Frontiers in Health Informatics www.healthinformaticsjournal.com
ISSN-Online: 2676-7104
2024; Vol 13: Issue 8 Open Access

REDUCING MARINE POLLUTION THROUGH GREEN SHIP TECHNOLOGIES AND CIRCULAR ECONOMY STRATEGIES

Sk. Kamal Ahmed,
email: skkamalahmed.mar@gmail.com
orcid id: 0009-0006-6461-5495

Ehamadul Haque Ani ,
email: ani.jh.mae@gmail.com

Monisha Das
email: monishadas934@gmail.com

Cite this paper as: Sk. Kamal Ahmed, Ehamadul Haque Ani , Monisha Das (2024), Reducing Marine Pollution Through Green Ship Technologies And Circular Economy Strategies. *Frontiers in Health Informatics, 13(8) 4540-4551*

ABSTRACT
Marine pollution, a widespread and intensifying global concern, significantly endangers the health and biodiversity of marine ecosystems. The marine industry, an essential element of global commerce, substantially contributes to pollution through multiple sources, including exhaust emissions, ballast water discharge, and garbage disposal. This study examines the possibilities of combining green shipping technologies with circular economy techniques to reduce marine pollution and advance a more sustainable maritime industry. The paper examines all foreign agreements, rules, and policies relevant to environmentally friendly transportation. Scholarly papers and business reports are also under review to assess the success of these concepts and pinpoint possible problems for the marine sector. It also provides ideas on how to make maritime activities more environmentally friendly. This article investigated the probable advantages of green ship technologies and cycle economies for ocean cleanup. By reducing waste and pollution, green technologies mitigate the harm human activity brings to the environment; two examples are ecologically friendly materials and energy-efficient motors. Promoting material reuse and recycling enables concepts from the circular economy to be used in operations and shipbuilding. These techniques taken collectively could enable the maritime industry to maintain marine habitats, reduce its environmental impact, and eventually become more sustainable. The findings reveal that the adoption of green ship technologies can substantially decrease harmful emissions and discharges, thereby minimizing the industry's environmental footprint. Similarly, the implementation of circular economy strategies fosters a more resource-efficient and sustainable maritime sector by promoting waste minimization and resource reuse. This study emphasizes the importance of collaborative efforts among stakeholders, including policymakers, industry leaders, and researchers, to accelerate the transition towards a greener and more circular maritime economy. The benefits and drawbacks of implementing these concepts in worldwide transportation are investigated in this work.
Keywords: *Maritime Pollution, Reduce, Strategies, Green Ship, Circular Economy.*

Corresponding author: *Sk. Kamal Ahmed, email: , orcid id: 0009-0006-6461-5495*

INTRODUCTION

Marine pollution comprises chemicals and debris, predominantly from terrestrial sources and subsequently transported into the ocean by water or wind. This pollution causes harm to the environment, the health of all organisms, and global economic systems (Yu et al., 2023). Traditionally, maritime safety is prioritized due to its implications for environmental concerns. Environmental protection entails mitigating detrimental impacts on infrastructure, health, air, water, soil, and coastal ecosystems. All parties must agree that methods for anticipating and reporting environmental conditions have markedly advanced, especially in scientific analysis. This can provide direction on establishing the necessary connections. In the maritime and other industries, vessel protection and marine pollution are interconnected for safety and environmental concerns (Sulaiman et al., 2013). The notion of maritime circularity has garnered heightened focus to tackle difficulties stemming from the net-zero objectives of the maritime sector. The circular economy offers potential answers to these difficulties via reuse, remanufacturing, and recycling activities (Okumus et al., 2024).
O'Shea et al. (2018) found that toxins in the ocean have long existed; creating problems, that modern society is still trying to solve. Because of pollution, marine life has numerous challenges (Khan, 2018). Carroll et al. (2017) state that light and sound are two contaminants that can reach the marine environment through many pathways and sources. The better-known contaminants also fall under this group. The well-being of the ocean and the businesses that rely on it can only be improved if we take global action to end marine pollution (Willis et al., 2022). Feingold and Willige (2024) state that around 90% of the world's goods are transported via the maritime industry, making it an integral part of global trade and economic development. Air emissions (including sulfur oxides, nitrogen oxides, and carbon monoxide), oil spills, solid waste, and hazardous compounds used in shipbuilding and maintenance are among the sources of marine pollution that vessels cause, according to Chowdhury et al. (2017).
Walker et al. (2018) state that several regulatory bodies, including the International Maritime Organization (IMO), have passed stringent regulations to lessen the environmental impact of shipping. According to Agarwala (2023) and Felício et al. (2021), sustainable shipping and marine pollution have been revolutionized by the principles of green ship technology and the circular economy. Al-Enazi et al. (2021) listed several ways ships can lessen their environmental impact. These include using alternative fuels (such as ammonia, hydrogen, or LNG), wind-assisted propulsion, scrubbers, systems for treating ballast water, and air lubrication. Sustainable shipbuilding, effective resource utilization throughout the ship's lifetime, recycling, and waste-to-energy conversion are key tenets of the circular economy (Chowdhury, 2024). The maritime sector may be able to reduce carbon emissions, damage to the environment, and resource consumption by adopting these practices. This study aims to assess the potential of green ship technology and circular economy strategies to lessen the environmental impact of the maritime industry's pollution. This analysis aims to examine the challenges, benefits, and policy ramifications of sustainable inventions. Recycling ships in an eco-friendly manner and finding alternative fuels are a few examples of these advancements in trash management.

METHODOLOGY

This research used secondary sources and a doctrinal legal research method to examine how green ship technologies and circular economy strategies can help clean up the oceans. As part of the study, many international agreements, laws, and rules are being examined. These include IMO rules and the Hong Kong Convention for ship recycling. Additionally, academic journals, industry reports, and case studies are examined to assess the effectiveness and challenges of implementing these solutions within the maritime sector. A comparative legal analysis evaluates global best practices and policy frameworks that support sustainable maritime operations. This study does not include empirical data but synthesizes existing legal and scholarly literature to provide critical insights and recommendations for enhancing regulatory compliance and environmental sustainability in the shipping industry.

Marine Pollution from the Shipping Industry

Tanker loading and unloading, ship movements inside ports and ship hoteling (lighting, heating, refrigeration, and ventilation) cause air pollution (Kwon et al., 2023). Ship fuel and oil spills, unintentional chemical, and oil spills during loading and unloading, and prohibited slop release pollute ports and nearby areas (Roberts et al., 2023). Other sources of pollution include toxic antifouling coatings like tributyltin that restrict marine development on hulls and alien organisms in ballast water that disturb ecosystems and harm local fish stocks (Byrnes & Dunn, 2020). Ships squander a lot when working. IMO, Annexes I-V regulate ocean discharge and non-dumping (Fares, 2023). Between 1925 and 2002, marine transportation CO_2 emissions nearly tripled. During the same period, SO_2 emissions tripled. Shipping has grown rapidly over the past century, endangering global ozone depletion (Organisation de coopération et de développement économiques, 2010). Recent studies suggest that ships' CO_2, NO_x, and SO_2 emissions account for 2%–3% (perhaps 4%), 10%–15%, and 4%–9% of worldwide anthropogenic emissions (Sidhartha & Cheriyan, 2012). Ship's bilge water mixes with engine and equipment room or repair oil. Solid garbage, chemicals, oil, and airborne contaminants may be in bilge water (Amran & Mustapha, 2020). Even after filtering bilge water, tiny oil levels might kill fish or cause long-term damage (Huang et al., 2011). Ship noise can affect marine animals that communicate, navigate, and consume with sound (Erbe et al., 2019). Ocean floor plastics affect plastic mobility and surface currents. Biofouling, marine biota interactions, degradation, fragmentation, and additive leaching affect sinking (Dimassi et al., 2022). Untreated ballast water can affect the environment, public health, and economy because ships carry dangerous invasive aquatic organisms across the world's waters (Hasanspahić et al., 2022).

Green Ship Technologies

In the last few decades, the maritime industries have been working hard to meet the growing demands of the environment by implementing operations strategies and creating new technologies (S.E. Hirdaris & Y.F. Cheng, 2012). As part of these technical steps, energy-efficient ships are being built using efficient blades, energy-saving devices, and other new technologies. Air lubrication, wind-assisted propulsion, and solar power are also given special attention (de Kat & Mouawad, 2019).

Table 1: Green Ship Technologies and Their Impact on Marine Pollution Reduction (Compiled by Author)

Technology	**Description**	**Benefits**	**Source**
No Ballast System	Ships designed to operate without ballast water, preventing the transfer of sediments and microorganisms.	Reduces the risk of invasive species transfer and minimizes marine ecosystem disruption.	(Lakshmi et al., 2021)

LNG Fuel for Propulsion	Use of liquefied natural gas (LNG) as a cleaner fuel alternative for main engines.	Lowers CO_2, NOx, and SOx emissions, improving air quality.	(Livaniou & Papadopoulos, 2022)
LNG Fuel for Auxiliary Engines	Utilization of LNG for continuous-running auxiliary engines onboard vessels.	Reduces overall emissions and improves energy efficiency.	(Wurster et al., 2014)
Sulfur Scrubber System	Installs exhaust gas scrubbers to remove sulfur from emissions.	Achieves up to 95% SOx reduction, limiting acid rain and air pollution.	(Teuchies et al., 2020)
Advanced Rudder and Propeller System	Optimized propeller and streamlined rudder design for fuel efficiency.	Reduces fuel consumption by up to 4%, lowering carbon emissions.	Green Ship of The Future, 2016
Speed Nozzle	Enhances propulsion efficiency, commonly used in supply vessels and tugs.	The Rice Speed Nozzle attained a 7% reduction in fuel consumption, improving fuel efficiency.	(David Barringhaus & Robert Olds, n.d.)
Hull Paint	Special coatings applied to reduce hull resistance and improve hydrodynamics.	A small layer of paint on the hull of vessel is decreasing CO2 emissions by 4%. Reduces fuel consumption by up to 12%.	(Autoliners, 2022) (Seacoat, 2025)
Waste Heat Recovery System	Captures waste heat from exhaust gases to generate steam for onboard use.	Reduces fuel consumption between 2% to 5%, improving energy efficiency.	(Westhoeve et al., 2022)
Exhaust Gas Recirculation (EGR)	Recirculates exhaust gases to lower combustion temperature and reduce NOx emissions.	Lowers NOx emissions by 50 to 60%, improving air quality.	(Woodyard, 2009)
Water in Fuel	Injects water into fuel before combustion to	Reduces NOx emissions up to	(Dibelius et al., 1971,

Technology	reduce cylinder temperature.	50%, minimizing pollution.	Kotob et al., 2020)
Improved Pump and Cooling Water System	Optimizes cooling systems to decrease energy resistance and improve efficiency.	Optimizing ship-cooling water systems, especially with variable speed pumps, can save 1% to 4% fuel consumption. Variable-speed pumps in cooling water systems save a lot of power. Studies have shown that pumping can be lowered by 20% to 50% of power, depending on the system and utilization.	(Durmusoglu et al., 2015) (Wang et al., 2023)
Sail and Kite Propulsion System	Uses wind-assisted propulsion to supplement traditional engines.	WAPS have already saved between 4.5% and 9% on fuel costs, and they could save up to 25% if installed as a retrofit.	(DNV, n.d.)
Sandwich Plate System (SPS)	Uses composite metal plates bonded with polyurethane elastomer instead of conventional steel structures.	Reduces ship weight, corrosion, and maintenance costs, supporting green ship recycling.	(Ismail et al., 2021)

Circular Economy Strategies in Maritime Sector

The circular economy has drawn much interest as a possible solution to the maritime sector's complex problems (Okumus et al., 2024). Major economic sectors dedicated to becoming carbon neutral by 2050 share the goal of creating a circular economy (de Avila Segade, 2023). The circular economy concept aims to maximize value extraction and retention while increasing resource utilization through reuse, repair, remanufacturing, and recycling (Kirchherr et al., 2023). Barriers to recycling that stakeholders mentioned were low awareness, problems with regulations and certification, long vessel lifecycles, long distances between yards, a lack of technical expertise, how people felt about remanufactured goods and problems with tracking equipment (Okumus et al., 202). The circular economy might solve these problems by encouraging recycling, reusing, and remanufacturing

(Okumus et al., 2024) projects.

Key Circular Economy Strategies in the Shipping Industry

Ship Recycling & Responsible Dismantling (Hong Kong Convention)

Ship recycling is one of the most important parts of the circular economy in the marine sector. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (HKC), which was signed in 2009, sets rules for properly breaking down old ships (Jain et al., 2013).

Waste-to-Energy Conversion Onboard Ships

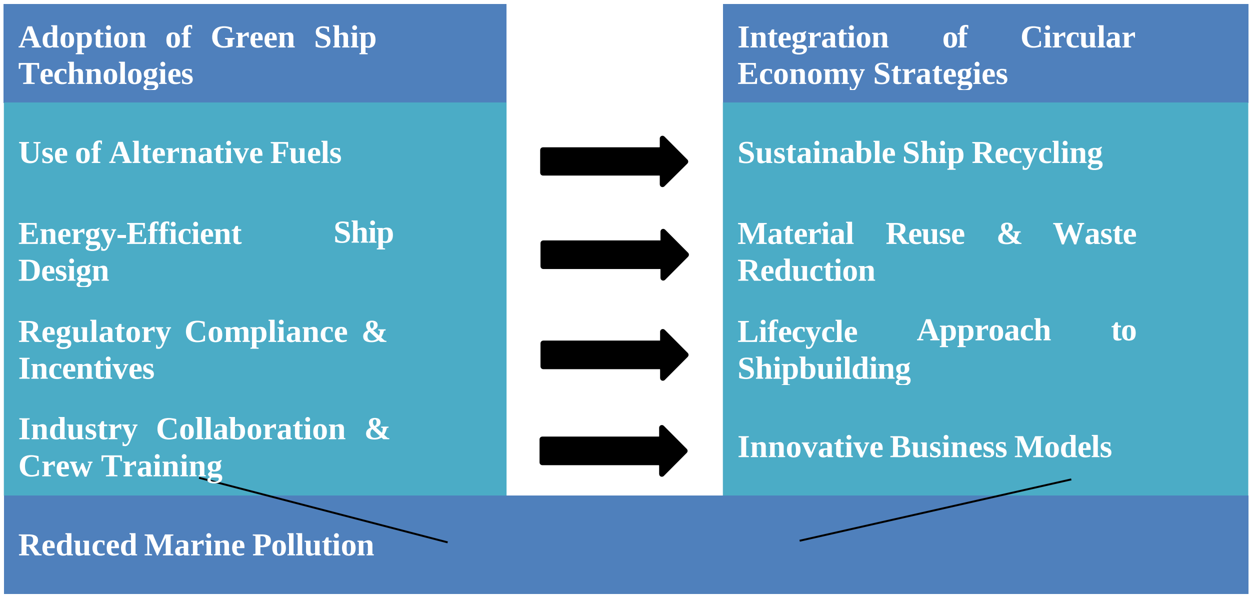
The most recent cruise ships can carry an ever-growing number of people and limit their environmental effects to the areas where their routes take them. The solid waste that is made greatly increases this effect. Because of this, we show a new way to get energy out of this trash (Anderson, 2021). Toneratti et al. (2022) say that microwave-assisted pyrolysis (MAP) and micro auto gasification (MAG) will take the trash and turn it into synthesis gas (syngas), which the ship can use directly for energy.

Reusing Scrapped Materials from Old Ships

Ship recycling has become increasingly important in recent years because of the need for sustainable practices in the maritime industry and the increased awareness of environmental issues (Moussa et al., 2024). Effective ship recycling (SR) aims to produce no waste during activities. This helps the UN reach Sustainable Development Goal (SDG) 12 by ensuring "sustainable consumption and production". As ElMenshawy et al. (2024) say, the SR industry is very important to the lifecycle of ships because it helps recover important resources like steel and creates work in many coastal areas worldwide. To get back materials and parts from ships that have ended their useful lives (EoL), they must be destroyed and reused. Tola et al. (2023) say that this makes raw materials "circular," which may benefit the environment and the economy.

Eco-Friendly Shipbuilding Practices

A substantial quantity of waste and contaminants is emitted during shipbuilding procedures (Lučin et al., 2023), posing significant risks to human health and environmental quality (Rahman & Karim, 2015), which has detrimental effects on society and contributes significantly to air pollution and greenhouse gas emissions (Vakili et al., 2023). In order to lessen the environmental impact of ship construction and operation, various activities are included in green shipbuilding techniques (Lučin et al., 2023). These include using innovative materials to reduce emissions, using alternative fuels, and energy-efficient designs (Önal, 2023). During shipbuilding, lightweight materials can increase vessel payload for a given size or weight. They enable higher speeds. They minimize fuel usage and environmental pollution for a given payload and distance (Noury et al., n.d.). Ships often develop biofouling from prolonged seawater immersion, which includes barnacles and algae. Anti-fouling coatings on vessel hulls are one of the best ways to address this issue. Due to the global focus on environmental sustainability, anti-fouling coatings that are effective and meet strict environmental criteria are in demand (Wu et al., 2024). Marine self-polishing anti-fouling coatings have unique chemical features. Seawater hydrolyzes ester or metal-oxygen linkages in the coating matrix (Liang et al., 2024). This hydrolytic reaction erodes the hull coating, releasing hazardous chemicals, including copper ions and biocides, into the water. Copper ions have broad-spectrum biotoxicity and can impair the metabolism of algae, bacteria, and small marine organisms, preventing biofouling (Ali et al., 2024). Zero-emission ship propulsion systems must replace fossil fuel-based ones to reach the IMO's 2050 target of decarbonizing shipping (Arabnejad et al., 2024). There is significant promise for lowering CO_2 emissions with fuel cell-powered hybrid power systems and other types of wind-assisted propulsion (Xing et al., 2020). Wind-assisted ship propulsion (WASP), especially with Flettner rotors, saves fuel and improves the environment for many ships (Lu & Ringsberg, 2020).



This flowchart illustrates the relationship between key strategies, their implementation, and the expected outcomes in reducing marine pollution.

Challenges

Adopting environmentally favorable technologies, including fuel cells, hybrid power, and energy-saving devices, is difficult for small and medium-sized shipping companies due to the substantial upfront investment required (Stark et al., 2022). Certain technologies, including onboard emissions remediation systems and carbon capture, are prohibited for large commercial vessels (Hanson et al., 2021). IMO regulations, including MRPOL, EEXI, and CII, are enforced in varying locations and manners, as per Czermański et al. (2022). Due to the regulatory framework's deficiencies, managing pollutants, disposing of waste, and controlling ballast water are all difficult (Bark et al., 2024). The regulatory framework impedes all of these sectors.

CONCLUSION

In conclusion, the pressing issue of marine pollution, driven largely by the shipping industry, necessitates urgent and collaborative action from all sectors. As highlighted, the adoption of green ship technologies and circular economy strategies presents viable pathways to mitigate the environmental impact of maritime operations. By embracing innovations such as alternative fuels, energy-efficient designs, and sustainable ship recycling, we not only reduce harmful emissions but also contribute to the conservation of marine ecosystems. However, the successful implementation of these practices relies heavily on robust regulatory frameworks and industry collaborations. It is imperative that stakeholders governments, shipping companies, and environmental organizations work together to enhance compliance and incentivize sustainable practices across the maritime sector. With global trade increasingly dependent on shipping and the dire state of our oceans, the time to act is now. The integration of sustainable technologies and practices not only safeguards marine health but also fosters economic resilience and sustainable development for future generations. Let us commit to transforming the maritime industry and paving the way for a cleaner, more sustainable ocean.

REFERENCES

1. Ali, A., Culliton, D., Fahad, S., Ali, Z., Kang, E.-T., & Xu, L. (2024). Nature-inspired anti-fouling strategies for combating marine biofouling. *Progress in Organic Coatings*, *189*, 108349. https://doi.org/10.1016/j.porgcoat.2024.108349
2. Arabnejad, M. H., Thies, F., Yao, H.-D., & Ringsberg, J. W. (2024). Zero-emission propulsion system featuring, Flettner rotors, batteries and fuel cells, for a merchant ship. *Ocean Engineering*, *310*, 118618. https://doi.org/10.1016/j.oceaneng.2024.118618
3. Bark, O., Solarte-Vasquez, M., & Inkinen, T. (2024). Smart regulations in maritime governance: Efficacy, gaps, and stakeholder perspectives. *Marine Pollution Bulletin*, *202*, 116341. https://doi.org/10.1016/j.marpolbul.2024.116341
4. Blanco, E. C., Sánchez, A., Martín, M., & Vega, P. (2023). Methanol and ammonia as emerging green fuels: Evaluation of a new power generation paradigm. *Renewable and Sustainable Energy Reviews*, *175*, 113195. https://doi.org/10.1016/j.rser.2023.113195
5. Chowdhury, S. (2024). *Lean Management Strategies for Sustainable Ship Recycling in the Circular Economy*. [PhD Thesis]. https://doi.org/10.13140/RG.2.2.33978.09926
6. Czermański, E., Oniszczuk-Jastrząbek, A., Spangenberg, E. F., Kozłowski, Ł., Adamowicz, M., Jankiewicz, J., & Cirella, G. T. (2022). Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection. *Marine Policy*, *145*, 105259. https://doi.org/10.1016/j.marpol.2022.105259
7. Hanson, E., Nwakile, C., & Hammed, V. O. (2025). Carbon capture, utilization, and storage (CCUS) technologies: Evaluating the effectiveness of advanced CCUS solutions for reducing CO2 emissions. *Results in Surfaces and Interfaces*, *18*, 100381. https://doi.org/10.1016/j.rsurfi.2024.100381
8. Liang, H., Shi, X., & Li, Y. (2024). Technologies in Marine Antifouling and Anti-Corrosion Coatings: A Comprehensive Review. *Coatings*, *14*(12). https://doi.org/10.3390/coatings14121487
9. Lu, R., & Ringsberg, J. W. (2020). Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology. *Ships and Offshore Structures*, *15*(3), 249–258. https://doi.org/10.1080/17445302.2019.1612544
10. Lučin, B., Čarija, Z., Alvir, M., & Lučin, I. (2023). Strategies for Green Shipbuilding Design and Production Practices Focused on Reducing Microplastic Pollution Generated during Installation of Plastic Pipes. *Journal of Marine Science and Engineering*, *11*(5). https://doi.org/10.3390/jmse11050983
11. Moussa, A. A., Farag, Y. B. A., Gunbeyaz, S. A., Fahim, N. S., & Kurt, R. E. (n.d.). *Development and research directions in ship recycling: A systematic literature review with bibliometric analysis*.
12. Noury, P., Hayman, B., McGeorge, D., & Weitzenböck, J. (n.d.). *LIGHTWEIGHT CONSTRUCTION FOR ADVANCED SHIPBUILDING - RECENT DEVELOPMENT*.
13. Önal, M. (2023). Ship recycling perspective on environmental impacts—A case study for the ships in service. *Heliyon*, *9*(10), e21157. https://doi.org/10.1016/j.heliyon.2023.e21157
14. Rahman, A., & Karim, M. (2015). Green Shipbuilding and Recycling: Issues and Challenges. *International Journal of Environmental Science and Development*, *6*, 838–842. https://doi.org/10.7763/IJESD.2015.V6.709
15. Sødal, S. (2009). *Fuel cells in shipping: Higher capital costs and reduced flexibility*.

16. Stark, C., Xu, Y., Zhang, M., Yuan, Z., Tao, L., & Shi, W. (2022). Study on Applicability of Energy-Saving Devices to Hydrogen Fuel Cell-Powered Ships. *Journal of Marine Science and Engineering*, *10*(3). https://doi.org/10.3390/jmse10030388
17. Tola, F., Mosconi, E. M., Marconi, M., & Gianvincenzi, M. (2023). Perspectives for the Development of a Circular Economy Model to Promote Ship Recycling Practices in the European Context: A Systemic Literature Review. *Sustainability*, *15*(7). https://doi.org/10.3390/su15075919
18. Vakili, S., Schönborn, A., & Ölçer, A. I. (2023). The road to zero emission shipbuilding Industry: A systematic and transdisciplinary approach to modern multi-energy shipyards. *Energy Conversion and Management: X*, *18*, 100365. https://doi.org/10.1016/j.ecmx.2023.100365
19. Wu, S., Wu, S., Xing, S., Wang, T., Hou, J., Zhao, Y., & Li, W. (2024). Research Progress of Marine Anti-Fouling Coatings. *Coatings*, *14*(9). https://doi.org/10.3390/coatings14091227
20. Xing, H., Spence, S., & Chen, H. (2020). A comprehensive review on countermeasures for CO2 emissions from ships. *Renewable and Sustainable Energy Reviews*, *134*, 110222. https://doi.org/10.1016/j.rser.2020.110222
21. Agarwala, N. (2023). Promoting Circular Economy in the shipping industry. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *7*(4), 2276984. https://doi.org/10.1080/25725084.2023.2276984
22. Al-Enazi, A., Okonkwo, E. C., Bicer, Y., & Al-Ansari, T. (2021). A review of cleaner alternative fuels for maritime transportation. *Energy Reports*, *7*, 1962–1985. https://doi.org/10.1016/j.egyr.2021.03.036
23. Amran, N. A., & Mustapha, S. N. A. (2020). Oil–Water Separation Techniques for Bilge Water Treatment. In P. T. Chandrasekaran, M. S. Javaid, & A. Sadiq (Eds.), *Resources of Water*. IntechOpen. https://doi.org/10.5772/intechopen.91409
24. Byrnes, T. A., & Dunn, R. J. K. (2020). Boating- and Shipping-Related Environmental Impacts and Example Management Measures: A Review. *Journal of Marine Science and Engineering*, *8*(11). https://doi.org/10.3390/jmse8110908
25. Carroll, A. G., Przeslawski, R., Duncan, A., Gunning, M., & Bruce, B. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. *Marine Pollution Bulletin*, *114*(1), 9–24. https://doi.org/10.1016/j.marpolbul.2016.11.038
26. Chowdhury, K. M., Mili, M., & Akhter, S. (2017). Pollution by Shipping Industry in the Northern Bay of Bengal: A Review Study. *"Imperial Journal of Interdisciplinary Research (IJIR)*, *3*.
27. Dimassi, S. N., Hahladakis, J. N., Yahia, M. N. D., Ahmad, M. I., Sayadi, S., & Al-Ghouti, M. A. (2022a). Degradation-fragmentation of marine plastic waste and their environmental implications: A critical review. *Arabian Journal of Chemistry*, *15*(11), 104262. https://doi.org/10.1016/j.arabjc.2022.104262
28. Dimassi, S. N., Hahladakis, J. N., Yahia, M. N. D., Ahmad, M. I., Sayadi, S., & Al-Ghouti, M. A. (2022b). Degradation-fragmentation of marine plastic waste and their environmental implications: A critical review. *Arabian Journal of Chemistry*, *15*(11), 104262. https://doi.org/10.1016/j.arabjc.2022.104262
29. Erbe, C., Marley, S. A., Schoeman, R. P., Smith, J. N., Trigg, L. E., & Embling, C. B. (2019). The Effects of Ship Noise on Marine Mammals—A Review. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00606

30. Felício, J., Rodrigues, R., & Caldeirinha, V. (2021). Green Shipping Effect on Sustainable Economy and Environmental Performance. *Sustainability*, *13*, 4256. https://doi.org/10.3390/su13084256
31. Hasanspahić, N., Pećarević, M., Hrdalo, N., & Čampara, L. (2022). Analysis of Ballast Water Discharged in Port—A Case Study of the Port of Ploče (Croatia). *Journal of Marine Science and Engineering*, *10*(11). https://doi.org/10.3390/jmse10111700
32. Huang, Y.-J., Jiang, Z., Zeng, J., Chen, Q.-Z., Zhao, Y., Liao, Y., Shou, L., & Xu, X. (2011). The chronic effects of oil pollution on marine phytoplankton in a subtropical bay, China. *Environmental Monitoring and Assessment*, *176*, 517–530. https://doi.org/10.1007/s10661-010-1601-6
33. Kwon, J.-W., Yeo, S., & Lee, W.-J. (2023). Assessment of Shipping Emissions on Busan Port of South Korea. *Journal of Marine Science and Engineering*, *11*(4). https://doi.org/10.3390/jmse11040716
34. Organisation de coopération et de développement économiques (Ed.). (2010). *Globalisation, transport and the environment*. OCDE publishing.
35. O'Shea, F. T., Cundy, A. B., & Spencer, K. L. (2018). The contaminant legacy from historic coastal landfills and their potential as sources of diffuse pollution. *Marine Pollution Bulletin*, *128*, 446–455. https://doi.org/10.1016/j.marpolbul.2017.12.047
36. Roberts, T., Williams, I., Preston, J., Clarke, N., Odum, M., & O'Gorman, S. (2023). Ports in a Storm: Port-City Environmental Challenges and Solutions. *Sustainability*, *15*(12). https://doi.org/10.3390/su15129722
37. Rogowska, J., & Namieśnik, J. (2010). Environmental Implications of Oil Spills from Shipping Accidents. *Reviews of Environmental Contamination and Toxicology*, *206*, 95–114. https://doi.org/10.1007/978-1-4419-6260-7_5
38. Sidhartha, J., & Cheriyan, R. K. (2012). *The Enviornmental Impacts Of International Maritime Shipping Past Trends And Future Perspectives*. *10*.
39. Walker, T., Adebambo, O., Del, M., Feijoo, A., Elhaimer, E., Hossain, T., Johnston Edwards, S., Morrison, C., Romo, J., Sharma, N., Taylor, S., & Zomorodi, S. (2018). *Environmental Effects of Marine Transportation* (pp. 505–530). https://doi.org/10.1016/B978-0-12-805052-1.00030-9
40. Willis, K. A., Serra-Gonçalves, C., Richardson, K., Schuyler, Q. A., Pedersen, H., Anderson, K., Stark, J. S., Vince, J., Hardesty, B. D., Wilcox, C., Nowak, B. F., Lavers, J. L., Semmens, J. M., Greeno, D., MacLeod, C., Frederiksen, N. P. O., & Puskic, P. S. (2022). Cleaner seas: Reducing marine pollution. *Reviews in Fish Biology and Fisheries*, *32*(1), 145–160. https://doi.org/10.1007/s11160-021-09674-8
41. Anderson, K. R. (2021). Tourism Impact on Environmental Sustainability: A Focus on the Cruise Industry. In S. A. R. Khan (Ed.), *Tourism*. IntechOpen. https://doi.org/10.5772/intechopen.93922
42. de Kat, J. O., & Mouawad, J. (2019). Green Ship Technologies. In H. N. Psaraftis (Ed.), *Sustainable Shipping: A Cross-Disciplinary View* (pp. 33–92). Springer International Publishing. https://doi.org/10.1007/978-3-030-04330-8_2
43. Dibelius, N. R., Hilt, M. B., & Johnson, R. H. (1971). *Reduction of Nitrogen Oxides From Gas Turbines by Steam Injection: Vol. ASME 1971 International Gas Turbine Conference and Products Show*. https://doi.org/10.1115/71-GT-58
44. Durmusoglu, Y., Koçak, G., Deniz, C., & Zincir, B. (2015, October). *Energy Efficiency Analysis of Pump Systems in A Ship Power Plant and A Case Study of A Container Ship*.

45. ElMenshawy, O. M., Ülkü, M. A., & Hsuan, J. (2024). Navigating Green Ship Recycling: A Systematic Review and Implications for Circularity and Sustainable Development. *Sustainability*, *16*(17). https://doi.org/10.3390/su16177407
46. Ismail, A., Zubaydi, A., Piscesa, B., Tuswan, & Chandra Ariesta, R. (2021). Study of sandwich panel application on side hull of crude oil tanker. *Istrazivanja i Projektovanja Za Privredu*, *19*, 1090–1098. https://doi.org/10.5937/jaes0-30373
47. Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling*, *194*, 107001. https://doi.org/10.1016/j.resconrec.2023.107001
48. Kotob, M. R., Lu, T., & Wahid, S. S. (2020). Experimental Study of Direct Water Injection Effect on NOx Reduction from The Gas Fuel. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *76*(3), 92–108. https://doi.org/10.37934/arfmts.76.3.92108
49. Lakshmi, E., Priya, M., & Achari, V. S. (2021). Systems and Operation of Ballast Water in Ships with the Changing Ballast Water Management Policy. In C. Reusser (Ed.), *Modern Ship Engineering, Design and Operations*. IntechOpen. https://doi.org/10.5772/intechopen.99552
50. Livaniou, S., & Papadopoulos, G. A. (2022). Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation. *Sustainability*, *14*(24). https://doi.org/10.3390/su142416364
51. Okumus, D., Andrews, E., & Gunbeyaz, S. A. (2024). Developing circularity metrics for the maritime industry: A stakeholder focused study. *Ocean Engineering*, *312*, 119158. https://doi.org/10.1016/j.oceaneng.2024.119158
52. Okumus, D., Gunbeyaz, S. A., Kurt, R. E., & Turan, O. (2024). An Approach to Advance Circular Practices in the Maritime Industry through a Database as a Bridging Solution. *Sustainability*, *16*(1). https://doi.org/10.3390/su16010453
53. Okumus, D., Gunbeyaz, S., Kurt, R., & Turan, O. (2023). Circular economy approach in the maritime industry: Barriers and the path to sustainability. *Transportation Research Procedia*, *72*, 2157–2164. https://doi.org/10.1016/j.trpro.2023.11.701
54. S.E. Hirdaris & Y.F. Cheng. (2012). *The Role of Technology in Green Ship Design*. https://doi.org/10.13140/RG.2.1.4242.0564
55. Teuchies, J., Cox, T. J. S., Van Itterbeeck, K., Meysman, F. J. R., & Blust, R. (2020). The impact of scrubber discharge on the water quality in estuaries and ports. *Environmental Sciences Europe*, *32*(1), 103. https://doi.org/10.1186/s12302-020-00380-z
56. Toneatti, L., Deluca, C., Fraleoni Morgera, A., Piller, M., & Pozzetto, D. (2022). Waste to Energy Onboard Cruise Ships: A New Paradigm for Sustainable Cruising. *Journal of Marine Science and Engineering*, *10*(4). https://doi.org/10.3390/jmse10040480
57. Wang, J., Zhao, F., Sun, L., Hou, Y., & Chen, N. (2023). Research on the Energy Savings of Ships' Water Cooling Pump Motors Based on Direct Torque Control. *Processes*, *11*(7). https://doi.org/10.3390/pr11071938
58. Westhoeve, J., Mestemaker, B., van Biert, L., & Blom, E. (2022, May). *Effect of waste heat recovery systems on the fuel economy of dredging vessels*.
59. Woodyard, D. (2009). Chapter Three Exhaust Emissions and Control. In D. Woodyard (Ed.), *Pounder's Marine Diesel Engines and Gas Turbines (Ninth Edition)* (Ninth Edition, pp. 61–86). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-7506-8984-7.00003-5

60. Wurster, R., Weindorf, W., Zittel, W., Schmidt, P., Heidt, C., Lambrecht, U., Lischke, A., & Müller, S. (2014). *LNG as an alternative fuel for the operation of ships and heavy-duty vehicles*.
61. Jie Zheng, Cungen Liu, Zhongqin Lin. Low-Carbon Development of Green Ships and Related Strategies. Strategic Study of CAE, 2020, 22(6): 94–102 https://doi.org/10.15302/J-SSCAE-2020.06.012
62. O'Shea, F. T., Cundy, A. B., & Spencer, K. L. (2018). The contaminant legacy from historic coastal landfills and their potential as sources of diffuse pollution. *Marine Pollution Bulletin*, *128*, 446-455.
63. Khan, F. R. (2018). Ecotoxicology in the Anthropocene: Are We Listening to Nature's Scream? *Environmental Science & Technology*, *52*(18), 10227–10229. https://doi.org/10.1021/acs.est.8b04534
64. Autoliners, H. (2022, January 5). *How a coat of paint makes our vessels more sustainable*. Hoeghautoliners.com; Höegh Autoliners. https://www.hoeghautoliners.com/news/how-a-coat-of-paint-makes-our-vessels-more-sustainable
65. de Avila Segade, J. M. G. (2023, July 7). *Circular economy in the maritime industry*. MAPFRE Global Risks. https://www.mapfreglobalrisks.com/en/risks-insurance-management/article/circular-economy-in-maritime-industry/
66. Feingold, S., & Willige, A. (n.d.). *These are the world's most vital waterways for global trade*. World Economic Forum. Retrieved February 19, 2025, from https://www.weforum.org/stories/2024/02/worlds-busiest-ocean-shipping-routes-trade/
67. Seacoat. (2025, January 21). Life-cycle assessment of hull coatings: Minimizing environmental impact throughout the vessel's lifetime., *LLC - Sustainable Fuel Efficient Hull Coatings for Maritime Vessels*. https://www.seacoat.com/life-cycle-assessment-of-hull-coatings-minimizing-environmental-impact-throughout-the-vessels-lifetime/
68. OLDS. (n.d.). *Maximising Propulsion effeciency*. Com.au. Retrieved February 20, 2025, from https://www.olds.com.au/marine/maximizing_propulsion_efficiency/index.html
69. Cyprus Shipping News. (2023, July 20). *Royal Caribbean's newest cruise ships will convert waste to energy*. https://cyprusshippingnews.com/2023/07/20/royal-caribbeans-newest-cruise-ships-will-convert-waste-to-energy/
70. Green Ship of The Future. (2016, November 2). *Technologies implemented*. https://greenship.org/major-studies/8500-teu-container-vessel-study/technologies-implemented/
71. DNV. (n.d.). *WAPS – wind assisted propulsion systems*. Retrieved February 20, 2025, from https://www.dnv.com/maritime/insights/topics/waps-wind-assisted-propulsion-systems/
72. Sulaiman, O., Saharuddin, A. H., & Kader, A. S. A. (2013). *Towards sustainable green ship technology*.
73. Yu, R.-S., Yang, Y.-F., & Singh, S. (2023). Global analysis of marine plastics and implications of control measure strategies. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1305091