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# The paradigm of maritime sustainability and the evolution of the MARPOL regulatory framework

**Cristina-Andreea TUDOR**[1*]

[1] "Mircea cel Batran" Naval Academy, Faculty for Navigation and Naval Management, Fulgerului Street No.1, Constanta, Romania
***cristina.tudor@anmb.ro**

**Abstract**. Maritime transport is essential to global trade but generates significant environmental pressures through operational discharges, atmospheric emissions, ballast-water transfers and accidental pollution. This paper examines the environmental footprint of shipping, the structure and function of the MARPOL regulatory framework, Romania's role in implementing international requirements, and the challenges associated with the transition toward sustainable maritime transport. The discussion is organized around the current research context, the regulatory framework, the analytical approach and the implications for future environmental governance. Particular attention is given to the relationship between environmental protection, technological innovation, regulatory enforcement and the economic continuity of maritime trade.
**Keywords:** pollution, maritime transport, MARPOL, marine ecosystem, environmental sustainability.

## 1. Introduction

Maritime transport is a central component of global trade because it enables the movement of large cargo volumes over intercontinental distances. However, shipping also produces environmental pressures that affect marine ecosystems, coastal communities and public health. These pressures arise both from routine operations and from accidental events such as collisions, groundings and chemical or oil spills.

The International Convention for the Prevention of Pollution from Ships (MARPOL), adopted under the auspices of the International Maritime Organization (IMO), represents the principal international legal instrument for preventing pollution from ships. In Romania, the convention is implemented within the national maritime regulatory framework, including through Law No. 6/1993. The purpose of this paper is to examine the relationship between maritime activity, environmental risks and the evolution of regulatory and technological responses.

The paper addresses three research questions: (1) what are the main environmental pressures associated with modern shipping; (2) how does MARPOL address operational and accidental pollution; and (3) what regulatory, technological and institutional measures are relevant to the transition toward sustainable maritime transport?

The literature identifies maritime pollution as a multidimensional problem involving atmospheric emissions, oil and chemical contamination, waste generation, invasive aquatic species and the accumulation of contaminants in marine food webs. Research on ship accidents emphasizes the

potential for acute ecological damage and the importance of prevention, preparedness and response mechanisms (Wan et al., 2022), (Barbieri et al., 2025).
Studies and institutional reports also describe the environmental consequences of conventional marine fuels, including emissions of sulfur oxides, nitrogen oxides and particulate matter (Bučinskas et al., 2024). Other research focuses on microplastics and contaminants in seafood, highlighting potential implications for food security and human health (Barbieri et al., 2025), (Unuofin, 2023).

The regulatory literature examines MARPOL alongside wider international maritime and environmental instruments. The convention's annex-based structure provides requirements for oil, noxious liquid substances, harmful substances in packaged form, sewage, garbage and air pollution (IMO, 2011), (Saquib, 2025). Recent studies additionally discuss the legal and institutional challenges produced by emerging technologies and evolving maritime operations (Eslam, 2025).

The reviewed sources indicate that sustainability in shipping is increasingly associated with decarbonization, alternative fuels, digital optimization and stronger environmental governance. Nevertheless, the literature also identifies economic and infrastructural barriers to the adoption of cleaner technologies (Wahidul et al., 2025), (Yuhan et al., 2025).

## 2. Methodology

This study uses a qualitative, narrative review methodology based on selected scientific publications, international institutional documents and regulatory materials. The sources were examined thematically and organized into four analytical categories: (1) environmental impact of maritime transport; (2) MARPOL regulatory framework; (3) Romania's institutional and geographical context; and (4) sustainability-oriented technological and policy responses.

The analysis is interpretive rather than statistical. It compares the principal environmental risks identified in the literature with the regulatory mechanisms and transition measures discussed in the selected sources. The methodology is intended to provide a structured synthesis and to identify areas requiring further empirical investigation.

### *2.1. Environmental impact of maritime transport*

The reviewed material indicates that shipping-related pollution can be divided into operational pollution and accidental pollution. Operational pollution includes oily bilge-water discharges, sewage, garbage, air emissions and the release of substances associated with ship maintenance. Ballast-water operations may also transfer non-native organisms between geographically distant ecosystems (Walker, 2016).

Accidental pollution is associated with events such as collisions, groundings, structural failures and cargo-related incidents. These events may result in the release of oil, hazardous chemicals or other pollutants into the marine environment. Their consequences depend on the type and quantity of the released substance, hydrometeorological conditions, the proximity of sensitive ecosystems and the effectiveness of emergency response mechanisms.

### *2.2. MARPOL regulatory framework*

The analysis confirms that MARPOL provides a comprehensive regulatory framework for addressing different sources of ship-generated pollution. Its annex-based structure establishes specific requirements concerning oil pollution, noxious liquid substances, harmful substances transported in packaged form, sewage, garbage and air pollution (IMO, 2011), (Saquib, 2025).

The effectiveness of these requirements depends not only on the existence of international regulations but also on their implementation through technical standards, shipboard procedures, documentation, inspections and monitoring mechanisms. Compliance therefore represents an institutional process involving flag states, port states, ship operators, classification organizations and other maritime authorities (Eslam, 2025).

The results also indicate that MARPOL should be considered part of a broader maritime environmental governance system. Other international and regional instruments address related issues, including ballast-water management, marine ecosystem protection and the reduction of greenhouse-

gas emissions. These instruments complement the MARPOL framework and demonstrate the increasing complexity of contemporary maritime environmental regulation (EMSA).

However, the presence of formal regulations does not automatically guarantee the elimination of pollution risks. The practical results of regulatory implementation depend on the consistency of inspections, the availability of adequate port reception facilities, the quality of reporting systems and the capacity of authorities to identify and sanction non-compliance.

### *2.3. Romania's institutional and geographical context*

Romania's geographical position on the western coast of the Black Sea creates a relevant context for the application of international maritime environmental standards. The presence of major port infrastructure, particularly the Port of Constanta, connects national maritime activity with international shipping routes and regional commercial networks.

The analysis indicates that the implementation of MARPOL requirements in Romanian maritime areas must be considered alongside the environmental characteristics of the Black Sea. As a semi-enclosed marine basin, the Black Sea may present particular vulnerabilities related to pollutant accumulation, limited water exchange and the interaction between maritime activities and land-based sources of pollution (Bădescu-Secu, 2025).

Port operations may generate environmental pressures through ship traffic, cargo handling, waste management, bunkering activities and the reception of ship-generated waste. Effective environmental management therefore requires cooperation between port operators, maritime authorities, environmental institutions and shipping companies.

Nevertheless, the reviewed material does not provide sufficient empirical data to quantify the precise contribution of each pollution source within Romanian maritime waters. This limitation indicates the need for further field-based research involving environmental monitoring, port-level pollution inventories and assessments of regulatory compliance.

### *2.4. Sustainability-oriented technological and policy responses*

The literature and policy documents describe a transition toward lower-emission maritime transport. The options under consideration include liquefied natural gas, methanol, ammonia, hydrogen-based systems, wind-assisted propulsion and digital voyage optimization. The practical suitability of each option depends on vessel type, route characteristics, fuel availability, safety requirements and port infrastructure (Wahidul et al., 2025), (Yuhan et al. 2025).

The transition also creates financial and organizational challenges. Shipowners may need to retrofit existing vessels or invest in new propulsion systems, while ports must develop suitable bunkering, waste-reception and monitoring infrastructure (UNCTD, 2025).

## 3. Results and discussions

### *3.1. The Relationship between Regulation and Environmental Effectiveness*

The results suggest that MARPOL represents a necessary foundation for maritime pollution prevention, but its effectiveness depends on the quality of implementation and enforcement. International conventions establish common obligations, while national authorities and maritime organizations are responsible for translating these obligations into operational practices.

A significant issue concerns the difference between formal compliance and effective environmental protection. A vessel may possess the required documentation and equipment while still generating environmental risks due to inadequate maintenance, procedural failures, inaccurate reporting or insufficient monitoring. This observation supports the need for an integrated compliance approach combining documentary verification, technical inspection and environmental performance assessment.

The findings also indicate that regulatory effectiveness should not be evaluated exclusively through the number of inspections or detected violations. Additional indicators may include the frequency of

pollution incidents, the quality of waste reception services, the management of ship-generated waste and the capacity of authorities to respond to non-compliance.

### *3.2. The Interaction between Maritime Development and Environmental Protection*

Maritime transport contributes significantly to international trade and economic development. At the same time, the expansion of maritime activity may increase environmental pressures in ports and coastal areas. This creates a policy challenge involving the coordination of economic objectives with environmental protection requirements.

The analysis indicates that environmental measures may generate additional operational and financial costs for shipowners, port operators and maritime authorities. Investments in cleaner fuels, emission-reduction equipment, waste-management systems and monitoring technologies may require substantial financial resources.

However, the long-term implications of environmental degradation—including ecosystem damage, increased remediation costs and risks to coastal communities—should also be considered. A sustainable maritime policy therefore requires an assessment that incorporates both the immediate costs of compliance and the potential long-term benefits of pollution prevention.

Rather than treating environmental protection and maritime competitiveness as mutually exclusive objectives, the findings support an integrated approach based on technological innovation, regulatory predictability and coordinated infrastructure development.

### *3.3. Challenges Associated with Alternative Fuels and Emerging Technologies*

The transition toward alternative fuels introduces several technical and regulatory uncertainties. Different fuels present distinct characteristics in terms of energy density, storage requirements, safety risks, availability and environmental performance throughout their lifecycle.

For this reason, the adoption of a particular alternative fuel cannot be evaluated solely on the basis of its potential to reduce direct emissions during vessel operation. A comprehensive assessment should also consider fuel production, transportation, storage, bunkering and possible emissions throughout the supply chain.

Emerging technologies may also require amendments to existing operational procedures and training systems. Crews and port personnel must be prepared to manage new equipment, safety procedures and emergency scenarios. Regulatory frameworks must consequently evolve in parallel with technological development.

The analysis suggests that a fragmented approach, in which individual shipowners or ports adopt isolated solutions, may limit the effectiveness of the wider transition. Coordinated planning between governments, ports, fuel suppliers, technology developers and research institutions is necessary to support interoperability and infrastructure compatibility.

### *3.4. Implications for Romania and the Black Sea Region*

The Romanian maritime sector provides a relevant case for examining the interaction between international environmental regulation and regional maritime development. The Port of Constanța and associated maritime activities create opportunities for economic growth but also require effective management of ship-generated pollution and environmental risks.

In the Black Sea region, environmental governance should consider the combined influence of maritime transport, coastal development, industrial activity and land-based pollution. Pollution prevention measures applied exclusively to vessels may therefore be insufficient if other significant sources are not addressed through complementary policies.

The implementation of international requirements in Romania could be strengthened through improved environmental monitoring, the modernization of port reception facilities, the development of transparent compliance indicators and greater cooperation among national and regional institutions.

Nevertheless, the present analysis is primarily documentary and does not establish a direct causal relationship between specific regulatory measures and measured environmental improvements in

Romanian waters. Such a relationship would require longitudinal environmental data, port-specific statistics and systematic comparisons between regulatory interventions and pollution indicators.

### *3.5. Research Gaps and Scientific Implications*

The reviewed literature indicates several areas in which further research is needed. First, there is a need for more detailed empirical data concerning the quantity and composition of pollutants generated by vessels operating in the Black Sea. Second, the effectiveness of port reception facilities should be evaluated using consistent operational and environmental indicators.

Third, future studies should investigate the lifecycle environmental performance of alternative marine fuels rather than focusing exclusively on emissions during vessel operation. Fourth, research could examine the relationship between regulatory inspections, detected non-compliance and actual environmental outcomes.

From a methodological perspective, future investigations could combine qualitative documentary analysis with quantitative environmental monitoring, interviews with maritime stakeholders and comparative case studies of ports in the Black Sea region. Such mixed-method research would provide a more comprehensive understanding of the relationship between regulation, technological transition and environmental performance.

## 4. Conclusions

Maritime transport remains indispensable to global trade, yet its environmental footprint requires continuous regulatory, technological and institutional responses. The reviewed evidence demonstrates that pollution risks arise from both routine ship operations and accidental events, affecting marine biodiversity, ecosystem services and potentially human health.

MARPOL constitutes the principal international framework for addressing these risks. Its effectiveness is strengthened when legal requirements are supported by inspections, monitoring, adequate port facilities and national implementation. In Romania, the protection of the Black Sea environment is closely connected to the effective application of international rules in and around major maritime gateways such as Constanta Port.

However, there are certain limitations to the MARPOL Convention. Although traditional pollutants have been significantly reduced, climate change and new maritime technologies are revealing severe structural limitations in the management of modern pollution risks. Sustainable maritime transport should therefore be approached as an integrated process involving pollution prevention, decarbonization, technological innovation, institutional cooperation and economic planning.

Future research should move beyond conceptual synthesis and develop empirical assessments of maritime pollution and regulatory performance. Relevant directions include: (1) measuring pollutant concentrations in port and coastal areas; (2) evaluating MARPOL compliance indicators; (3) assessing the effectiveness of port reception facilities; (4) comparing the life-cycle impacts of alternative marine fuels; (5) investigating ballast-water management in the Black Sea; and (6) analyzing the economic implications of decarbonization for Romanian ports and shipping operators.

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- Conceptualization: C-A .T.
- Methodology: C-A.T.
- Investigation: C-A.T.
- Writing original draft: C-A.T.
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