasize coordination across the entire supply chain rather than isolated improvements in ship or port performance. Environmentally conscious management focuses on optimizing vessel

routes, port operations, and hinterland connections to reduce redundant movement and idle time key sources of fuel waste and emissions. When ships spend fewer hours waiting at anchor or navigating congested routes, emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and volatile organic compounds (VOCs) decrease significantly, leading to improved local air quality and reduced ozone-related impacts. Recent studies in maritime logistics show that digitalization, data transparency, and intermodal coordination are critical tools for emission reduction. Integrating port community systems, digital twins, and real-time monitoring allows for more precise scheduling between ports and vessels, cutting unnecessary fuel use. The application of artificial intelligence (AI) in predicting port congestion and weather-related delays also helps optimize routing decisions, preventing detours and excess consumption [41].

Strategies for Environmental Optimization

Several approaches have proven effective in minimizing the environmental footprint of maritime supply chains:

- Route and Network Optimization: Dynamic voyage planning supported by digital data reduces idle sailing and enables flexible re-routing to less congested ports, lowering CO_2 and NO_x emissions.
- Modal Shifts: Strengthening connections between maritime transport, railways, and inland waterways reduces reliance on long-haul trucking, cutting both emissions and logistics costs.
- Just-in-Time (JIT) Operations: Synchronizing ship arrivals with port readiness reduces waiting time at anchorage, minimizing unnecessary fuel burn and port congestion.
- Energy-Efficient Port Infrastructure: Shore-side electricity (cold ironing) and renewable-powered terminals allow ships to shut down auxiliary engines while berthed, further reducing air pollutants.
- Digitalization and Coordination: Advanced data systems and real-time communication between ports, carriers, and hinterland operators enhance transparency and enable continuous optimization across the entire supply chain.

According to UNCTAD's Review of Maritime Transport [42], sustainable supply chain integration could reduce total GHG emissions from the shipping sector by 15–20% by 2030 if coordinated digital and intermodal systems are fully implemented, underscoring the critical role of integrated management. Through route optimization, digital coordination, and cleaner port operations, the industry can substantially reduce emissions and strengthen its contribution to global decarbonization and ozone-layer protection efforts.

Maritime Transport, Emissions, and Ozone Layer Protection

Stratospheric ozone plays a pivotal role in Earth's atmospheric system by filtering harmful ultraviolet-B (UV-B) radiation, thereby protecting human health, ecosystems, and biogeochemical cycles. The thinning of the ozone layer threatens increased rates of skin cancer, cataracts, and damage to terrestrial and marine biota [27]. At the same time, human activities contribute to atmospheric emissions that can indirectly or directly interfere with ozone chemistry.

Maritime transport is among the backbone sectors of global trade, moving approximately 80 % of world goods by volume and underpinning global supply chains. Though vital to economic growth, the shipping sector is a

non-negligible source of air pollutants, including nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon dioxide (CO_2), particulate matter (PM), and volatile organic compounds (VOCs). These emissions interact with atmospheric processes, contributing to tropospheric ozone formation, altering oxidant balances, and potentially influencing stratospheric ozone via coupled chemistry–climate mechanisms.

The synergy between industrial activity and maritime transport is bidirectional: the industrial sector provides fuels, ship components, and refrigerants (historically some containing ozone-depleting substances, ODSs), while maritime operations support industrial logistics. Ships may release ODSs during servicing, maintenance, or disposal, and their combustion emissions provide chemical precursors altering oxidant budgets in the lower and mid atmosphere. Thus, carefully dissecting how shipboard practices and exhaust emissions influence ozone dynamics is vital for crafting mitigation policies that balance trade imperatives with atmospheric integrity [43].

5.0. Summary

This research explores (1) the mechanisms through which maritime emissions and shipboard ODS use can influence ozone-related chemistry, and (2) the international regulatory responses particularly those under the International Maritime Organization (IMO) aimed at mitigating these effects.

International Standards and Regulations (IMO)

The International Maritime Organization (IMO), a specialized UN agency, is tasked with regulating maritime safety, security, and preventing pollution from ships. As environmental challenges linked to shipping have grown, IMO's mandate has expanded to incorporate air pollution control and climate mitigation in shipping. Among its core instruments is MARPOL (International Convention for the Prevention of Pollution from Ships), which integrates pollution standards for various media including air, oil, sewage, and waste (MARPOL 73/78). MARPOL's Annex VI specifically addresses air pollution and the use of ODSs on vessels.

Annex VI entered into force in May 2005 and has been amended several times to tighten controls on emissions and fuel quality (e.g., the 2008 amendments). It mandates that ships must not emit ODSs deliberately, limits SO_x and NO_x emissions, and imposes record keeping requirements for ODS usage onboard. It also permits the creation of more stringent zones Emission Control Areas (ECAs) where stricter limits apply. Regulation 13 (NO_x) sets tiered NO_x emission limits based on engine build dates and operating regimes. Engines built after 2000 or modified significantly are subject to stricter limits. Tier II standards apply globally to newer ships, while Tier III standards are enforced in designated NO_x Emission Control Areas (NECAs) for ships built after 2016.

Regulation 14 regulates sulfur content in marine fuels and constrains PM emissions. After 2020, fuel sulfur (outside ECAs) is capped at 0.50 % m/m, and in ECAs, stricter limits apply (as low as 0.10 %). Alternatively, ships may deploy approved scrubber systems to meet equivalent emission reductions. Annex VI prohibits deliberate emissions of classical ozone depleting substances (e.g. CFCs, halons) from ship systems, except in critical uses. Ships must keep an Ozone Depleting Substances Record Book documenting use, servicing, and disposal.

IMO has also implemented technical and operational measures like the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, promoting efficiency and

emission reduction. These measures indirectly support ozone layer protection by minimizing greenhouse gas emissions and atmospheric perturbations. However, enforcement remains a challenge due to differences in national capabilities, limited monitoring, and technological constraints. New tools such as satellite-based detection and airborne monitoring are improving compliance verification. Economic barriers also exist, as retrofitting and fuel transition require major investments. Emerging frameworks such as the IMO Net-Zero Framework (2025) and policy integration with the Montreal Protocol offer future opportunities for synergistic protection of both climate and ozone integrity.

Modern Technologies and Innovations

The maritime sector has undergone significant technological transformations in recent decades to reduce its environmental footprint, particularly regarding air pollution and ozone-related impacts. Innovations in ship design, propulsion systems, and alternative fuels are key strategies that contribute to mitigating both greenhouse gas emissions and substances that affect atmospheric ozone chemistry.

One major area of innovation involves ship design optimization. Modern vessels are increasingly built using hydrodynamically optimized hull forms that minimize water resistance, thereby reducing fuel consumption and emissions. Technologies such as air lubrication systems, which create a layer of air bubbles beneath the hull to decrease friction, can improve energy efficiency by 5–10%. Additionally, wind-assist technologies including rigid sails, rotor sails, and suction wings are being integrated into new ship designs and retrofits to harness wind power

Economic and Operational Challenges in Maritime Transport

Economic Obstacles

Financial costs represent one of the main obstacles facing shipping companies in implementing sustainable practices. For instance, transitioning to low-sulfur fuel or using environmentally friendly alternatives such as liquefied natural gas or biofuels requires significant investment in fuel procurement, engine upgrades, and the installation of emission cleaning systems (scrubbers). Moreover, profits are affected by fluctuations in global fuel prices and changes in demand for maritime transport, which increases economic uncertainty and makes investment in clean technologies financially risky.

Operational Obstacles

Operational barriers represent a direct challenge to implementing sustainable practices. Compliance with international regulations such as MARPOL Annex VI requires careful monitoring of NO_x, SO_x, and particulate matter emissions, as well as documentation of the use of ozone-depleting substances (ODSs) in maintenance and operations. Companies also face difficulties applying these standards to older fleets that cannot be easily modified. Modern monitoring technologies and performance analysis tools, such as satellites and smart sensors, are helpful but expensive and require specialized operational training.

Challenges in Applying Sustainable Practices

Implementing sustainability practices in maritime transport faces multiple interrelated challenges. Even after regulatory compliance, companies face:

- High cost of transitioning to low-emission fuels, which reduces ozone and climate-impacting emissions.
- Difficulty in adapting older ships to modern technologies, such as energy management systems and performance analysis to improve fuel efficiency.
- Coordination of logistics between the ship, the port, and land supply chains, which limits fuel efficiency and increases port dwell time, leading to higher emissions.
- Need for trained and specialized personnel to implement environmental procedures efficiently, as a lack of expertise reduces the effectiveness of sustainability programs and affects compliance with international standards.

In summary, despite clear regulatory frameworks to reduce emissions and protect the ozone layer, economic constraints, operational limitations, and difficulties in applying sustainable practices represent a major challenge for shipping companies in achieving a balance between sustainability and profitability.

Recommendations

1. Strengthen International Compliance: Enhance global enforcement mechanism frameworks, particularly under the International Maritime Organization (IMO) and MARPOL Annex VI, to ensure strict global adherence to emissions and hazard mitigation limits.

2. Accelerate Green Innovation: Promote industry-wide transitions toward sustainable zero-emission alternative fuels (such as green methanol and ammonia) and optimize marine propulsion technologies to phase out heavy fossil-fuel reliance.

3. Enforce Non-Hazardous Maintenance Pathways: Mandate the implementation of eco-friendly, non-toxic alternatives for shipboard chemical maintenance and strictly monitor the onboard Inventory of Hazardous Materials (IHM).

4. Integrate Post-Spill Recovery Planning: Shift emergency response frameworks from focusing solely on immediate technical cleanups to developing comprehensive, long-term socioeconomic and environmental recovery strategies for vulnerable coastal societies.

Declarations

Source of Funding

This study received no specific grant from any funding agency.

Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for Publication

The authors declare that they approved this study for publication.

Authors' Contributions

All the authors contributed in the Conception and Design of the work, Data collection, Drafting the article, and Critical revision of the article.

Availability of Data and Materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable in this study.

Ethical Approval

Not applicable in this study.

Informed consent

Not applicable in this study.

References

[1] International Maritime Organization (IMO) (2020). MARPOL Annex VI: Regulations for the prevention of air pollution from ships (Regulation 12: Ozone-depleting substances). IMO Publishing.

[2] Saber, D., Yousfi, N., Selmi, S., Alotaibi, M., Alotaibi, N., Alharthi, R., Alwgdani, H., & Alotaibi, R. (2025). Optimization of last-mile delivery in KSA. Quantum Journal of Engineering, Science and Technology, 6(1): 71–83.

[3] United Nations Environment Programme (2019). Environmental effects of ozone depletion and its interactions with climate change: 2018 assessment. https://www.unep.org/

[4] United Nations Environment Programme (2023). Montreal Protocol on Substances that Deplete the Ozone Layer: 2023 progress report.

[5] World Meteorological Organization (2018). Scientific assessment of ozone depletion: 2018. https://www.wmo.int/

[6] Walker, T.R., Adebambo, O., Del Aguila Feijoo, M.C., et al. (2019). Environmental effects of marine transportation. In C. Sheppard (Ed.), World Seas: An Environmental Evaluation (2nd Ed.), Pages 505–530, Academic Press. https://doi.org/10.1016/b978-0-12-805052-1.00030-9.

[7] Glavan, I., Poljak, I., Mustać, M., & Lonić, I. (2022). Natural refrigerant on board marine vessels. Journal of Maritime & Transportation Science. https://doi.org/10.18048/2022.62.03.

[8] Tsai, W.T. (2024). Environmental policies and countermeasures for phase-out of ozone-depleting substances (ODS) over the last 30 years: Case study in Taiwan. Preprints. https://doi.org/10.20944/preprints202407.1142.v1.

[9] McLinden, M.O. (2026). Thermodynamics of refrigerants: Or why did we ever go with the F-gases? International Journal of Refrigeration, 190: 107033. https://doi.org/10.1016/j.ijrefrig.2026.107033.

[10] Singha, P., Das, C., Köster, L., Kochunni, S.K., Dasgupta, M.S., Widell, K.N., et al. (2025). Thermodynamic comparison of various refrigerants for an on-board R290 refrigeration system with economizer subcooling in small fishing boats. Thermal Science and Engineering Progress, Pages 103443.

[11] Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. Journal of Energy Storage, 43: 103254.

[12] CE Delft & UMAS. (2019). Study on methods and considerations for the determination of greenhouse gas emission reduction for international shipping. Final report prepared for the European Commission.

[13] International Maritime Organization (IMO) (n.d.). Ozone-depleting substances (Regulation 12). https://www.marpoltraininginstitute.com/mmskorean/marpol/annex_vi/r12.htm.

[14] Cunha, I., Moreira, S., & Santos, M.M. (2015). Review on hazardous and noxious substances (HNS) involved in marine spill incidents: An online database. Journal of Hazardous Materials, 285: 509–516. https://doi.org/10.1016/j.jhazmat.2014.11.005.

[15] Geng, P., Mao, H., Zhang, Y., Wei, L., You, K., Ju, J., & Chen, T. (2017). Combustion characteristics and NOx emissions of a waste cooking oil biodiesel blend in a marine auxiliary diesel engine. Applied Thermal Engineering, 115: 947–954.

[16] GESAMP (2019). The revised GESAMP hazard evaluation procedure for chemical substances carried by ships (Reports and Studies No. 102). International Maritime Organization (IMO).

[17] National Academies of Sciences, Engineering, and Medicine (2016). Spills of diluted bitumen from pipelines: A comparative study of environmental fate, effects, and response. The National Academies Press.

[18] Singh, R., & Pahlavan, M. (2025). Overview of sustainable maritime transport optimization and operations. Sustainability, 17: 6460. https://doi.org/10.3390/su17146460.

[19] Kim, T., & Lee, S. (2025). Ship voyage route waypoint optimization using reinforcement learning considering topographical factors and fuel consumption. Journal of Marine Science and Engineering, 13: 1554. https://doi.org/10.3390/jmse13081554.

[20] Karampour, A., & González, P. (2025). Data-driven propulsion load optimization: Reducing fuel consumption and greenhouse gas emissions in double-ended ferries. Journal of Marine Science and Engineering, 13: 688. https://doi.org/10.3390/jmse13040688.

[21] Zhang, Q., & Wang, L. (2025). Leveraging machine learning and optimization models for enhanced seaport efficiency. Maritime Economics & Logistics. Springer. https://doi.org/10.1057/s41278-024-00309-w.

[22] Saber, D., Alzaydani, G., Alali, J., et al. (2024). The implementation of lean and green approaches (G&L) to enhance the operational and environmental performance of a manufacturing plant: A review. Global Journal of Engineering and Technology.

[23] Saber, D., Alghamdi, H.M., Alhuthali, G.K., et al. (2025). Additive manufacturing (3D printing) and the future of supply chains: Opportunities, challenges, and trends. Global Journal of Engineering and Technology Advances, 25(3): 51–64. https://doi.org/10.30574/gjeta.2025.25.3.0336.

[24] Oliveira, C., & Martins, J. (2025). Process optimization in sea ports: Integrating sustainability and efficiency through a novel mathematical model. Journal of Marine Science and Engineering, 13: 119. https://doi.org/10.3390/jmse13010119.

[25] Li, H., & Chen, X. (2025). Enhancement strategy for port resilience: Shipping route optimization methods based on network characteristics of ports. Journal of Marine Science and Engineering, 13: 325. https://doi.org/10.3390/jmse13020325.

[26] International Maritime Organization (IMO) (2021). Fourth IMO GHG Study 2020. IMO Publishing.

[27] European Environment Agency (EEA) (2023). The environmental impacts of international shipping: Emissions to air and water. EEA Report Series. Copenhagen.

[28] Kaamoush, M., El-Sayeh, M., & Omar, M.Y. (2025). Observing air quality in Egypt's Alexandria Port based on the consequences of the COVID-19 lockdown. Discover Sustainability, 6: 699.

[29] International Energy Agency (IEA) (2025). How the shipping sector could save on energy costs. IEA Commentaries. https://www.iea.org/commentaries/how-the-shipping-sector-could-save-on-energy-costs.

[30] Lee, P.T.-W., Kwon, O.K., & Ruan, X. (2019). Sustainability challenges in maritime transport and logistics industry and its way ahead. Sustainability, 11: 1331. https://doi.org/10.3390/su11051331.

[31] Kawamura, Y., Sales, J., & Georgiev, P. (2026). Committee IV.1: Design methods, principles and criteria. In W. Wu & J. Ding (Eds.), Proceedings of the 22nd International Ship and Offshore Structures Congress (Volume 1). ISSC 2025, Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-95-2668-0_7.

[32] Orysiak, E., & Shuper, M. (2025). Economic impacts of decarbonizing the LNG fleet in the Baltic Sea. Energies, 18: 4975. https://doi.org/10.3390/en18184975.

[33] Ahmed, S., Li, T., Zhou, X.Y., Yi, P., & Chen, R. (2025). Quantifying the environmental footprints of biofuels for sustainable passenger ship operations. Renewable and Sustainable Energy Reviews, 207: 114919. https://www.sciencedirect.com/science/article/pii/s1364032124006452.

[34] Inal, O.B., & Deniz, C. (2026). Structured review of maritime life cycle assessment. Marine Sustainability and Technology, 18: 100293. https://doi.org/10.1016/j.sftr.2026.101936.

[35] International Maritime Organization (IMO) (2023). 2023 Guidelines for the Development of the Inventory of Hazardous Materials. Resolution MEPC.379(80), IMO Publishing, London.

[36] Yuksel, O., Blanco-Davis, E., Fuentes, G., Takvam, T., & Tsoulakos, N. (2026). Hybrid propulsion and alternative fuels in maritime transport: A Panama Canal-centred assessment. Journal of Marine Engineering & Technology, Pages 1–31. https://doi.org/10.1080/20464177.2026.2684075.

[37] Seithe, G.J., Bonou, A., Giannopoulos, D., Georgopoulou, C.A., & Founti, M. (2020). Maritime transport in a life cycle perspective: How fuels, vessel types, and operational profiles influence energy demand and greenhouse gas emissions. Energies, 13(11): 2739. https://doi.org/10.3390/en13112739.

[38] Saber, D., Algethami, R., Algorashi, et al. (2024). Utilizing industrial engineering methods and strategies to determine optimal inventory levels of spare parts: A review. Global Journal of Engineering and Technology Advances, 20(1): 20–35.

[39] Cocuzza, E., Ignaccolo, M., Marinacci, C., et al. (2025). Sustainable strategies for ports and maritime logistics: A methodological approach to green transition. Sustainability, 17(13): 5739. https://doi.org/10.3390/su17135739.

[40] Saber, D., Alharthi, L., & Alghamdi, D. (2022). Improvement in Taif roses' perfume manufacturing process by using work study methods: A case study. Asian Journal of Applied Science and Technology, 6(4): 66–80.

[41] International Maritime Organization (IMO) (2024). Digitalization and data transparency in maritime logistics: Technical and operational guidance for emission reduction. IMO Publishing, London.

[42] United Nations Conference on Trade and Development (UNCTAD) (2024). Review of Maritime Transport 2024: Navigating Maritime Chokepoints. United Nations Publications. https://unctad.org/publication/review-maritime-transport-2024.

[43] Im, U., Leung, W., & Christensen, J.H. (2021). Emissions from international shipping and atmospheric impact. Atmospheric Chemistry and Physics, 21: 12495–12521.