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STATE AND DYNAMICS OF ENVIRONMENTAL IMPACT FROM SHIPPING IN THE BLACK SEA REGION: TRENDS, CHALLENGES, AND TECHNOLOGICAL RESPONSES

The Black Sea region is one of the key transportation arteries between Europe, the Caucasus and Asia, with more than 140 million tons of various cargoes passing through it annually. Therefore, the intensification of shipping combined with the lack of strict environmental regulations, such as emission control zones (ECAs), is creating growing pressure on the marine environment. The article provides an overview of quantitative indicators of the impact of maritime transport on the Black Sea ecosystems with a focus on CO_2, NO_x, SO_x *emissions, noise pollution, biodiversity loss, and local environmental hazards. It also highlights current research in the field of ecology, logistics, energy efficiency, and the latest technologies that form the basis for the development of a long-term regional policy, taking into account the goals of the European Green Deal and the Convention on the Protection of the Black Sea against Pollution. The most vulnerable areas, including the Danube Delta, the Odesa coast, and the Bosphorus Strait, are identified. A comparison with the environmental standards of the Baltic Sea is made, which allows to identify regulatory gaps. A number of technological solutions are proposed, including cold ironing, LNG, scrubbers, and digital MRV systems. Particular attention is paid to policy initiatives: the creation of a pilot SECA zone, unification of port electrification policies, introduction of mandatory emissions monitoring, and creation of the Black Sea Green Shipping Fund. Recommendations for the implementation of a comprehensive strategy for environmental safety of navigation in the Black Sea based on the principles of sustainable development and interstate cooperation are presented. An analytical comparison of the environmental situation in the Black Sea with other sea basins where successful emission control and fleet modernization practices have already been implemented is made. Based on this comparison, the author substantiates the feasibility of adapting such instruments in the Black Sea context, taking into account the geopolitical complexity of the region.*

Key words: *shipping, environmental safety, maritime transportation, MARPOL Annex VI,* CO_2, NO_x, SO_x *emissions, SECA zone, IMO, port electrification, cold ironing, ecosystem risks, biodiversity, noise pollution, ballast water, decarbonization of the fleet, LNG, scrubber technologies, energy efficiency, MRV system, green shipping, environmental policy, transnational governance, sustainable development.*

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СТАН ТА ДИНАМІКА ЕКОЛОГІЧНОГО НАВАНТАЖЕННЯ ВІД СУДНОПЛАВСТВА В ЧОРНОМОРСЬКОМУ РЕГІОНІ: ТЕНДЕНЦІЇ, ВИКЛИКИ, ТЕХНОЛОГІЧНІ ВІДПОВІДІ

Чорноморський регіон є однією з ключових транспортних артерій між Європою, Кавказом та Азією, через яку щорічно проходить понад 140 млн тонн різних вантажів. Тому інтенсифікація судноплавства в поєднанні з відсутністю жорстких екологічних регуляцій, таких як зони контролю викидів (SECA), створює зростаючий тиск на морське середовище. У статті представлено огляд кількісних показників впливу морського транспорту на екосистеми Чорного моря з акцентом на обсяги викидів CO_2, NO_x, SO_x, *шумове забруднення, втрати біорізноманіття та локальні екологічні небезпеки. Також висвітлено сучасні дослідження в галузі екології, логістики, енергоефективності та новітніх технологій, що формують підґрунтя для розробки довгострокової регіональної політики з урахуванням цілей Європейського зеленого курсу та Конвенції із захисту Чорного моря від забруднення. Визначено найбільш вразливі зони, зокрема дельту Дунаю, узбережжя Одеси та Босфорську протоку. Проведено порівняння з екологічними стандартами Балтійського моря, що дозволяє окреслити нормативно-регуляторні прогалини. Запропоновано низку технологічних рішень, серед яких cold ironing, впровадження LNG, scrubbers та цифрові MRV-системи. Окрема увага приділена політичним ініціативам: створенню пілотної SECA-зони, уніфікації політик електрифікації портів, запровадженню обов'язкового моніторингу викидів та створенню фонду «Зелене судноплавство Чорного моря». Подано рекомендації щодо реалізації комплексної стратегії екологічної безпеки судноплавства в Чорному морі на основі принципів стійкого розвитку та міждержавної співпраці. Проведено аналітичне зіставлення екологічної ситуації в Чорному морі з іншими морськими басейнами, де вже впроваджено успішні практики контролю за викидами та модернізації флоту. На основі цього порівняння обґрунтовано доцільність адаптації подібних інструментів у чорноморському контексті з урахуванням геополітичної складності регіону.*

Ключові слова: *судноплавство, екологічна безпека, морські перевезення, MARPOL Annex VI, викиди* CO_2, NO_x, SO_x, *зона SECA, IMO, портова електрифікація, cold ironing, екосистемні ризики, біорізноманіття, шумове забруднення, баластні води, декарбонізація флоту, LNG, scrubber-технології, енергоефективність, MRV-система, зелене судноплавство, екологічна політика, транснаціональне управління, стійкий розвиток.*

Problem statement

The Black Sea region, a key transportation corridor between Europe, the Caucasus, and Central Asia, is experiencing a steady increase in shipping intensity. At the same time, the environmental impacts of this activity remain poorly controlled due to the lack of strictly regulated areas (e.g., SECA), insufficient coordination between littoral states, and fragmented environmental monitoring systems. Increased emissions of CO_2, NO_x, and SO_x, as well as localized forms of pollution (oil emissions, ballast water, noise) pose a systemic risk to unique marine ecosystems, particularly in areas of transboundary vulnerability (the Danube Delta, the Bosphorus and Kerch Straits). Currently, there is no integrated assessment of the environmental impact of shipping in the Black Sea, taking into account quantitative indicators, regulatory context, and technological practices.

Literature review

The analysis of sources allows us to identify several key areas of research and international reports that form the context for assessing the environmental impact of shipping in the Black Sea. The data from the reports of international organizations – EMSA, IMO, UNECE, UNCTAD, UNEP – reflect the current volumes of cargo flows, levels of CO_2, NO_x, SO_x emissions, as well as regulatory gaps compared to the SECA zones of other seas [1–7]. These documents provide a quantitative basis for building environmental scenarios and assessing the state of pollution.

The peer-reviewed articles [8–14] cover current trends in alternative fuels, decarbonization of maritime transport, emissions from 1970 to 2021, and prospects for the global transition to hydrogen and biofuels. Studies [15–20] focus on the national and regional levels, covering energy efficiency, the impact of new technologies, environmental logistics, and regulatory management.

This study aims to provide a comprehensive overview of the current state and dynamics of the environmental load from maritime transport in the Black Sea region, focusing on quantitative data, international regulations, technical innovations, and environmental management practices. Particular attention is paid to analyzing emissions, comparing with other sea basins (Baltic, English Channel), identifying vulnerable areas, and formulating proposals for implementing a regional sustainable shipping policy.

Main research materials

The Black Sea is a strategically important transportation artery for Europe and Asia, with more than 140 million tons of cargo passing through it annually, including oil, grains, containers, and industrial products [1, 2]. The region's key ports – Odesa, Constanta, Istanbul, Varna, and Batumi – function as transshipment centers and logistics hubs for international trade. The growing shipping intensity, especially in the last decade, has created high environmental pressure on coastal and open waters.

According to the European Maritime Safety Agency (EMSA), in 2022 alone, CO_2 emissions from shipping in the Black Sea exceeded 10 million tons, comparable to some EU countries' national emissions [3]. Additionally, SO_x and NO_x emissions cause water acidification, eutrophication, reduced oxygen levels, and threats to biodiversity. The following areas are considered particularly vulnerable: the Danube Delta, Ukrainian coast near Odesa, Bosphorus Strait and the waters of Istanbul and Bulgarian coast (ports of Varna and Burgas)

The UNEP and the Black Sea Commission observe a consistent trend of exceeding permissible concentrations of oil products and heavy metals and increased local algal blooms near port areas. At the same time, unlike the Baltic Sea or the English Channel, the Black Sea region is not yet designated as ECA/SECA zones following MARPOL Annex VI, which permits the use of high-sulfur fuels without additional restrictions [4].

The increasing number of tankers, bulk carriers, and Ro-Ro vessels worsens the situation. In 2022, over 42,000 vessels passed through the Bosphorus Strait alone, many of which were potential sources of pollution [5]. This heightens the need for stricter regulations and the implementation of modern eco-technologies, such as cold ironing, LNG propulsion, scrubbers, and port electrification.

Trends: development of shipping and environmental impact in the Black Sea region

The last decade has demonstrated a clear upward trend in cargo turnover and ship calls to Black Sea ports, especially in Ukraine, Romania, Bulgaria, and Turkey. According to EMSA [1], in 2022, over 85,000 ship calls were recorded at Black Sea ports, the majority being tankers (30 %), bulk carriers (25 %), Ro-Ro ships (15 %), and container ships (12 %). The highest concentration is noted in the ports of Istanbul, Constanta, and Odesa.

The fuel mix is also changing. After the introduction of the global sulfur content limit of 0.5 % in fuels (from 2020, MARPOL Annex VI), the vast majority of the fleet switched to VLSFO. However, the use of LNG as a fuel is still limited, in particular due to the lack of appropriate infrastructure in the region. Nevertheless, the port of Constanta has already announced plans to build an LNG terminal by 2026 [2].

At the same time, there is a gradual introduction of cold ironing technologies that reduce emissions in ports by connecting the ship to the shore power grid. Pilot projects are being implemented in Burgas, Varna, and Constanta with the support of the EU [3].

The introduction of digital environmental logbook systems that collect data on fuel consumption, emissions tracking, and route optimization is also becoming widespread. These data are reported through the EMSA THETIS-MRV system and used to compile annual analytical reviews [4].

Despite these changes, the Black Sea remains a region with low environmental regulation compared to the Baltic and North Seas, both of which have long been designated as ECA/SECA zones. This creates a «regulatory gap» that hinders the introduction of cleaner technologies in the area [5]. Meanwhile, after 2025, the EU is expected to increase pressure for the expansion of eco-zones, which may alter the environmental policies of member states.

One key indicator of the intensity of environmental burdens in the region is the fleet's composition that regularly visits Black Sea ports. According to EMSA and Black Sea MoU data, six main types of vessels form the backbone of regional shipping. Tankers and bulk carriers account for the largest traffic share due to their transportation of energy, grain, and raw materials. These vessels are energy-intensive and have the most significant carbon footprint per cargo unit (Table 1).

Table 1

Fleet Composition in the Black Sea Region (2022)

Ship Type	Port Calls (2022)	Share (%)
Tankers	25,500	30 %
Bulk Carriers	21,200	25 %
Ro-Ro	12,700	15 %
Container Ships	10,200	12 %
General Cargo	8,500	10 %
Others	5,900	8 %

As can be observed from the table, tankers account for more than a third of all ship calls (30 %), which is critical from an environmental perspective due to the potential for oil spills. Bulk carriers (25 %) and Ro-Ro vessels (15 %) also play a significant role, especially in the context of intensive short-sea traffic between countries in the region. Container and general cargo ships (22 % together) indicate active trade and intensive logistics. Such a fleet structure requires the introduction of differentiated environmental approaches adapted to the type of ship and the nature of its route. This is especially important given the need to introduce regional regulations such as ECA/SECA to reduce the impact of the most polluting ships.

The graph in Figure 1 shows the dynamics of the number of ship calls to the ports of the Black Sea countries during 2018–2022. The largest load is consistently recorded in Turkey, with a gradual increase. Romania shows a steady growth, while Ukraine has a decline in 2020–2021 with a partial recovery in 2022. This picture makes it possible to assess the geographical distribution of environmental pressure and set environmental policy priorities for each country.

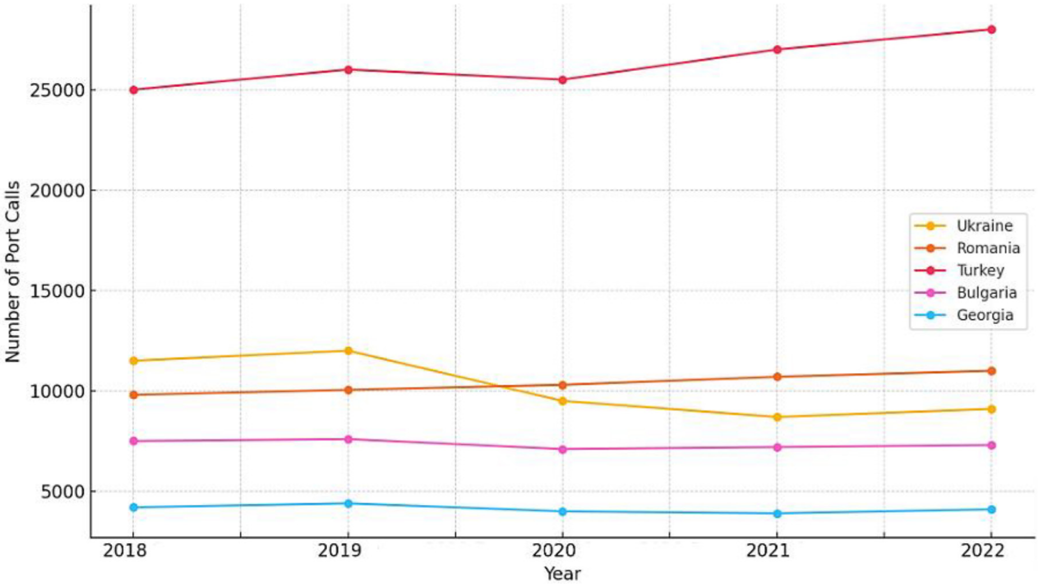

Fig. 1. Port Calls in the Black Sea by Country (2018–2022)

Challenges: environmental risks and regulatory gaps

Despite the economic importance of shipping, the Black Sea region faces a number of acute environmental challenges, which are significantly exacerbated by an insufficient regulatory framework and weak integration into global environmental regimes.

One of the key risks is chemical pollution. According to the Black Sea Commission [1], the coastal zones of Odesa, Varna, and Burgas have recorded a 3–5-fold exceedance of the maximum permissible concentrations of oil products. Particularly dangerous are discharges from ballast water, which contain residual fuel oil, bacteria, and heavy metals and can lead to the introduction of invasive species.

Another challenge is the underwater noise generated by large ships (especially bulk carriers and tankers). According to a study by EMSA [2], the noise intensity in the areas near the Bosphorus and the Danube Delta far exceeds environmentally safe levels, affecting the vital activity of cetaceans and fish.

A separate problem is the lack of SECA/ECA zone status. All Black Sea coastal states currently allow the use of fuels with a high sulfur content (up to 0.5 %), which, under conditions of heavy traffic, leads to the accumulation of sulfur oxides (SO_x) and nitrogen oxides (NO_x), which cause acidification of the marine environment and local eutrophication [3].

There are also periodic leaks of oil products from ships while docking in ports or maneuvering, especially in conditions of outdated port infrastructure. These accidents are not always subject to mandatory reporting, making monitoring and preventing recurrence difficult.

In addition, the ecosystems of the Danube Delta, the northwestern Black Sea shelf, and the adjacent lagoons are already in a state of critical overload due to the cumulative impact of maritime transport, agricultural runoff, and industrial pollution [4].

Technological answers: the transition to cleaner shipping

In response to the growing environmental burden in the Black Sea, recent years have seen the introduction of a number of technological solutions aimed at reducing emissions, improving environmental monitoring, and increasing energy efficiency.

One of the leading areas is cold ironing (shore power), which involves connecting ships to the shore power grid while they are docked in port. This practice eliminates the need for ship diesel engines and reduces local emissions by up to 90 % of CO_2 and 95 % of SO_x/NO_x. The ports of Constanta, Burgas, and Varna have already implemented pilot projects with support from the European Union's CEF program [1].

There is a growing interest in using liquefied natural gas (LNG) in marine energy. Although the infrastructure in the Black Sea is still being developed, projects in Romania and Turkey show the prospects for LNG bunker terminals by 2026 [2]. LNG can reduce SO_x emissions to almost zero and NO_x emissions by 80 % compared to HFO.

Another solution is the implementation of scrubber-type treatment plants, which enable the continued use of heavy fuel while treating the exhaust. According to EMSA, over 12 % of ships operating in the region are already equipped with scrubbers [3].

Digital solutions, such as automated reporting systems (MRV), satellite monitoring (CleanSeaNet), and tools for optimizing ship routes and speed, are also being intensively developed. They not only increase transparency but also create a basis for future integration with market-based carbon regulation mechanisms (EU ETS from 2024) [4].

Cooperation with the Baltic Sea, which has long functioned as an SECA/ECA zone, also plays an important role. The experience of switching to clean fuels, implementing ballast systems, and preparing port infrastructure serves as a technological model for the Black Sea.

Recommendations for environmental safety policy in the Black Sea

Five strategic directions of regional environmental policy have been formulated based on a comprehensive analysis of the environmental situation and trends in maritime transportation in the Black Sea region. Their implementation will significantly reduce the level of marine pollution and increase the environmental sustainability of shipping.

1. Establishment of a Pilot SECA Zone (2025–2027).

The most appropriate approach is to introduce a Sulphur Emission Control Area (SECA) in the northwestern sector of the Black Sea, specifically in the coastal waters of Ukraine and Romania. This would entail a concerted initiative at the International Maritime Organization (IMO) level, the European Maritime Safety Agency (EMSA), and national environmental services. The pilot zone will enable testing new fuel quality and emission standards without the need for immediate extension to the entire basin.

2. Unification of Port Electrification.

Policies In the context of combating local emissions of CO_2, SO_x, and NO_x, it is vital to develop cold ironing (shore power) infrastructure in the region's key ports. Constanta, Varna, Istanbul, and Odesa ports may become the first participants in a unified regional program that includes standardized technical specifications for connections, tax benefits for shipowners, and subsidy mechanisms from government agencies.

3. Mandatory Emissions Reporting (by 2026).

Introducing a system for monitoring, reporting, and verifying emissions (MRV) in the Black Sea will enhance the transparency of maritime transport and provide a reliable database for decision-making. All vessels calling at the region's ports should be required to report real fuel consumption, vessel routes, and CO_2, NO_x, and SO_x emissions.

4. Establishment of the Black Sea Green Shipping Fund.

This initiative envisions the creation of a special fund that would gather resources from EU programs (Green Deal, CEF), international environmental funds, and national budgets to finance the "green" renewal of the fleet. Low-interest grants or loans could be utilized for installing scrubbers, converting ships to LNG or hybrid power systems, and reconstructing port facilities.

5. Conclusion of Bilateral Environmental Agreements (BETAs).

To improve the effectiveness of control over transboundary pollution zones, it is recommended that neighboring states establish bilateral agreements. These agreements can regulate the environmental regime in the most sensitive areas, such as the Danube Delta, the Bosphorus, and the Kerch Straits. This would allow for the coordinated implementation of ship speed limits, ballast water requirements, noise control, and joint monitoring.

To improve the effectiveness of environmental regulation of maritime transport in the Black Sea, a package of policy initiatives aimed at reducing shipping's harmful impact on the marine environment is proposed. Below is an overview of the key steps that can be implemented in an interstate format (Table 2).

These measures will help reduce pollution, increase monitoring transparency, and ensure that shipping is adapted to modern environmental challenges. This strategy also brings the Black Sea region closer to the standards of sustainable maritime development adopted in the Baltic, North Sea, and other IMO eco-zones.

Table 2

Policy Measures for Black Sea Maritime Sustainability

No.	Policy Initiative	Description
1	Establishment of a Pilot SECA Zone (2025–2027)	Designate the NW Black Sea (Ukraine and Romania) as a SECA with phased implementation via IMO, EMSA, and national authorities
2	Harmonization of Port Electrification Policies	Implement shore power (cold ironing) in key ports with standardized interfaces and state/EU co-financing
3	Mandatory Emissions Reporting (MRV System)	Deploy a regional MRV platform requiring vessels to report fuel use and emissions (CO_2, NO_x, SO_x)
4	Black Sea Green Shipping Fund	Launch a financial instrument to subsidize LNG retrofits, scrubbers, and port environmental upgrades
5	Bilateral Environmental Traffic Agreements (BETAs)	Foster state-to-state agreements for managing pollution in shared zones (e.g., Bosporus, Danube Delta, Kerch Strait)

Conclusions

The study demonstrated that the Black Sea region continues to be a crucial center for international shipping while also being an environmentally vulnerable maritime system. The increase in cargo flows through the ports of Turkey, Romania, and Ukraine is accompanied by a rise in negative environmental impacts, primarily due to greenhouse gas emissions, noise, and oil pollution. Tankers, bulk carriers, and Ro-Ro vessels constitute the majority of the fleet and are the primary sources of significant stress on the marine environment. At the same time, the lack of officially established emission control zones in the region, such as SECA or ECA, considerably undermines the potential for effective environmental regulation.

Despite the challenges, the region has already started implementing some technological solutions, such as electrifying berths (cold ironing), introducing scrubbers, using alternative fuels (LNG), and launching digital platforms for emissions monitoring (MRV). The ports of Constanta, Burgas, and Varna demonstrate the potential to adapt to EU environmental standards.

A coherent regional policy needs to be developed to achieve environmentally safe and economically sustainable shipping in the Black Sea. Priority measures include the creation of a pilot SECA zone, unification of port electrification programs, introduction of mandatory emissions reporting, formation of a trust fund to support the «green» fleet, and conclusion of cross-border environmental agreements. A coordinated strategy involving the littoral countries, the EU, and the IMO is the key to preserving the ecological balance of the Black Sea in the face of growing logistical pressures.

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