

Review Article

SUSTAINABLE BALLAST WATER MANAGEMENT: MITIGATING ECOLOGICAL IMPACTS AND SUPPORTING MARINE AND COASTAL BIODIVERSITY

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ARTICLE HIGHLIGHTS

- Reviews global ballast water management for ecological sustainability
- Integrates technological, policy, and social perspectives
- Links ballast water control to Sustainable Development Goals (SDGs)
- Identifies hybrid treatment systems as most effective and eco-safe
- Proposes strategies for harmonized global compliance and cooperation

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ABSTRACT

Ballast water is indispensable for the stability and safety of ships but remains a major pathway for invasive species, pathogens, and pollutants, generating ecological, economic, and public health risks. This review synthesizes evidence from recent literature (2020 - 2025) to evaluate impacts, governance frameworks, and treatment technologies. Ecologically, ballast discharge accelerates biodiversity loss, alters food webs, and increases harmful algal blooms, while economically it undermines fisheries, aquaculture, tourism, and coastal infrastructure. Social consequences include threats to food security and the well-being of communities reliant on marine resources. The review critically assesses existing measures such as the International Maritime Organization's Ballast Water Management Convention and national policies, highlighting persistent challenges in monitoring, enforcement, and capacity building, particularly in developing regions. Emerging treatment technologies, including advanced oxidation processes, electrochlorination, and nanotechnology, show promising efficacy but remain costly and energy-intensive. Comparative analysis indicates that hybrid treatment systems, which integrate mechanical filtration with UV or chemical disinfection, offer the most balanced compromise between compliance, effectiveness, and ecological safety. Case studies illustrate both successful applications and barriers linked to cost, scalability, and operational complexity. A distinctive contribution of this review is the explicit integration of ballast water management with the United Nations Sustainable Development Goals, especially SDG 14 (Life below Water). We argue that aligning regulatory, technological, and financial strategies with SDG indicators is essential for measuring progress and driving accountability. Future priorities include optimizing hybrid technologies for affordability, harmonizing international regulations, incentivizing industry compliance, and strengthening cooperative capacity building. Advancing sustainable ballast water management is urgent to safeguard marine ecosystems, sustain coastal economies, and protect global public health.

Keywords: ballast water management, biodiversity loss, invasive species, sustainable development

INTRODUCTION

Ballast water is indispensable for maritime operations, providing stability and safety for ships during voyages (Dobrucali *et al.* 2024). Yet its uncontrolled discharge remains a critical pathway for invasive species and pathogens, driving biodiversity loss, ecological imbalance, and significant economic and public health costs (Kraus 2023; Sempere-Valverde *et al.* 2021). Despite decades of awareness, effective solutions remain fragmented, with uneven adoption of treatment technologies and weak enforcement capacity across regions. These persistent gaps make ballast water management a pressing international challenge requiring coordinated innovation and governance.

The introduction of invasive species through ballast water has caused major ecological disruptions, undermining biodiversity and ecosystem stability worldwide (Slišković *et al.* 2021). For example, zebra mussels in North America clogged water intake systems and displaced native species, leading to severe economic losses (Lower *et al.* 2024), while the comb jelly *Mnemiopsis leidyi* in the Black Sea collapsed fisheries by consuming key plankton resources (Javidpour *et al.* 2020). These well-documented cases illustrate both the ecological and economic stakes of unmanaged ballast water and highlight why stronger, globally coordinated management strategies remain urgently needed (Dobrucali *et al.* 2024).

To address these risks, international frameworks such as the International Maritime Organization's (IMO) Ballast Water Management Convention (BWMC) were introduced to minimize the transfer of harmful aquatic organisms and pathogens. While the BWMC represents a critical step forward, its global effectiveness remains limited by uneven enforcement capacity, disparities in national resources, and variable compliance levels (David & Gollasch 2015). At the same time, ballast water treatment technologies remain complex and resource-intensive, creating further barriers to universal adoption. These challenges underscore the persistent gap between regulation, technological readiness, and global implementation.

This review responds to these challenges by providing a structured analysis of the ecological, economic, health, and social consequences of ballast water discharge. It critically evaluates advances in treatment technologies; including

ultraviolet irradiation, filtration systems, and chemical methods, and assesses their effectiveness in limiting invasive species transfer (Obayomi *et al.* 2024). In addition, case studies of implementation are reviewed to highlight both successful practices and persistent barriers, offering insight into the feasibility and scalability of different approaches (Güney 2022; Kraus 2023).

A distinctive contribution of this review is its explicit integration of ballast water management with the United Nations Sustainable Development Goals (SDGs) (IMO 2017). By linking regulatory and technological strategies to global sustainability targets, the review highlights the need to balance environmental protection with economic and social priorities. In particular, ballast water management contributes not only to SDG 14 (Life below Water) but also to SDG 3 (Health) and SDG 8 (Decent Work and Economic Growth), positioning the maritime sector as a key actor in advancing sustainability objectives (Olaniyi *et al.* 2024; Kolios 2024).

This review addresses critical dimensions of ballast water management, including biodiversity loss, economic risks for fisheries and coastal communities, and the health and social consequences of disrupted ecosystems (Andrews *et al.* 2021; Ward *et al.* 2022). It evaluates regulatory frameworks and recent technological advancements while identifying persistent barriers to adoption and enforcement. Actionable insights for research and policy are emphasized, with attention to feasibility and scalability of proposed solutions (Bailey *et al.* 2022). By bridging research, policy, and practice, this review seeks to strengthen international efforts to mitigate the impacts of ballast water discharge and to advance a more sustainable and equitable maritime sector (Olaniyi *et al.* 2024; Bulgakov *et al.* 2025; Mba 2025).

METHODOLOGY

To achieve the objectives outlined above, this review analyzed published studies, policy reports, and technical documents from 2000 to 2025 relevant to ballast water management and its ecological, economic, and technological dimensions. Relevant literature was collected from peer-reviewed journals, books, and international agency publications. The information was then classified thematically into ecological, economic, health, and social impacts, regulatory frameworks, and treatment technologies. Thematic analysis

was used to synthesize insights from different disciplines and identify research gaps related to policy, technology, and sustainability.

The literature search was performed using databases including Scopus, Web of Science, and Google Scholar with keywords such as “ballast water management,” “invasive species,” “treatment technologies,” and “sustainable development goals.” Studies were included if they presented ecological, economic, health, or policy implications of ballast water management, while purely engineering-focused technical papers without environmental relevance were excluded. Duplicates were removed, and relevant non-English sources were included when they provided substantial regional or contextual insights. This approach ensured comprehensive and balanced coverage of interdisciplinary perspectives relevant to sustainable ballast water management.

REVIEW

Ecological Impacts of Ballast Water

Ballast water introduces invasive species and pollutants such as heavy metals and microplastics that disrupt marine ecosystems and food webs (Landrigan *et al.* 2020; Kurniawan *et al.* 2022). These invasions alter biodiversity patterns and ecological functioning, but also generate long-term risks for public health and food security (Kraus 2023a; Adeniran-Obey & Osagie 2024). Well-documented cases such as zebra mussels in the Great Lakes and comb jellies in the Black Sea demonstrating significant environmental and economic impacts (Shiganova *et al.* 2019; Burlakova *et al.* 2023).

Invasive species not only reduce biodiversity but also destabilize nutrient cycles and transform habitats. A prominent example is the lionfish invasion in the Atlantic, which has led to marked declines in native fish populations and disrupted trophic dynamics (Acero *et al.* 2019; Mayfield *et al.* 2021). Such biodiversity erosion diminishes ecosystem resilience, weakening the capacity of marine systems to buffer against climate change impacts and pollution stressors (Gallardo *et al.* 2024).

Ballast water also acts as a vector for pathogens such as *Vibrio cholerae*, associated with cholera outbreaks, and for harmful algal blooms (HABs) that contaminate seafood and coastal waters (Yñiguez *et al.* 2021). Beyond biological threats, chemical pollutants, including microplastics, bioaccumulate in marine organisms, infiltrating the food chain and posing direct risks to human health and food security (Jahromi *et al.* 2021; Zendehboudi *et al.* 2024). As global shipping intensifies, these combined pressures amplify, underscoring the urgency of implementing scalable treatment systems and stricter regulatory enforcement (Dobrucali *et al.* 2024).

The cumulative ecological and health impacts of ballast water highlight the importance of developing evidence-based strategies that integrate ecological risk assessment with policy and technology innovation (Adraktas 2024; Onyena & Nwaogbe 2024). To provide a structured overview, Table 1 synthesizes key ecological impacts, their underlying causes, and representative references, offering a concise reference point for subsequent analysis.

Table 1 Overview of the ecological impacts, causes, and references for each invasive species introduced through ballast water

Species	Effect	Cause	References
Lionfish (<i>Pterois volitans</i>) in its native Indo-Pacific region	Disrupt native marine populations in the Gulf of Mexico, the Caribbean, and US Eastern Seaboard	Introduced via ornamental fish trade and possible via ballast water from Indo-Pacific regions	MacIsaac <i>et al.</i> (2016); Williams <i>et al.</i> (2013)
Zebra Mussel (<i>Dreissena polymorpha</i>)	Clogs water intake pipes, outcompetes native species, alters aquatic food web	Introduced via ballast water from transoceanic ships from Europe	van Der Gaag <i>et al.</i> (2016); Burlakova <i>et al.</i> (2023)
Comb Jelly (<i>Mnemiopsis leidyi</i>)	Collapse of anchovy fishery, impacting local biodiversity and fishing industry	Transported via ballast water from ships from the eastern US	Shiganova <i>et al.</i> (2023)
European Green Crab (<i>Carcinus maenas</i>) in North America	Significant ecological disruptions, predation on native shellfish, competition with local species, impacted shellfish industries	Introduced via ballast water from Europe	Grosholz <i>et al.</i> (2000); Jeffery <i>et al.</i> (2017)

Species	Effect	Cause	References
Chinese Mitten Crab (<i>Eriocheir sinensis</i>)	Ecological disruption, erosion, damage to flood control systems, competition with native species	Introduced via ballast water from ships traveling from Asia	Crocetta <i>et al.</i> (2020); Trichkova <i>et al.</i> (2017)
Round Goby (<i>Neogobius melanostomus</i>)	Outcompetes native fish, alters benthic communities, preys on eggs and young of native fish	Introduced via ballast water from the Black and Caspian Seas	Cerwenka <i>et al.</i> (2023); van Deurs <i>et al.</i> (2021)
Japanese Kelp (<i>Undaria pinnatifida</i>)	Forms dense underwater forests, outcompetes native seaweeds, impacts native marine life and mussel farms	Introduced via ballast water from ships traveling from Asia	Epstein & Smale (2017); South <i>et al.</i> (2017)
Asian Tiger Shrimp (<i>Penaeus monodon</i>) in the United States	Dominant predator, impacts native shrimp and fish species, alters food webs	Introduced via ballast water from seafood and aquaculture products	Aguirre-Pabón <i>et al.</i> (2023); Petatán-Ramírez <i>et al.</i> (2020)
Northern Pacific Seastar (<i>Asterias amurensis</i>) in Australia	Preys on native marine organisms, declines in native species, disrupts marine ecosystems. impacts local fisheries	Introduced via ballast water from ships from Asia	Byrne <i>et al.</i> (2016); Ellis (2022)
Asian Shore Crab (<i>Hemigrapsus sanguineus</i>) in the Northeastern United States	Outcompetes native species, alters coastal community structure, reduction in native crab and mollusk populations.	Introduced via ballast water	Espinosa-Novo <i>et al.</i> (2023); Griffen <i>et al.</i> (2020)
Brown Tree Snake (<i>Boiga irregularis</i>)	Caused extinction of bird and reptile species, threatens biodiversity and human health	Introduced via ballast water and cargo shipments	Boback <i>et al.</i> (2022); Siers <i>et al.</i> (2024)
<i>Vibrio cholerae</i> and <i>Escherichia coli</i>	Risk of cholera outbreaks in coastal communities	Ballast water from regions with cholera outbreaks	Lakshmi <i>et al.</i> (2021); Soleimani <i>et al.</i> (2021)
Harmful Algal Blooms (HABs) in the Baltic Sea and Mediterranean Sea	Production of toxins that contaminate seafood and water supplies, health risks to humans and marine life	Spread via ballast water carrying algal cysts	Karlson <i>et al.</i> (2021); Tsikoti & Genitsaris (2021)
Cryptosporidium and Giardia	Causes gastrointestinal illness outbreaks	Ballast water from contaminated regions.	Kraus (2023)
Sea lamprey (<i>Petromyzon marinus</i>)	Cause declines in native fish populations, such as lake trout (<i>Salvelinus namaycush</i>)	Introduction to the Great Lakes	Mattes & Kitson (2021)
Heavy metals (Fe, Cu, Pb)	Bioaccumulation	Ballast water from vessels from various regions	Hassaan & El Nemr (2021); Onyena & Nwaogbe (2024)
Microplastic	Threat to wildlife and marine environment	Ballast water	Naik <i>et al.</i> (2021); Thushari & Senevirathna (2020)

Economic, Environmental, and Social Impacts

Ballast water discharge produces significant economic and social consequences by disrupting ecosystem services that support fisheries, aquaculture, and tourism (Gollasch & David 2019; Kraus 2023). Ballast water discharge produces significant economic and social consequences by disrupting ecosystem services that support fisheries, aquaculture, and tourism.

Fisheries and aquaculture are particularly vulnerable to the cascading effects of invasive species and pathogens introduced via ballast water. The collapse of the Black Sea's anchovy population following the invasion of the comb jelly *Mnemiopsis leidyi* created severe economic hardship for fishing communities (Knowler 2005). Similarly, the spread of pathogens such as *Cryptocaryon irritans* has disrupted aquaculture production, undermining food security and market stability (Giari *et al.* 2022). Coastal infrastructure

also bears high costs: zebra mussel infestations in the Great Lakes have demanded costly recovery and repair interventions (Lower *et al.* 2024). In addition, tourism and recreational fishing decline when degraded ecosystems deter visitors, reducing local business income and weakening regional economic resilience (van Beukering *et al.* 2014; Sukhikh *et al.* 2019).

The social consequences of ballast water discharge are equally profound, especially in coastal regions where cultural identity and livelihoods are deeply intertwined with native marine species. Invasive organisms displace native stocks, eroding traditional fishing practices, weakening intergenerational knowledge transfer, and threatening cultural heritage. For example, the Mediterranean fisheries disrupted by the comb jelly have not only suffered ecological and economic setbacks but also cultural dislocation for communities whose identities are bound to these fisheries (Zenetos *et al.* 2010; Kraus 2023).

Implementing ballast water management systems requires substantial financial investment, with installation costs estimated between USD 500,000 and USD 5 million per vessel, in addition to significant operational and maintenance expenses (Gerhard *et al.* 2019; Hardiyanto *et al.* 2023). While these upfront costs pose challenges for shipowners, they are outweighed by the long-term savings achieved through avoided ecological damage and infrastructure repair. For example, proactive measures could have significantly reduced the billions spent on recovery and restoration efforts necessitated by the zebra mussel invasion (van Der Gaag *et al.* 2016; BCWF Watershed Team 2025). Such cost-benefit framing highlights ballast water management not only as an ecological imperative but also as a financially rational investment.

International frameworks such as the IMO Ballast Water Management Convention introduce additional compliance costs for shipowners, yet they remain critical instruments for averting large-scale ecological disruption and economic loss (Outinen *et al.* 2024). To balance regulatory stringency with feasibility, governments can deploy supportive measures, such as tax incentives, subsidies, and resource-sharing programs, that lower financial barriers, foster equitable compliance across regions, and accelerate the adoption of cost-effective treatment technologies (Becqué *et al.* 2018).

Regulatory Frameworks and Policies

The International Maritime Organization's Ballast Water Management Convention (BWMC) establishes the first binding global framework for regulating ballast water treatment and discharge, requiring vessels to implement exchange and onboard treatment systems to limit invasive species transfer (David & Gollasch 2015). However, its enforcement varies widely due to institutional and financial disparities among member states (IMO 2004). The hierarchical structure of international, national, and regional governance frameworks is summarized in Figure 1.

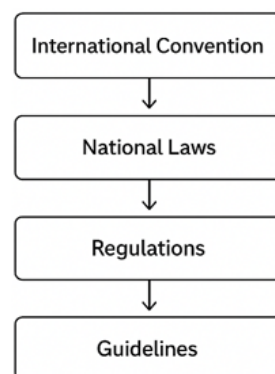


Figure 1 Regulatory framework for ballast water management

Beyond the BWMC, individual nations and regions have enacted supplementary frameworks tailored to local contexts. For example, the United States enforces the National Invasive Species Act (NISA), which obliges vessels to treat or exchange ballast water, while China has formally aligned with BWMC standards (Verna & Harris 2016; Hao 2020; United States Coast Guard 2023). Regional initiatives, such as those in the Baltic Sea and the Great Lakes, target specific ecological vulnerabilities and complement international obligations. Yet, disparities in enforcement and implementation across jurisdictions expose persistent gaps in global governance, underscoring the importance of harmonized policies and mechanisms for sharing best practices (Jetoo 2018).

Enforcing ballast water regulations remains a persistent challenge, constrained by technical limitations such as the absence of reliable real-time compliance detection and the high costs of advanced monitoring technologies. Effective enforcement requires rigorous inspections and international coordination, which are unevenly implemented. Promising developments include targeted surveillance in high-risk areas and

collaborative port programs, both of which have demonstrated early success (Wang *et al.* 2020; Bailey *et al.* 2022). In addition, emerging tools, such as automated monitoring systems and integrated data-sharing platforms, offer pathways to more scalable and transparent compliance regimes (Fournier *et al.* 2018; Olaniyi *et al.* 2024; Melnyk *et al.* 2025). Strengthening these measures is essential not only to maximize the impact of existing frameworks but also to enhance global trust in regulatory effectiveness.

Ballast Water Treatment Technologies

Ballast water treatment employs a diverse range of approaches, mechanical, chemical, physical, biological, and increasingly integrated systems, to mitigate the risks of invasive species and pathogen transfer. Filtration remains the most widely adopted baseline method and is frequently paired with complementary techniques such as electrolysis, electrochlorination, or UV disinfection. More advanced options, including ozonation, cavitation, deoxygenation, and advanced oxidation processes, provide additional pathways for compliance but present varying levels of cost, operational complexity, and ecological trade-offs (Balaji *et al.* 2019; Duan *et al.* 2023). Treatment choices should be evaluated not only by efficacy but also by scalability and environmental footprint, aligning with SDG sustainability principles. Figure 2 provides a flowchart summarizing these categories of treatment technologies, complementing the detailed comparisons presented in Tables 2 and 3.

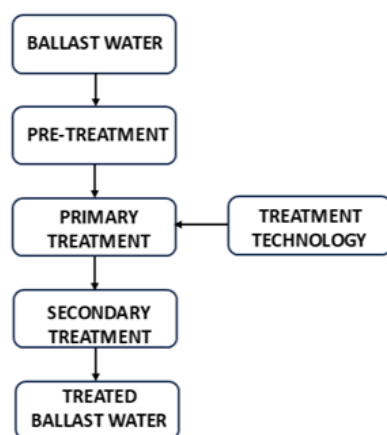


Figure 2 Ballast water treatment systems

Mechanical Methods

Mechanical methods, including filtration and cyclonic separation, remain foundational to ballast water treatment, physically removing particulate matter and organisms. Filtration technologies such

as disk filters, filter bags, and cartridges differ in efficiency depending on pore size, filter design, and cleaning mechanisms. These approaches are highly effective at capturing larger particles, microplastics, and soft-bodied plankton but are less successful against microorganisms below the filtration threshold. Their overall performance is strongly contingent on maintenance practices, as heavy sediment loads reduce flow rates and increase pressure drops, thereby influencing operational reliability and long-term cost efficiency (Drake *et al.* 2016; Naik *et al.* 2021). While effective as a first barrier, mechanical methods require pairing with other treatments to ensure microbial safety.

Chemical Methods

Chemical methods aim to balance disinfection effectiveness with ecological safety, offering multiple options for ship operators. Chlorination remains cost-effective and widely adopted but generates harmful by-products such as trihalomethanes (THMs), which raise ecological and regulatory concerns (Kurniawan *et al.* 2022). Ozonation is rapid and leaves no persistent residues, yet it produces toxic bromate in seawater and requires substantial energy inputs (Seridou *et al.* 2024). UV radiation combined with hydrogen peroxide offers a more environmentally friendly approach, though its efficiency declines in turbid waters. Peracetic acid is another low-impact disinfectant but poses handling challenges due to its corrosive properties. Selecting among these methods requires balancing operational feasibility, regulatory compliance, and environmental impact, highlighting the trade-offs inherent in chemical approaches (Hess-Erga *et al.* 2019; Yoon *et al.* 2021). Chemical approaches remain cost-effective but risk undermining sustainability unless by-product management strategies are prioritized.

Physical Methods

Physical approaches, including UV radiation, heat treatment, deoxygenation, cavitation, and ultrasound, neutralize organisms by altering environmental conditions rather than adding chemicals. UV radiation is widely adopted for its ability to damage microbial DNA across a broad spectrum of organisms without producing chemical residues, though its effectiveness declines in turbid waters. Heat treatment achieves full sterilization by elevating water temperature but is energy-intensive and often impractical at scale. Deoxygenation suppresses aerobic

organisms through inert gas injection, reducing chemical dependency but requiring specialized infrastructure. Cavitation and ultrasound disrupt microbial cell structures via rapid pressure fluctuations and acoustic energy, though both are limited by high energy demands (Estévez-Calvar *et al.* 2018; Hess-Erga *et al.* 2019; Balaji *et al.* 2019). These methods are valued for minimizing chemical use but face feasibility challenges related to energy efficiency and equipment requirements. Physical methods are environmentally preferable but require optimization for variable water conditions and energy efficiency.

Biological Methods

Biological methods, while still largely experimental, represent innovative approaches that harness ecological interactions to manage invasive species. Strategies include introducing natural predators, parasites, or competitors (Dafforn 2025) and exploring genetic biocontrol techniques (Teem *et al.* 2020). These approaches carry the advantage of potentially reducing chemical and energy use, yet they require rigorous ecological risk assessment to avoid unintended disruptions. Current research emphasizes combining biological agents with mechanical, chemical, or physical methods to enhance sustainability and long-term effectiveness (Drake *et al.* 2016; Kraus 2023). Biological methods are promising for long-term sustainability but should only be deployed as part of controlled, integrated approaches.

Combined Systems

Integrated systems combine mechanical, chemical, physical, and in some cases biological methods to maximize treatment efficiency while minimizing ecological side effects. For example,

filtration can precede UV or heat treatment to lower turbidity and enhance disinfection, while electrochlorination can complement UV systems to maintain performance under challenging conditions. Experimental biological techniques, such as the use of natural predators, are also being incorporated into hybrid frameworks (Nwigwe & Kiyokazu 2023).

The strength of integrated approaches lies in their ability to address diverse contaminants simultaneously, thereby reducing chemical dependency, minimizing by-product formation, and improving overall sustainability. Nevertheless, these systems are constrained by high complexity, steep regulatory requirements, and significant financial costs. Ongoing research is focused on optimizing configurations and reducing operational burdens, positioning integrated systems as a promising long-term solution for balancing ecological protection with regulatory compliance in ballast water management (Eleyadath *et al.* 2021). Integrated systems illustrate the shift toward holistic solutions, though cost barriers must be addressed for widespread scalability.

Comparison among Treatments

A comparative overview of available treatment methods is presented in Tables 2 and 3, which synthesize the relative strengths, limitations, and contextual suitability of physical, chemical, biological, and integrated approaches. Rather than serving as exhaustive descriptions, these summaries provide a framework for aligning technological choices with ecological, economic, and regulatory priorities. Comparative frameworks highlight not just technical differences but also policy relevance, supporting decision-making at both ship and regulatory level.

Table 2 Comparison of physical and mechanical methods for ballast water treatment

Treatment method	Advantage	Disadvantage	Effectiveness	Operational complexity	References
Mechanical filtration	Effective in removing large particles and organisms	Requires regular maintenance	Effective for larger organisms, limited for smaller microorganisms	Simple operation, requires regular maintenance	Williams <i>et al.</i> (2013); Naik <i>et al.</i> (2021)
Multistage filtration	High efficiency in removing large particles and organisms	Requires regular filter changes and space	High for particles and larger organisms	Moderate, requires space and labor	Guilbaud <i>et al.</i> (2019); Naik <i>et al.</i> (2021); Duan <i>et al.</i> (2023)
Membrane filtration	High efficiency in removing particles and microorganisms	High capital and operational costs	Very high	High, requires advanced systems	Dong <i>et al.</i> (2021)

Treatment method	Advantage	Disadvantage	Effectiveness	Operational complexity	References
UV Treatment	No chemical residues in the environment	Less effective in turbid waters, requires clear water	Effective against bacteria, viruses, protozoa	Moderate, requires system management and lamp maintenance	Ejder <i>et al.</i> (2024); Sari & Gunawan (2024)
Heat Treatment	Effective against a wide range of microorganisms	Requires high energy and costly infrastructure	High effectiveness	High, requires advanced systems and monitoring	Balaji <i>et al.</i> (2019); Iswantoro <i>et al.</i> (2023)

Notes:

- Effectiveness: Degree of success in inactivating/removing target organisms.
- Operational complexity: Technical skills, maintenance, and resources required.
- Sources: Studies supporting performance of each method.
- Implication: Physical/mechanical methods are robust for larger organisms but need integration with other approaches for microbial safety.

Table 3 Comparison of chemical and biocide-based methods for ballast water treatment

Treatment method	Advantage	Disadvantage	Effectiveness	Operational complexity	References
Chemical Disinfection (e.g., Chlorine, Sodium Hypochlorite)	Effective against a broad range of microorganisms	Chemical residues can impact environment	High disinfection efficiency	Moderate, requires handling chemicals and monitoring dosages	Kurniawan <i>et al.</i> (2022)
Biobased Biocides	Natural and environmentally friendly substances	May be less effective against all microorganisms	Variable effectiveness	Moderate, requires biocide management	Kim <i>et al.</i> (2018)
Ozonation	Effective against many pathogens and microorganisms	High cost and operational complexity	Very high effectiveness	High, requires specialized equipment and monitoring	Herwig <i>et al.</i> (2006); Díaz-Domínguez <i>et al.</i> (2024)
Electro-coagulation	Treats small particles and organic matter	Energy-intensive, requires electrode maintenance	High in removing particles and organic matter	Moderate to high, complex operation	Duan <i>et al.</i> (2023); Effendi <i>et al.</i> (2024)

Notes:

- Effectiveness: Strength of microbial/particle removal.
- Operational complexity: Chemical handling, equipment, and monitoring burden.
- Sources: Key references evaluating method efficiency and limitations.
- Implication: Chemical/biocide methods are powerful but raise concerns about ecological residues, cost, and sustainability.

Industry Trends and Best Practices

The ballast water treatment industry is increasingly adopting innovative practices and standards to develop systems that are both efficient and environmentally responsible. Key trends include modular and scalable designs that provide flexibility across vessel types and operational profiles. Best practices emphasize sustainability by integrating energy-efficient designs, minimizing waste, and lowering operational footprints. At the same time, industry-wide collaboration is strengthening standardized guidelines and certification processes, which enhance consistency, reliability, and compliance across diverse treatment technologies (Apetroaei *et al.* 2018; Lakshmi *et al.* 2021).

Emerging Technologies for Ballast Water Treatment

Emerging technologies such as advanced oxidation processes (AOPs), electrochlorination, and nanotechnology are reshaping ballast water management by offering alternatives that balance disinfection efficiency with sustainability. AOPs, which rely on reactive hydroxyl radicals generated by ozone or UV with hydrogen peroxide, demonstrate strong efficacy but remain limited by high energy demands, advanced infrastructure needs, and by-product management challenges (Golfinopoulos *et al.* 2024). Electrochlorination, which generates chlorine-based disinfectants through seawater electrolysis, is already widely adopted due to its cost-effectiveness and ease of integration into

ship systems, though careful monitoring of toxic by-products like trihalomethanes is essential (Moreno-Andrés *et al.* 2018; Park *et al.* 2025). Nanotechnology methods, including nanofiltration and photocatalytic nanoparticles, show promise for high efficiency but face barriers related to cost, scalability, and uncertain environmental risks (Poornima *et al.* 2022; Melnyk *et al.* 2025b).

Adoption patterns reflect these strengths and weaknesses: electrochlorination dominates current use, AOPs are operational but require optimization for energy and ecological safety, and nanotechnology remains experimental. Collectively, these approaches illustrate a research gap: while promising, they require further refinement and scaling before contributing fully to sustainable ballast water management.

Innovations in Existing Technologies

Recent innovations in traditional ballast water treatment methods, mechanical, chemical, physical, and biological, aim not only to improve efficiency and reduce costs but also to align with stricter global sustainability and regulatory demands (Bui *et al.* 2021). Mechanical systems now incorporate advanced pore designs and optimized flow rates to enhance particle retention while minimizing energy penalties (Tsolaki & Diamadopoulos 2010). Chemical treatments increasingly emphasize reducing by-product toxicity, while physical methods such as UV radiation are being adapted to function reliably under varied water qualities (Kurniawan *et al.* 2022; Golfnopoulos *et al.* 2024).

The critical shift lies in their integration with regulatory compliance: rather than incremental improvements, these advances address enforcement gaps by offering more predictable performance, lower operational costs, and reduced ecological risks (Feng *et al.* 2023; Durlík *et al.* 2024). This highlights both progress achieved and the need for further innovation to ensure that treatment technologies remain scalable and feasible across diverse shipping contexts.

Economic and Environmental Considerations

The adoption of ballast water treatment technologies depends on balancing economic feasibility with long-term environmental sustainability (Makkonen & Inkinen 2021; Ishola & Kontovas 2022; Nie *et al.* 2023; Ejder *et al.* 2024). Beyond simple cost-benefit calculations, stakeholders increasingly rely on life cycle assessments (LCAs) to account for environmental

footprints from production through disposal (Kurniawan *et al.* 2022). This shift highlights a research gap: while LCAs are widely applied in other maritime sectors, their use in ballast water management remains limited and inconsistent.

Electrochlorination continues to be attractive due to lower upfront costs, but unresolved challenges with toxic by-products complicate its sustainability profile (Kurniawan *et al.* 2022). By contrast, advanced oxidation processes (AOPs) and nanotechnology require high initial investments but offer greater efficiency, regulatory alignment, and reduced ecological risks in the long term (Devendrapandi *et al.* 2024). Thus, selecting appropriate technologies is not just a technical or financial decision but a strategic trade-off among compliance requirements, ecological responsibility, and operational viability (Durlík *et al.* 2024).

Case Studies and Practical Applications

Case studies of ballast water management highlight not only the strategies and technologies employed, but also the lessons learned that can inform broader adoption. While successful implementations exist, widespread uptake is still constrained by technical challenges, financial burdens, and uneven regulatory enforcement (Wang & Corbett 2021). Addressing these barriers requires innovation and cooperation, but also analytical reflection on what has worked and why. Capacity building, technological innovation, and regional collaboration remain essential, yet the real value of case studies lies in their transferability and potential to guide scalable, sustainable ballast water practices (Khaskheli *et al.* 2023).

Port-level Initiatives

The Great Lakes region has implemented rigorous ballast water inspection and treatment requirements, leading to measurable reductions in invasive species introductions. Although compliance monitoring is resource-intensive, this case demonstrates that early detection and strict enforcement can prevent long-term ecological damage (Bailey *et al.* 2022). Investing in strong port-level monitoring yields high ecological returns and can be adapted to other high-risk entry points.

National and Regional Frameworks

The Baltic Sea Action Plan integrates ballast water management into a wider regional marine protection framework. By combining IMO guidelines with coordinated monitoring, Baltic

states achieved higher compliance compared to individual enforcement alone (Baltic Marine Environment Protection Commission 2021). Regional harmonization reduces loopholes and enables smaller states to share resources for compliance.

Industry-led Adoption

Some shipping companies, particularly those operating globally, have installed treatment systems ahead of regulatory deadlines. This has given them operational flexibility across jurisdictions and improved corporate reputation. Early voluntary adoption can lower long-term costs and create competitive advantage, aligning compliance with business interests (Rivas-Hermann *et al.* 2015; Celestin 2023).

Sustainable Development and Future Directions

Ballast water discharge remains a major pathway for invasive species and pathogen spread, imposing significant ecological, economic, and public health costs worldwide. These challenges also hinder progress toward Sustainable Development Goals (SDGs) related to marine conservation, public health, and sustainable economic growth (Lv *et al.* 2024). Although multiple treatment technologies exist, their adoption remains uneven, depending on vessel type, shipping route, and financial capacity. Addressing these disparities requires ongoing research to develop efficient and eco-friendly treatment systems, alongside stronger global monitoring and compliance mechanisms (Melnik *et al.* 2025).

Mechanical filtration and UV treatment remain widely applied but are constrained by water turbidity and maintenance needs. Chemical disinfection provides broad efficacy yet generates toxic by-products requiring careful neutralization. Advanced oxidation processes and nanotechnology demonstrate superior microbial inactivation but remain costly and energy-intensive, limiting scalability. A key contribution of this review is the comparative evidence that hybrid systems, such as filtration combined with UV or electrochlorination, offer higher compliance rates and improved sustainability compared to single-method approaches (Hess-Erga *et al.* 2019; Dong *et al.* 2023).

Policymakers play a critical role in strengthening regulatory frameworks, funding capacity-

building, and facilitating technology transfer. Effective enforcement requires investment in port inspection capabilities, standardized reporting, and international cooperation to assist low-resource flag states in meeting BWMC requirements (Bailey 2015; Feng *et al.* 2023; Durlik *et al.* 2024).

Summary of Key Findings

Ballast water threatens aquatic ecosystems and economies by introducing non-native species that outcompete native fauna, alter food webs, and disrupt ecosystem services. These invasions cause direct economic losses in fisheries, aquaculture, and tourism, while also imposing long-term costs related to ecosystem restoration and public health measures (McLaughlan & Aldridge 2013).

Improved ballast water management is essential to mitigate these impacts while supporting broader sustainability objectives. This review integrates technological, regulatory, and socio-economic perspectives to propose measurable SDG-aligned indicators, thereby enabling assessment of progress toward SDG 14 and related targets.

Effective regulations are critical to successful ballast water management, but regulatory alignment and enforcement remain uneven across regions (Olaniyi *et al.* 2024). We recommend harmonized standards, incentive mechanisms for adoption of hybrid technologies, and the establishment of regional monitoring hubs to support compliance and data sharing (Zreik 2024).

CONCLUSION

Effective ballast water management is essential to mitigate environmental, economic, and public health challenges caused by untreated discharges. Such discharges introduce invasive species, reduce biodiversity, and spread pathogens, directly affecting marine ecosystems, and industries such as fisheries, aquaculture, and tourism.

Global standards, such as the IMO's Ballast Water Management Convention provide a critical framework for risk reduction but continue to face uneven enforcement and resource disparities across regions. Emerging technologies, including advanced oxidation processes, electrochlorination, and nanotechnology, demonstrate strong potential for enhancing efficiency and sustainability. Further research is required to optimize these methods for ecological safety, operational reliability, and cost effectiveness.

Integrated systems that combine mechanical, chemical, and physical treatments offer robust solutions by overcoming the limitations of single-method approaches. Their broader adoption, however, depends on harmonized international policies, compliance incentives, and capacity-building in resource-limited regions. Importantly, aligning ballast water management with Sustainable Development Goal (SDG) 14 provides a novel pathway for protecting marine ecosystems, strengthening coastal economic resilience, and advancing global environmental health.

Policymakers, researchers, and industry stakeholders must prioritize refining technologies, enhancing monitoring and compliance systems, and fostering stronger cooperation. By embedding these efforts within the SDG framework, the maritime sector can accelerate innovation, achieve measurable sustainability outcomes, and mitigate ballast water's negative impacts, ensuring the long-term protection of marine ecosystems for future generations.

RECOMMENDATION

Effective ballast water management requires a comprehensive approach that integrates advanced treatment technologies, strengthened regulatory frameworks, international collaboration, and alignment with sustainability goals. Hybrid systems combining mechanical, chemical, and physical methods should be prioritized, along with continued research into innovative solutions like advanced oxidation processes and nanotechnology. Global and regional policies, such as the International Maritime Organization's Ballast Water Management Convention, need harmonization and consistent enforcement, supported by financial incentives to ease the adoption of advanced technologies. International cooperation is essential for sharing best practices and building capacity in under-resourced regions. By embedding ballast water management within sustainable development strategies, the maritime industry can protect biodiversity, support economic resilience, and promote global environmental health.

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