Romanian Journal of Ecology & Environmental Chemistry, 7(2), 2025
https://doi.org/10.21698/rjeec.2025.212

Communication

Modern techniques for pollution control onboard ships

CRISTINA-ANDREEA TUDOR

„Mircea cel Batran" Naval Academy, Faculty for Navigation and Naval Management, 1 Fulgerului Street, Constanta, Romania,
**Corresponding author: cristina.tudor@anmb.ro*

Received: 24.11.2025 | *Reviewed: 08.12.2025* | *Accepted: 18.12.2025*

Abstract
Marine pollution is a critical problem for water ecosystems, human health and global ecology. Ships pollute the sea with oil discharges, garbage, air emissions, chemical spills and ballast water, so that it is important to adopt proper pollution prevention solutions. According to the International Convention for the Prevention of Pollution from Ships (MARPOL), vessels have to use oil-water separators, double hulls, emission control systems, and waste management devices to limit their environmental footprint. The control of liquid pollution is performed with the help of innovative response plans, procedures and the development of oil absorbing technologies. The release of garbage is reduced by sorting waste and using recycling, incineration and other techniques. Reducing air pollution means using renewable energy sources, scrubbers, low sulfur fuels, energy-efficient engines, wind-solar associated propulsion systems, and treating ballast water to prevent the spread of invasive species. Ships must also have wastewater treatment plants as well as stocks of biodegradable cleaning products to comply with sewage and chemical discharge regulations. Artificial intelligent based pollution monitoring, hybrid and alternative energies (hydrogen and ammonia) are modern technical solutions to address this problem.

Keywords: *pollution, regulation, technology, maritime, sustainability*

INTRODUCTION

Global shipping activities have a high demand in the maritime industry while at the same time contribute to a significant amount of environmental pollution. Ships emit harmful toxins from ballast water release and produce multiple solid waste streams which have a devastating impact on marine environments [1]. The International Maritime Organization (IMO) and MARPOL have since introduced new environmental regulations to attempt to mitigate this negative impact [2]. Advances in various technologies such as alternative fuels, exhaust gas cleaning systems and waste management technologies are pushing the shipbuilding industry towards a more sustainable mode of operation. The aim of this article is to review current pollution control methods on ships and assess their efficacy. Solutions that can be implemented without compromising vessel operation will lead to a reduced impact of shipping activities on the environment.

MATERIALS AND METHOD

Major sources of pollution onboard ships

Air pollution

Harmful gases such as sulfur oxides (SO_2), nitrogen oxides (NO_2), and carbon dioxide (CO_2) evacuated by vessels lead to climate change and health issues that affect citizens residing nearby ports [3]. The provisions of MARPOL Annex VI regulate ship pollution through emission control that promotes the use of environmentally friendly fuels. Combined use of scrubbers and low-sulfur fuels allows a maritime industry pollution control through their symbiotic eruption system [4,5]. Innovations and binding regulations need to continue in order to achieve reliable reductions of air pollution in the maritime industry [6,7].

Water pollution
The three main sources of pollution from maritime ships are ballast water discharge, oil spills and chemical waste disposal [8]. Ballast water systems that stabilize vessels have the drawback of transporting invasive species that disrupt the marine biodiversity [9,10]. The IMO's Ballast Water Management Convention demands ships operating under its control to implement water treatment solutions such as filtering and ultraviolet (UV) methods before ballast water discharge [11,12]. Substantial environmental hazards emerge when vessels release oil accidentally or through operational discharges resulting in the contamination of marine habitats and coastal regions [13].

Solid waste and oil spills
Ships produce considerable amounts of solid waste by discharging plastics, food waste and hazardous materials [14,15]. Marine pollution caused by improper waste disposal produces severe consequences which harm not only the marine ecosystem but also the coastal habitats [16]. The waste regulations established by MARPOL Annex V demand vessels to deploy onboard facilities for waste recycling and incineration together with waste treatment systems [2]. Modern ships use waste compactors and sewage treatment plants to reduce the environmental impacts [17]. Plastic materials represent some of the most dangerous pollutants since they disintegrate very slowly while being commonly found throughout ocean environments. Enhancement of waste separation methods and a reduction in single-use plastics utilization will decrease pollution effects of the environment.

Modern pollution control techniques
Alternative fuels and energy efficiency
The marine industry shifts to alternative fuel solutions with the aim of decreasing the environmental pollution and optimization of energy performance. Liquefied natural gas (LNG) is the primary alternative fuel that ensures substantial reductions of SO_2 and NO_2 emissions [18]. The use of hydrogen with ammonia-based fuels is under development as zero-emission alternatives.

Exhaust gas cleaning systems (scrubbers)
Vessels use scrubbers as their principal emissions reduction technology for sulfur oxides which allows them to observe MARPOL Annex VI standards [2]. The scrubber market includes three main system technologies: open-loop, closed-loop and hybrid scrubbers. Open-loop scrubbers clean contaminants using seawater resulting in environmental concerns because treated water is discharged into marine waters. The recycling method of cleaning water in closed-loop systems reduces discharges to the environment. Hybrid scrubbers assure the flexibility to function between open and closed modes according to regulation needs. The pollution efficiency achieves up to 98% for SO_2 emissions so that this technology is appropriate.

Waste management and recycling
Some of the substantial wastes produced by ships include plastic materials, dining leftovers and possible dangerous substances. The MARPOL Annex V regulations for waste disposal obligate ships to implement comprehensive methods for waste treatment along with separation procedures and adequate disposal systems [19]. Modern vessels deploy waste compactors, incinerators, and recycling systems to effectively manage their waste [20]. Companies try to develop circular economy strategies which turn waste materials into bio-fuel products. There remains a challenge in preserving consistent waste management practices taking into account that modern waste treatment technologies evolve at an inconsistent rate.

Ballast water treatment and control
Ships must operate ballast water treatment and management systems to block the dispersion of invasive species that arise when ballast water is released. Modern systems use filtration technologies and UV treatment methods to eradicate dangerous organisms. The effectiveness increases by applying

chemical purification methods with the use of approved biocides [21]. Draining ballast water in open seas decreases the risk of biological spread into coastal ecosystems.

METHODS

Implementing modern technologies to reduce pollution on board of the newest type of container ship

The vessel under examination has a capacity of approximately 18.000 TEU and operates transoceanic routes. In order to comply with IMO MARPOL Annex VI regulation, ECA areas and decarbonization targets by 2050, the operator proposes to reduce pollutant emissions (NO_x, SO_x, CO_2) and water pollution. The main objective was to complete elimination of SO_x and a reduction of more than 50% in CO_2 emissions compared to 2008 levels by interacting a combination of modern pollution control technologies.

Table 1. Cost–Benefit and compliance analysis of shipboard environmental technologies

Technology	Exploitation	Main benefits
Hybrid scrubbers	SO_x reduction by exhaust gas scrubbing	≤0.1% sulfur content in discharge in ECA areas
System SCR+EGR	NOx reduction through catalysis and gas recirculation	NOx reduction up to 90%
Fuel Switch – LNG	Replacing heavy fuel oil with LNG	Almost complete removal of SO_x and particles
System Ballast Water Treatment (UV + filtration	Marine environment protection	Compliance with the Ballast Water Management Convention
Energy recovery system (shaft generator + waste heat recovery)	Uses waste heat energy	Fuel consumption reduction 3÷7%
Anti-fouling paint based on eco compounds	Reducing friction on the ship's hull	Improved energy efficiency 5÷10%
Real-time digital monitoring system (IoT)	Speed, route and consumption optimization	Further emission reduction

RESULTS AND DISCUSSION

Compared to similar ships using conventional fuels, after the first year of operation, the following results were obtained: 25% CO_2, 97÷99% SO_x, 80÷90% NO_x, 10÷15% fuel consumption, 85% particle (PM). Long-term operational costs have been significantly reduced, and the initial investments in technology will be compensated for in 5÷7 years.

Regarding restrictions encountered, table 2 highlights that technical and economic difficulties can be overcome through effective management and continuous technological adaptation. For each challenge, practical-strategic solutions are indicated.

The study shows how important it is to implement contemporary technologies for managing pollution on board ships.

Table 2. Technical and operational barriers to marine pollution reduction and recommended solutions

Restriction	Recommended solution
Limited space on board	Modular reconfiguration and compact equipment integration
High cost of systems	Green tax incentives and financing
Special maintenance and operational requirements	Automated systems and crew training
LNG availability in some ports	Optimized routes and detailed planning

Best practices

Comparative analysis and efficiency calculations

To assess the effectiveness of modern pollution reduction technologies in maritime transport, four representative methods were analyzed the use of LNG as fuel, the installation of scrubbers, ballast water treatment and on-board waste recycling.

The data from table 3 illustrates a comparison between the level of emission reduction and implementation costs for each technology. The data demonstrates an inversely proportional relationship between costs and some environmental benefits:

a) technologies with high global environmental impact (LNG) require major implementation costs;

b) solutions with specific compliance objectives (scrubbers, ballast treatment) offer very high reductions of targeted pollutants, at significantly lower costs;

c) waste management remains an area with high efficiency and adaptable costs, playing an essential role in overall operational sustainability.

Tabel 3. Comparative analysis of modern pollution control techniques on board ships

Pollution control method	Emission reduction (%)	Cost (USD)	Regulatory compliance
LNG Fuel	30% CO_2, 90%SO_2	$20M per vessel	IMO 2020
Scrubbers	98% SO_2	$5M per installation	MARPOL Annex VI
Ballast Treatment	99% biological removal	$1M per system	IMO Ballast Water Convention
Waste Recycling	70% Reduction	Varies	MARPOL Annex V

The LNG Fuel method generates the most comprehensive pollution reduction, offering an approximately 30% reduction in CO_2 emissions and almost 90% elimination of SO_2 emissions (Table 3). However, this significant benefit comes at a high cost, estimated at approximately $20 million per ship, which is the largest investment in the analysis. The technology is fully compliant with IMO 2020 requirements, which drastically limit the sulfur content in fuels.

Scrubbers have proven to be particularly effective in reducing sulfur oxide emissions, achieving efficiencies of up to 98%. The average investment is around $5 million, making them a very cost-effective solution for ships that continue to use conventional fuels. Compliance with MARPOL Annex VI is a key reason for their widespread adoption.

Ballast water treatment systems achieve a 99 % efficiency in removing biological organisms, preventing the transfer of invasive species into marine ecosystems. The cost per installation, approximately 1 million USD, represents a relatively small investment compared to the ecological impact prevented. These systems are mandatory under the IMO Ballast Water Management Convention.

On-board waste recycling contributes to a reduction of about 70% in the amount of polluting waste, and the costs vary depending on the type of system and the ship profile. The application of this method ensures compliance with MARPOL Annex V, which regulates the management of solid waste in the marine environment.

Deepwater Horizon oil spill response

Deepwater Horizon obtained the status of the most dangerous oil spill across extensive areas of the globe that reached 4.9 million barrels in 2010. The Macondo Prospect drilling site blowout led to serious environmental damage affecting the marine ecosystems and the residents settled near the coast. Multiple response strategies were elaborated, preventing the spread of surface pollutants by using barriers with controlled burning.

A huge investigation of the incident has been Accomplished by the National Commission on BP Deepwater Horizon Oil Spill which prompted them to ask for stronger habitat regulations and enhanced safety systems [13].

Adoption of LNG-Powered Ships
The shipping industry reoriented to LNG as a cleaner option to counter air pollution. In 2020, first LNG-powered ultra-large container vessel (ULCV), called CMA CGM Jacques Saade, was launched. As a matter of fact, the usage of LNG fuel resulted in a 99% removal of SO_2, 85% reduction of NO_2 and a 22% CO_2 emission limitation.

CONCLUSIONS

Modern maritime transport is undergoing an accelerated transformation driven by the need to reduce its impact on the marine environment and the atmosphere. Comparative analysis of technologies such as the use of LNG as fuel, scrubbers, ballast water treatment systems and on-board waste recycling demonstrates that each method contributes significantly to reducing different types of pollution.
However, there is no single solution that ensures full compliance with international regulations. Maximum efficiency can only be achieved by adopting an integrated package of technical, operational and digital measures. Also, the initial investments are compensated in the long term by reducing energy consumption, optimizing operations and increasing naval competitiveness in the context of increasingly strict IMO standards.
A comprehensive strategy to counter ships pollution which combines environmental responsibility with technological advancements and proper rules is required. In order to effectively prevent ships pollution, three strategic measures need to be implemented:

- ✓ Fitting the ship with modern technology equipment including oil-water separators, scrubbers, and energy-efficient engines to cut damaging emissions. The use of alternative fuel including LNG makes shipping operations more sustainable.
- ✓ Full compliance with international standards, especially with those established by MARPOL Convention, for preserving environmental quality. Wasting management, ballast water treatment and air pollution control are the main contributors to the protection of marine habitats.
- ✓ Environmental awareness ensured by a responsible behavior on the part of shipping companies. Their tasks should include crew members training and green technology investments for a long-term environmental protection. The ecological investments of the maritime industry need to be directed toward pollution management and ship maintenance for a substantial reduction in marine pollution and the protection of marine wildlife.

The case study demonstrates that introducing modern pollution control technologies on board ships can maximize long-term economic efficiency, guarantee compliance with international regulations and significantly improve environmental impact.
The vessel under review provides an example of best practices for moving to low-emission shipping, contribute to the industry's decarbonization goals by 2050.

REFERENCES

[1] BATRA, M., IMRAN, M., MANAGEMENT & HUMANITIES, **5**, no. 5, 2022, p. 523.
[2] International Maritime Organization (IMO). MARPOL-International Convention for the Prevention of Pollution from Ships, IMO Publishing, 2011. Available from: https://www.imo.org/en/about/Conventions/MARPOL [10.11.2025].
[3] LEHMAN, N., PANAGACOS, G., BARFOD, M.B., Transp. Res. D Trans. Environ., **146**, 2025, https://doi.org/10.1016/j.trd.2025.104902.
[4] WALKER, T. R., Marine Pollut. Bull., **105**, no. 1, 2016 p. 199, https://doi.org/10.1016/j.marpolbul.2016.02.029.
[5] HOIJUM, K., SILJUNG, Y., JUNGYUP, L., WON-JU, L., Ocean Eng., **280**, 2023, https://doi.org/10.1016/j.oceaneng.2023.114827.
[6] GOLBAZI, M., ARCHER, C., Atmos. Chem. Phys., **23**, no. 23, 2023, p.15057, https://doi.org/10.5194/acp-23-15057-2023.
[7] SPENGLER, T., TOVAR, B., Marine Pollut. Bull., **178**, 2022, https://doi.org/10.1016/j.marpolbul.2022.113589.

[8] JÄGERBRAND, A.J., BRUTEMARK, A., SVEDÉN, J.B., GREN, M., Sci.Total Environ., **695**, 2019, https://doi.org/10.1016/j.scitotenv.2019.133637.
[9] BUI, V.D., NGUYEN, P.Q.P., NGUYEN, D.T., Water Conserv. Manag., **5**, no. 2, 2021, p.121, https://doi.org/10.26480/wcm.02.2021.121.130.
[10] SARI, W.R., GUNAWAN, MUZHOFFAR, D.A.F., Marit. Technol. Res. J., **8,** no. 1, 2026, https://doi.org/10.33175/mtr.2026.281429.
[11] TSOLAKI, E., DIAMADOPOULOS, E., J. Chem. Technol. Biotechnol., **85**, no 1, 2010, p.19, https://doi.org/10.1002/jctb.2276.
[12] CHANG Y.C., LEE S., SUN, J., Chin. J. Int. Law, **23**, no. 1, 2024, p. 203, https://doi.org/10.1093/chinesejil/jmae001.
[13] BP GLOBAL. Environmental and Safety Report: Lessons from Deepwater Horizon, 2023. Available from: https://www.bp.com [10.11.2025].
[14] MATHIAS, J.E., GILLET, M.C., DISSELKOEN, H., JAMBECK, J.R., Marine Policy, **143**, 2022, https://doi.org/10.1016/j.marpol.2022.105127.
[15] BORRELLE, S.B., RINGMA, J., LAW K.L., MONNAHAN, C.C., LEBRETON, L., MCGIVERN A., MURPHY E., JAMBECK J., LEONARD G.H., HILLEARY M.A., ERIKSEN M., POSSINGHAM, H.P., DE FROND H., GERBER L.R., POLIDORO B., TAHIR, A., BERNARD M., MALLOS N., BARNES M., ROCHMAN, C.M., Science, **369**, no. 6510, 2020, p. 1515, https://doi.org/10.1126/science.aba3656.
[16] OSTLE ,C., THOMPSON, R.C., BROUGHTON, D., GREGORY, L., WOOTTON, M., JOHNS, D.G., Nat. Commun., **10**, 2019, https://doi.org/10.1038/s41467-019-09506-1.
[17] CHEN, Q., WU, W., GUO, Y., LI, J., WEI, F., Sci. Total Environ., 811, 2022, https://doi.org/10.1016/j.scitotenv.2021.151410.
[18] TOTALENERGIES. Advancements in LNG Fuel for Sustainable Shipping, 2023. Available from: https://totalenergies.com [10.11.2025].
[19] FLORES, H., MOTLAGH, N.H., ZUNIGA, A., LIYANAGE, M., PASSANANTI, M., TARKOMA, S., YOUSSEF, M., NURMI, P., Comput. Sci., 2020, https://doi.org/10.48550/arXiv.2005.09571.
[20] GAVRILOVA, A.N., GERASIMOV, A.V., SLADKOVA, S.V., SAMULENKOV, D.A., Ecol. Ind. Russia, **28**, no. 9, 2024, https://doi.org/10.18412/1816-0395-2024-9-34-39.
[21] VORKAPIĆ, A., RADONJA, R., ZEC, D., Transp. Technol., **30**, no. 3, 2018, p. 343.

Citation: Tudor, C.A., Modern techniques for pollution control onboard ships, *Rom. J. Ecol. Environ. Chem.*, **2025**, 7, no.2, pp. 115÷120.