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Progress in Ship Pollution Prevention and Control Technologies: Regulatory Drivers, Technical Pathways and Intelligent Governance

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Abstract

Shipping underpins global trade, yet ship operations remain an important source of environmental pressure through oil pollution, exhaust emissions, ballast-water-mediated biological invasions, sewage, garbage discharge, antifouling-system releases, and biofouling-related ecological risks. Under the progressively strengthened framework of MARPOL, the Ballast Water Management Convention, the Anti-Fouling Systems Convention, and the IMO energy-efficiency and carbon-intensity requirements, ship pollution control is moving from isolated end-of-pipe treatment toward an integrated regime that combines source reduction, process control, terminal treatment, and digital compliance governance. This review examines the major categories of ship-generated pollution and the corresponding control demands, with emphasis on oil-pollution prevention, exhaust aftertreatment, alternative and low-carbon fuels, shore power, ballast water treatment, sewage and garbage management, antifouling coatings, and biofouling control. It further evaluates the emerging role of digital monitoring, data-driven risk assessment, and port-ship-shore coordination in improving regulatory compliance and environmental performance. The literature indicates that low-sulfur fuels, exhaust gas cleaning systems, selective catalytic reduction, ballast water management systems, and shore-side electricity have reached different degrees of technical maturity. However, their environmental benefits remain conditional on fuel life cycles, port infrastructure, equipment cost, operational maintenance, washwater management, data reliability, and enforcement capacity. Future research should therefore move beyond single-pollutant control toward life-cycle assessment, multi-pollutant co-optimization, verifiable digital monitoring, and integrated governance across vessels, ports, energy suppliers, and regulatory authorities.

Keywords

Ship pollution; pollution prevention; MARPOL; exhaust emissions; ballast water treatment; shore power; alternative fuels; intelligent governance.

1. Introduction

Maritime transport is a central component of the global supply chain, but the environmental footprint of ships extends across construction, operation, port stay, maintenance, and end-of-life stages. Unlike many land-based sources, ship pollution is mobile, transboundary, operationally dispersed, and difficult to supervise continuously. It includes not only accidental or operational oil discharges, but also sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), greenhouse gases (GHGs), ballast-water-mediated invasive species, sewage, garbage, and ecological risks associated with antifouling coatings and hull biofouling [1,5-8]. These intertwined sources require a systems-level review rather than a narrow assessment of any single device or pollutant.

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Earlier pollution-control studies often focused on specific technical units, such as oily-water separators, exhaust gas cleaning systems, selective catalytic reduction (SCR), or ballast water treatment systems. Such studies have provided the basis for engineering compliance with individual regulations, but they do not fully address the combined environmental pressures faced by the shipping sector. In parallel, international regulation has become more stringent. MARPOL remains the principal convention for preventing operational and accidental pollution from ships, while Annex VI, the global 0.50% m/m sulfur limit, EEXI, CII, and the 2023 IMO GHG Strategy have broadened maritime environmental governance from conventional pollution control to energy efficiency, carbon intensity, and fuel transition [1-5].

From a technical perspective, ship pollution prevention can be grouped into three interrelated domains. The first addresses conventional pollutants through oil-pollution prevention, sewage treatment, garbage management, ballast water control, and antifouling-system regulation. The second concerns air pollutants and GHG emissions through low-sulfur fuels, exhaust gas cleaning, SCR, exhaust gas recirculation, shore-side electricity, energy-efficiency measures, and alternative fuels. The third focuses on digital governance, including online monitoring, emission accounting, deficiency prediction, risk-based inspection, and port-ship-shore data integration. These domains are not independent. Their performance depends on vessel type, engine configuration, route pattern, energy supply chain, port infrastructure, inspection regime, and commercial feasibility.

At present, several tensions remain unresolved. Low-sulfur fuels, scrubbers, shore power, LNG, methanol, ammonia, hydrogen, and operational energy-saving measures can all reduce certain emissions, but they differ markedly in life-cycle performance, investment cost, safety risk, infrastructure dependence, and regulatory readiness [14,15,21-23]. Emphasizing one pathway without considering its upstream energy source, port interface, and operational constraints may shift rather than reduce environmental burdens. This review therefore evaluates ship pollution prevention and control technologies from the perspectives of pollution type, regulatory driver, technical pathway, intelligent monitoring, and implementation challenge.

2. Ship-generated Pollution and Regulatory Constraints

Ship pollution is multi-source, multi-medium, and multi-stage. Oil pollution originates from tanker accidents, cargo or fuel-tank leakage, machinery-space bilge water, bunkering, ballast operations, and illegal discharge. Although the frequency of major tanker spills has decreased compared with earlier decades, accidental oil release can still cause extensive ecological and economic damage. Operational oil pollution is more continuous and often less visible, requiring reliable oily-water separation, oil-content monitoring, discharge control, record keeping, and adequate port reception facilities. MARPOL Annex I provides the core requirements for oil pollution prevention, including operational discharge rules, oil record books, structural requirements for tankers, and equipment for oil-contaminated water management [1].

Atmospheric emissions from ships include SOx, NOx, PM, black carbon, volatile organic compounds, and GHGs. SOx emissions are closely linked to fuel sulfur content, while NOx formation depends strongly on engine design, combustion temperature, and load profile. PM is associated primarily with heavy-fuel-oil combustion and incomplete combustion processes. MARPOL Annex VI introduced limits on air pollutants from ships, and the IMO 2020 sulfur cap substantially accelerated the use of low-sulfur fuels, exhaust gas cleaning systems, or alternative fuels [2,19]. At the same time, GHG mitigation has become a core component of ship pollution prevention. The entry into force of EEXI and CII requirements and the adoption of the 2023 IMO GHG Strategy have transformed environmental management from pollutant abatement to broader carbon-intensity and energy-system governance [3,4].

ISSN: 2710-0588

Ballast water discharge represents a major pathway for the transfer of harmful aquatic organisms and pathogens. Ships load and discharge ballast water in different regions, creating a route for non-indigenous species to colonize new ecosystems. The Ballast Water Management Convention, adopted in 2004 and in force since 2017, requires ships engaged in international voyages to manage ballast water and sediments according to approved ship-specific plans and performance standards, and to carry a ballast water record book and certificate [6]. Compared with oil and exhaust emissions, ballast water pollution is less visible and may have delayed ecological consequences, so control must emphasize source interruption, organism inactivation, compliance sampling, and port-state enforcement.

Sewage and garbage are important sources of coastal and port-area pollution. Ship sewage contains organic matter, nutrients, suspended solids, and microorganisms; untreated discharge may contribute to eutrophication and microbial contamination in sensitive waters. MARPOL Annex IV regulates sewage discharge and requires approved treatment systems, holding arrangements, surveys, and certification. MARPOL Annex V controls garbage from ships and is particularly important because it imposes a comprehensive prohibition on plastic disposal at sea [1]. These rules link shipboard treatment and storage to port reception facilities, making pollution prevention dependent on both vessel compliance and port capacity.

Antifouling systems and hull biofouling form another important dimension of ship pollution control. Historically, organotin-based antifouling coatings were highly effective but ecotoxic, which led to the Anti-Fouling Systems Convention and the prohibition of harmful organotin compounds [7,29,30]. The 2023 IMO Biofouling Guidelines further stress the need to manage biofouling to reduce the transfer of invasive aquatic species and to improve hydrodynamic performance [8]. Biofouling is therefore no longer a purely maintenance issue: it affects fuel consumption, emissions, invasive-species transfer, coating choice, in-water cleaning, and port-state biosecurity management [31,32].

3. Key Technologies for Ship Pollution Prevention and Control

Oil-pollution prevention technologies include structural protection, oily-water treatment, leakage monitoring, and emergency response. Structural measures such as double hulls, segregated ballast tanks, and safer cargo-tank arrangements reduce the probability of large releases during collision or grounding. Operational control relies on oily-water separators, bilge holding tanks, oil-content meters, automatic stopping devices, and electronic or paper record-keeping. Modern oily-water treatment may combine gravity separation, coalescence, membrane separation, adsorption, electrochemical processes, and advanced oxidation to improve the removal of emulsified oil and low-concentration hydrocarbons. For accidental spills, booms, skimmers, sorbents, dispersants, remote sensing, and response modelling remain essential, but their effectiveness depends strongly on sea state, oil type, weathering stage, and response time.

Exhaust-emission control technologies address SOx, NOx, PM, black carbon, and GHG emissions. Low-sulfur fuel is the most direct option for compliance with sulfur limits because it requires comparatively limited ship modification, but it may increase operating cost and raise issues related to fuel stability and lubricant compatibility. Exhaust gas cleaning systems allow ships to continue using high-sulfur fuel while removing SOx from exhaust gas. Their environmental controversy arises from washwater discharge, particularly in open-loop configurations, where acidic effluent, metals, nitrates, and polycyclic aromatic hydrocarbons may be transferred from the atmosphere to the marine environment [19,20]. Consequently, several ports and coastal states restrict open-loop scrubber discharge, and environmental evaluation of scrubbers must consider both air-emission reduction and water-pollution transfer.

ISSN: 2710-0588

NOx control is commonly achieved through engine-internal measures, SCR, and exhaust gas recirculation. SCR reduces NOx over a catalyst using ammonia or urea-derived ammonia and can achieve high reduction efficiencies under suitable exhaust temperature and catalyst conditions [16,18]. However, its performance is sensitive to engine load, exhaust temperature, catalyst aging, sulfur poisoning, urea logistics, and maintenance quality. Exhaust gas recirculation reduces NOx formation by lowering combustion temperature, but it may influence engine efficiency, soot formation, corrosion management, and aftertreatment requirements. These trade-offs illustrate why marine exhaust control cannot be evaluated through a single pollutant or a single device.

Shore-side electricity, also known as cold ironing or onshore power supply, reduces emissions from auxiliary engines during berthing by allowing ships to receive electricity from the port grid. This can lower local NOx, SOx, PM, CO2, and noise emissions near densely populated port areas [24,25]. Nevertheless, the climate benefit of shore power depends on grid carbon intensity, connection standards, vessel readiness, berth utilization, electricity price, and port infrastructure. Where the electricity mix contains a high share of renewable energy, the emission benefit is substantial; where electricity is fossil-intensive, life-cycle gains may be smaller. Therefore, shore power should be assessed as part of port energy planning rather than as a universal stand-alone solution.

Alternative and low-carbon fuels are central to long-term maritime decarbonization. LNG can reduce SOx and PM emissions and may reduce NOx depending on engine technology, but methane slip can compromise its GHG benefit and LNG remains a fossil fuel unless replaced by bio- or synthetic methane. Methanol is attractive because it is liquid at ambient conditions and can be used in dual-fuel engines, while green methanol could support a lower-carbon pathway. Ammonia contains no carbon and does not emit CO2 at the point of combustion, but its toxicity, corrosiveness, low reactivity, N2O/NOx formation, and bunkering risk require careful management. Hydrogen offers zero-carbon potential at the point of use, especially in fuel cells, but faces storage-density, cryogenic or high-pressure handling, safety, cost, and infrastructure constraints. Life-cycle assessment is therefore essential; comparing only onboard combustion emissions can misrepresent the true environmental performance of alternative fuels [21-23].

Ballast water treatment systems generally combine mechanical, physical, and chemical processes. Filtration is widely used as a pre-treatment to remove larger particles and organisms. Ultraviolet irradiation avoids chemical addition but is sensitive to water turbidity and organism shielding. Electrochlorination, ozone, heat, deoxygenation, and chemical biocides can be effective, but their use requires careful management of residual oxidants, by-products, corrosion, power demand, and safety [26-28]. The suitability of a ballast water system depends on ship type, flow rate, operating route, ballast-water quality, holding time, and maintenance capability. The next stage of development should address not only organism inactivation but also challenging water quality, commissioning tests, indicative sampling, energy use, by-product control, and practical compliance verification.

Sewage and garbage control technologies require coordination between shipboard systems and port reception services. Sewage treatment systems commonly rely on biological treatment, membrane bioreactors, disinfection, sludge management, and holding tanks. Membrane bioreactors can provide high effluent quality but require attention to membrane fouling, space constraints, energy use, and crew maintenance. Garbage management depends on segregation, compaction, storage, incineration where permitted, and reliable delivery to port reception facilities. Since shipboard space is limited, compliance depends strongly on crew training, practical record keeping, reception capacity, and inspection consistency.

Antifouling and biofouling-control technologies include biocidal coatings, foul-release coatings, low-surface-energy silicone systems, self-polishing coatings, biomimetic materials, ultrasonic or electrochemical systems, and robotic in-water cleaning. Effective biofouling management

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can reduce hull resistance, fuel consumption, and GHG emissions, while also reducing the risk of invasive-species transfer [8,31,32]. However, coating toxicity, paint lifetime, microplastic or biocide release, cleaning debris capture, and local biosecurity requirements must be evaluated together. Future antifouling technologies should therefore balance hydrodynamic benefit, ecological safety, cleaning feasibility, and regulatory acceptability.

4. Intelligent Monitoring, Risk Assessment and Life-cycle Management

The digitalization of maritime operations is shifting ship pollution prevention from equipment-based compliance toward data-driven, full-cycle governance. Conventional enforcement has relied on certificates, logbooks, port-state-control inspections, crew records, and manual sampling. These methods remain essential but are often retrospective and resource-intensive. Digital monitoring can collect fuel consumption, engine load, exhaust status, oily-water separator operation, ballast water treatment status, sewage and garbage records, and auxiliary-engine data in near real time, creating a basis for risk detection and compliance verification.

Emission monitoring and accounting are key elements of intelligent governance. Fuel-flow meters, exhaust sensors, automatic identification system (AIS) data, voyage data recorders, energy-management systems, and engine-performance data can be integrated to estimate ship emissions and carbon intensity. For port areas, AIS-based inventories combined with engine-load assumptions and vessel characteristics can support shore-power planning, port-air-quality management, and green-port strategies [12,24,35]. For international voyages, MRV-style data and carbon-intensity ratings can inform speed management, route optimization, technical retrofits, and alternative-fuel decisions.

Machine learning and data mining are increasingly used in ship-pollution risk assessment. Port-state-control inspection records, vessel age, ship type, flag state, recognized organization, previous deficiencies, detention history, and operational pattern can be used to predict high-risk ships or pollution-prevention deficiencies [33-35]. Compared with random inspection, risk-based models help regulatory authorities allocate inspection resources more efficiently. However, these systems must be transparent, auditable, and carefully validated, since biased or incomplete datasets may lead to misleading risk rankings.

Life-cycle management is essential for mature pollution-control assessment. The environmental benefit of a technology should not be judged solely at the onboard operation stage. Fuel production, transportation, storage, bunkering, equipment manufacturing, maintenance, emissions during use, waste streams, and end-of-life treatment all contribute to life-cycle performance. For example, alternative fuels are only low-carbon if their production pathways are sufficiently clean; shore power depends on grid carbon intensity; scrubber benefits must be evaluated against washwater discharge; and antifouling coatings must be assessed for toxicity release and in-water-cleaning impacts. Thus, pollution-control assessment should move from single-device accounting to multi-pollutant, life-cycle optimization.

Port-ship-shore coordination is equally important. Many pollution-control technologies cannot perform effectively without external infrastructure. Shore power requires grid capacity, standardized connections, appropriate electricity pricing, and onboard receiving equipment. LNG, methanol, ammonia, and hydrogen require bunkering infrastructure, safety protocols, trained personnel, and reliable supply chains. Sewage, garbage, sludge, and residues require adequate port reception facilities. Ballast water and biofouling management require information exchange among shipowners, ports, administrations, and service providers. Without such coordination, vessel-level technology upgrades may deliver limited environmental benefit.

ISSN: 2710-0588

5. Challenges and Future Directions

Although ship pollution prevention has developed into a broad technical system, its large-scale implementation still faces technological, economic, infrastructural, and governance challenges. First, the applicability boundaries of different pathways remain uncertain. Low-sulfur fuels, scrubbers, LNG, methanol, ammonia, hydrogen, shore power, and efficiency measures can reduce selected pollutants, but no single option is optimal for all ship types, routes, operating profiles, and regulatory zones. Technology selection must consider vessel size, voyage pattern, fuel availability, energy density, safety requirement, port facilities, life-cycle emissions, and economic feasibility.

Second, pollution-control measures may create synergies but may also shift environmental burdens. Scrubbers reduce airborne sulfur emissions but may increase marine contaminant discharge through washwater. LNG lowers SOx and PM but may suffer from methane slip. Shore power reduces local port emissions but depends on upstream electricity generation. Ammonia avoids carbon in the molecule but introduces toxicity, leakage, combustion, and NOx/N2O concerns. These examples show that future research must emphasize multi-pollutant co-optimization and life-cycle environmental assessment rather than isolated evaluation of local emission reductions.

Third, cost and infrastructure remain major barriers. Clean-fuel vessels, ballast water treatment systems, shore-power retrofits, exhaust aftertreatment, digital monitoring, and port reception facilities all require significant capital expenditure and maintenance capability. For small and medium-sized shipowners, payback uncertainty and fuel-price volatility may reduce the willingness to invest. At the same time, insufficient alternative-fuel bunkering networks, incompatible shore-power interfaces, limited reception facilities, and uneven maintenance services may prevent technologies from delivering their expected benefits.

Fourth, digital governance requires more reliable data and stronger verification mechanisms. Ship pollution management increasingly depends on sensor data, AIS data, electronic record books, emission inventories, and automated compliance models. However, sensor drift, missing data, inconsistent formats, cybersecurity risks, commercial confidentiality, and limited third-party verification can reduce data credibility. Future systems should therefore develop standardized data protocols, secure data-sharing frameworks, transparent algorithms, and independent verification mechanisms. Model interpretability is particularly important when machine learning outputs are used to prioritize inspections or support enforcement decisions.

Five future directions can be identified. First, pollution control should shift from single-pollutant treatment to multi-pollutant management that jointly considers oil pollution, exhaust emissions, GHGs, ballast water, sewage, garbage, antifouling systems, and biofouling. Second, shipboard end-of-pipe treatment should be integrated with source reduction, energy efficiency, voyage optimization, fuel transition, and port infrastructure. Third, local emission evaluation should be expanded to life-cycle assessment to avoid shifting environmental burdens across media or supply-chain stages. Fourth, regulatory compliance should increasingly rely on digital monitoring, risk-based inspection, and data-driven governance. Fifth, vessel-level upgrades should be embedded within port-ship-shore coordination, linking onboard equipment, energy supply, reception facilities, and regulatory enforcement into a coherent system.

In summary, ship pollution prevention and control is entering a transition phase in which conventional pollution abatement, decarbonization, digital compliance, and systems governance are converging. Strengthening MARPOL-based control of traditional pollutants remains necessary, but future progress will depend increasingly on life-cycle fuel assessment, alternative-fuel safety, multi-pollutant optimization, intelligent monitoring, and coordinated infrastructure development. Only by combining technological innovation, port and energy-

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system readiness, verifiable data, and enforceable governance can the shipping sector achieve a more robust transition toward greener and more sustainable maritime transport.

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