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Review Article

Trend for ballast water treatment system retrofits

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Abstract
Ballast water plays a crucial role in maintaining ship stability, yet it remains a major pathway for the spread of invasive marine species. Regulations introduced by the International Maritime Organization (IMO) now require vessels to treat ballast water before discharge, prompting widespread retrofitting of treatment systems. A broad review of research highlights the diverse adoption of prominent technologies, such as electrolysis and ozonation, alongside significant attention on ultraviolet (UV) treatment methods. The overall trend in ballast water management emphasizes greater system stability, lower operational costs, and improved ease of operation and maintenance over a single dominant technology. Publication trends show growing international collaboration and increasing focus on regulatory compliance, cost analysis, and environmental impact. Evaluations across various studies point to seven key aspects in retrofit planning, including system selection, spatial layout, compliance with international standards, and integration of advanced modeling tools. While many retrofit projects prioritize efficiency and cost, fewer have addressed long-term monitoring or biological risk mitigation. Differences in regulatory frameworks across countries create compliance gaps, while newer risks, such as persistent microorganisms and radioactive discharge, remain difficult to control with current systems. Emerging tools, including real-time monitoring devices and genetic testing methods, offer promise for improving system performance and post-installation validation. Retrofit planning increasingly incorporates digital engineering, helping to reduce installation time and minimize costs. Global cooperation remains essential, especially when managing compliance in international waters. Addressing both known and emerging challenges requires a combination of strong technical planning, legal harmonization, and environmental awareness. A more integrated approach will support sustainable marine operations and help safeguard ocean ecosystems from the long-term effects of untreated ballast water.

1. Introduction

Ballast water is essential for maintaining ship stability, maneuverability, and safety during maritime operations. However, it also acts as a major vector for the transfer of invasive aquatic species and harmful microorganisms across different marine ecosystems, causing significant ecological disruption and economic damage worldwide (Nwigwe & Kiyokazu, 2023). To address this, the International Maritime Organization (IMO) adopted the Ballast Water Management Convention (BWMC) in 2004, which came into force in 2017, establishing mandatory requirements for ships to install Ballast Water Treatment Systems (BWTS) that meet rigorous discharge standards, such as the

D-2 performance standard (Bui et al., 2021; Chatterjee, 2015; Güney, 2022). The D-2 standard limits the concentration of viable organisms in discharged ballast water to fewer than 10 organisms per cubic meter greater than or equal to 50 µm in minimum dimension, and fewer than 10 viable organisms per milliliter less than 50 µm and greater than or equal to 10 µm in minimum dimension (Romero-Martínez et al., 2024). Additionally, the IMO sets limits on concentrations of indicator microbes, such as toxicogenic *Vibrio cholerae* (less than 1 colony forming unit (cfu) per 100 mL), *Escherichia coli* (less than 250 cfu per 100 mL), and intestinal *Enterococci* (less than 100 cfu per 100 mL) as a human health standard (Casas-Monroy et al., 2022). Crucially, the IMO also adopted the Code for Approval of Ballast Water Management Systems (BWMS Code), Resolution MEPC.300(72), which took effect on 13 October 2019, to ensure uniform and proper application of the Convention's standards, and superseded previous guidelines like the G8. Furthermore, Resolution MEPC.169(57) details the Procedure for Approval of Ballast Water Management Systems that Make Use of Active Substances (G9) (IMO, 2008), aiming to determine the acceptability of active substances and preparations containing one or more active substances for ballast water management concerning ship safety, human health, and the aquatic environment. Hardiyanto et al. (2020) highlighted that the BWMC aims to effectively control and minimize the spread of non-indigenous species through ballast water discharge.

BWTS technologies include a variety of treatment methods, such as filtration systems, chemical disinfection, ultraviolet (UV) treatment, electrolysis, and ozone (Sari & Gunawan, 2024). Given that the IMO regulates BWTS design and production as controlled products, rigorous technical standards and type approval procedures are established by regulatory bodies. The BWMS Code, Resolution MEPC.300(72), outlines the testing and performance requirements for BWMS approval, including land-based and shipboard testing to ensure compliance with the D-2 performance standard and to prevent unacceptable harm to the ship, crew, environment, or public health. It also specifies appropriate design, construction, and operational parameters for BWMS approval. Each method carries unique operational characteristics, advantages, and constraints. For instance, Sari and Gunawan (2024) conducted a comprehensive review, demonstrating that UV treatment has been shown to be particularly effective for retrofit applications, offering high treatment efficiency with manageable operational costs. However, its adoption requires consideration of economic factors. Purchase prices can vary widely, from about \$0.2 million for smaller capacities to \$1.8 million for very large crude carriers (VLCCs), depending on flow rate and system features. Hardiyanto et al. (2023) also report initial purchase and installation costs, ranging from \$0.2 to \$1 million per vessel. Operational expenses are another critical factor. UV lamps typically have a limited lifespan of 8,000 - 12,000 hours, while filters require periodic cleaning or replacement due to sediment buildup. These aspects significantly affect long-term ownership costs. Blanco-Davis and Zhou (2014) estimated annual spares and maintenance costs at approximately \$15,260, whereas Mahmud et al. (2024) calculated replacement costs of eight UV lamps at €600 each, and filter inserts at €12,000 each, over a five-year period. Conversely, Nwigwe and Kiyokazu (2023) noted that chemical methods, while effective, can generate disinfection by-products that pose environmental concerns. Additionally, integration challenges, such as space limitations and compatibility with existing ballast water systems, complicate the selection of BWTS (Fearnley, 2017). Despite its advantages, UV technology faces notable limitations: high energy consumption, reduced efficacy in waters with high Total Suspended Solids (TSS), and limited suitability for large vessels with high flow rates. For example, Jang et al. (2020) demonstrated that BWMS involving UV units struggled to operate properly in waters with extreme turbidity (> 300 mg/L TSS), where filter clogging and reduced UV transmittance led to compliance failures. Similarly, Olsen et al. (2021) observed that biotic and abiotic particles, as well as fouling of quartz sleeves, significantly reduced UV efficiency due to shielding effects. On the scale of large bulk carriers, Thach and Hung (2023) found that effective compliance often required a very large number of high-power UV lamps, resulting in excessive energy demand and shortened lamp lifespan. These constraints are crucial in retrofit planning, as insufficient engineering visualization and planning may lead to costly errors and operational inefficiencies. Therefore, development trend discussions should avoid portraying UV technology as unequivocally superior. Instead, emerging approaches, such as filtration combined with membrane separation and deoxygenation, have demonstrated promising results, achieving IMO D-2 compliance in shipboard trials without generating chemical by-products and with comparatively lower operational complexity (Dong et al., 2023). Likewise, feedback from seafarers indicates that reliability, low frequency of alarms, and ease of maintenance are increasingly prioritized over single-technology efficiency (Yilmaz & Güney, 2023). The broader trajectory in ballast water treatment emphasizes improved reliability, reduced operational costs, and enhanced ease of operation and maintenance across all available technologies. Moreover, varying international and national regulatory frameworks, such as those of the IMO and the US Coast Guard, significantly impact technology selection and compliance pathways, as will be elaborated further in this review.

Figure 1 provides a clear visual summary of various Ballast Water Treatment System (BWTS) technologies, highlighting their core advantages and disadvantages. The figure captures the complexity behind selecting a BWTS due to trade-offs in efficacy, operational costs, environmental impact, and physical integration constraints on ships. For example, the filtration system is depicted as a non-chemical method effective against macroorganisms, simple in design, and safe for ship structures, but which carries high operating costs and depends on water quality. This aligns with Dong et al. (2023), who demonstrated that combining filtration, membrane separation, and deoxygenation technologies yields effective ballast water treatment meeting IMO D-2 standards without chemical by-products, presenting an environmentally friendly option suitable for shipboard conditions. Their shipboard testing affirmed reliable organism removal with a minimal environmental footprint, supporting the non-chemical filtration advantages shown in **Figure 1**.

	Advantages	Disadvantages
Filtration System	Non-chemical, effective for macroorganisms, simple, safe	High cost, needs maintenance, dependent on water quality
Chemical Disinfection	Effective, low cost, easy operation	Chemical residues, environmental risks, needs monitoring
Ultra-violet Treatment	Fast, chemical-free, good monitoring	High energy cost, no solute removal, needs space and maintenance
Deoxygenation Treatment	Simple, reduces oxygen, non-chemical	No solute removal, ecosystem impact, needs monitoring
Electrolysis	Non-chemical, effective, controllable	High cost and energy, sensitive, needs maintenance and space
Ozone	Non-chemical, effective, safe	Expensive, hazardous to humans, needs air supply and monitoring

Figure 1 Overview of advantages and disadvantages of common Ballast Water Treatment System (BWTS) technologies.

Figure 1's portrayal of chemical disinfection as effective, yet producing residues and requiring close monitoring, also echoes findings by Nwigwe and Kiyokazu (2023). Drillet et al. (2023) further provide operational insights, noting improvements in compliance rates during commissioning tests of BWTS, but highlighting the ongoing challenge of ensuring consistent treatment effectiveness, especially for organisms ≥ 50 μm, which remain a critical concern under international regulations. Moreover, the operational challenges of monitoring and sampling compliance, critical for validating BWTS efficacy, are underlined in Yuan et al. (2023), who emphasize the necessity of standardized and representative sampling methodologies for ballast water. Their work illustrates that proper sampling protocols are essential to accurately assess organism presence and to ensure that treatment systems meet discharge standards las a fundamental consideration complementing the regulatory context described in **Figure 1** and associated paragraphs.

From a regulatory perspective, the implementation of BWTS retrofits faces considerable challenges due to varying international and national regulations. Campara et al. (2019) compared the IMO BWMC and the United States Coast Guard (USCG) regulations, noting that, although both aim to prevent biological invasions, they vary in scope and stringency, creating compliance complexities for globally operating shipowners. The USCG applies more prescriptive testing and approval procedures, alongside additional mandates for reporting and operational monitoring. For example, during the first 28 months of BWTS reporting in the United States (September 2013 - December 2015), 58 different systems, more than 200 unique vessels, and 4.42 million m^3 of treated ballast water were accepted under provisional approval, reflecting a wide range of technologies and operational categories. As a baseline for early adoption, however, less than 2 % of the total monthly ballast discharge was treated during this period, even as the number of BWTS-equipped vessels and total treated volumes increased rapidly (Davidson et al., 2017). These BWTS included advanced oxidation, deoxygenation, electrolytic, filtration, filtration + UV, heat + deoxygenation, and ozone. Filtration combined with UV radiation (filtration + UV) was the most numerous category, with 25 different systems accepted by USCG. This highlights that, despite regulatory differences, efforts are being made to provide diverse technological options to meet varying compliance requirements. The approved systems included advanced oxidation, deoxygenation, electrolytic, filtration, filtration + UV, heat + deoxygenation, and ozone, with filtration + UV being the most common category, represented by 25 systems accepted by the USCG. This illustrates that, despite regulatory differences, efforts have been made to provide diverse technological options for compliance. The USCG's prescriptive approach, coupled with additional reporting requirements, reinforces these complexities (Gerhard et al., 2019). Hardiyanto et al. (2020) emphasized that such regulatory differences require careful consideration by ship operators when selecting and retrofitting BWTS to achieve global compliance. In the post-deadline landscape, the revised Ballast Water Management Convention reframes compliance from installation numbers to management system discipline. Certificate validity, updated Ballast Water Management Plans aligned with new operational procedures, equipment maintenance benchmarks, standardized crew records including enhanced electronic Ballast Water Record Book (BWRB) elements, and strengthened shore-based support have become critical determinants of day-to-day conformity and Port State Control (PSC) performance (Zhang, 2025). Recent port-state practices confirm this shift from installation to operational discipline. The Paris/Tokyo MoU Port State Control Concentrated Inspection Campaign on Ballast Water Management (1 September - 30 November 2025) issued a concise questionnaire in which negative responses to key items could result in detentions. Class guidance also highlighted recurrent deficiencies such as unapproved or misconfigured electronic record books, mismatched entries, unreported malfunctions, and outdated BWM Plans, underscoring documentation integrity, crew familiarization, and system functionality as daily compliance priorities (DNV, 2025b, 2025a).

Financial and operational impacts of BWTS retrofitting are significant. Jee and Oh (2018) performed a risk assessment for retrofitting ultraviolet BWTS on bulk carriers, underscoring risks related to crew safety, equipment integration, and maintenance. Additionally, Fearnley (2017) shared lessons learned from retrofitting complex military vessels, emphasizing the importance of detailed design, testing, and commissioning protocols to ensure compliance and operational reliability. The economic feasibility of BWTS installation is further challenged by costs associated with dry docking, system maintenance, energy consumption, and potential loss of cargo capacity (King & Hagan, 2013; Srivastava, 2024). Wang and Corbett (2021) analyzed cost-effectiveness scenarios, revealing that vessel-based BWTS may be less costly under current standards, but barge-based treatment systems could be viable under stricter regional regulations.

While multiple reviews have examined BWTS retrofitting, most have utilized either descriptive or systematic approaches exclusively. **Table 1** presents an overview of notable prior reviews, their scope, and methodologies. Balaji et al. (2014) provided a descriptive analysis spanning almost two decades, whereas Campara et al. (2019); Nwigwe and Kiyokazu (2023) combined descriptive and systematic reviews. However, few studies incorporate bibliometric analysis, which offers a quantitative insight into publication trends, collaboration networks, and thematic evolution. Sari and Gunawan (2024) specifically contributed by emphasizing systematic analysis, but did not integrate bibliometric methods. Existing reviews, while valuable, often provide descriptive or systematic syntheses in isolation, limiting their ability to deliver actionable insights or robust theoretical foundations for engineers and academics. There is a discernible gap in integrated analyses that not only categorize existing publications, but also explicitly demonstrate the scientific utility and practical implications of such classifications for advancing BWTS retrofit practices and informing future research directions.

Table 1 Summary of review article in BWTS study.

Authors	Number of papers evaluated	Source of database	Period of analysis	Type of review	Scope
Balaji et al. (2014)	74	Scopus	1996 - 2014	Descriptive Analysis	Worldwide
Campara et al. (2019)	37	ScienceDirect	1999 - 2019	Descriptive Analysis, Systematic Analysis	United States
Hardiyanto et al. (2020)	14	Google Scholar	2010 - 2019	Descriptive Analysis	Indonesia
Sayinli et al. (2022)	58	ScienceDirect	2000 - 2021	Descriptive Analysis	Worldwide
Nwigwe and Kiyokazu (2023)	89	Scopus	2001 - 2022	Descriptive Analysis, Systematic Analysis	Worldwide
Sari and Gunawan (2024)	57	Scopus, Google Scholar	2004 - 2024	Systematic Analysis	Worldwide

Building on these previous efforts, this review undertakes a comprehensive and integrated analysis by combining descriptive analysis, to track publication trends, leading authors, and geographic research distribution; bibliometric analysis, to reveal the intellectual structure, collaboration patterns, and keyword evolution; and systematic thematic synthesis, to classify and interpret research findings by thematic areas. Unlike prior reviews that primarily employ singular descriptive or systematic approaches, this study's unique contribution lies in its synergistic integration of these three methodologies. This multi-faceted approach enables the unveiling of previously obscured interconnections within the BWTS retrofit landscape, moving beyond mere classification to generate novel insights into the complex interplay of technological, regulatory, and operational factors. Specifically, this integration will provide engineers with clearer guidance on optimal system selection and installation strategies by elucidating the underlying drivers of research trends, while offering academics a robust framework for identifying unexplored theoretical avenues and critical research gaps. By applying this three-stage framework, this study aims to present a holistic understanding of BWTS retrofit research developments, identify knowledge gaps, and propose future research directions that address technological, regulatory, and operational challenges, thereby directly informing practical implementation and contributing to the theoretical advancement of maritime environmental engineering.

2. Methodology

This study employs a comprehensive three-stage research methodology to systematically analyze the literature on Ballast Water Treatment System (BWTS) retrofits. The first stage involves descriptive analysis, which aims to map the overall research landscape by summarizing key bibliometric indicators such as publication trends, prominent authors, and geographic distribution. Rivas-Hermann et al. (2015) conducted a similar descriptive analysis to identify prevailing research themes and regional contributions within BWTS studies, showing how this method effectively visualizes the evolution and breadth of research output. By providing an overview without making causal inferences, descriptive analysis establishes the foundational context for deeper investigations (Gregg et al., 2009).

The literature search for this stage was conducted using the Scopus database with the following query: TITLE-ABS-KEY (imo OR ballast AND system OR ballast AND water AND treatment AND system OR retrofit), filtered by English language and articles only (document type: article). This targeted search ensured the inclusion of peer-reviewed, relevant studies focused specifically on ballast water treatment systems and retrofitting practices. As Blanco-Davis and Zhou (2014) emphasize, such careful selection and filtering in descriptive analysis help maintain the quality and relevance of the data set, allowing a clear depiction of publication patterns and research hotspots. Nie et al. (2023) also highlight that descriptive analysis in environmental technology research is vital to capture the trajectory of innovations under varying regulatory and market conditions. It helps to contextualize how technological developments and stakeholder collaborations unfold over time. Therefore, by using descriptive analysis, this study not only quantifies, but also qualitatively frames the research activities surrounding BWTS retrofits.

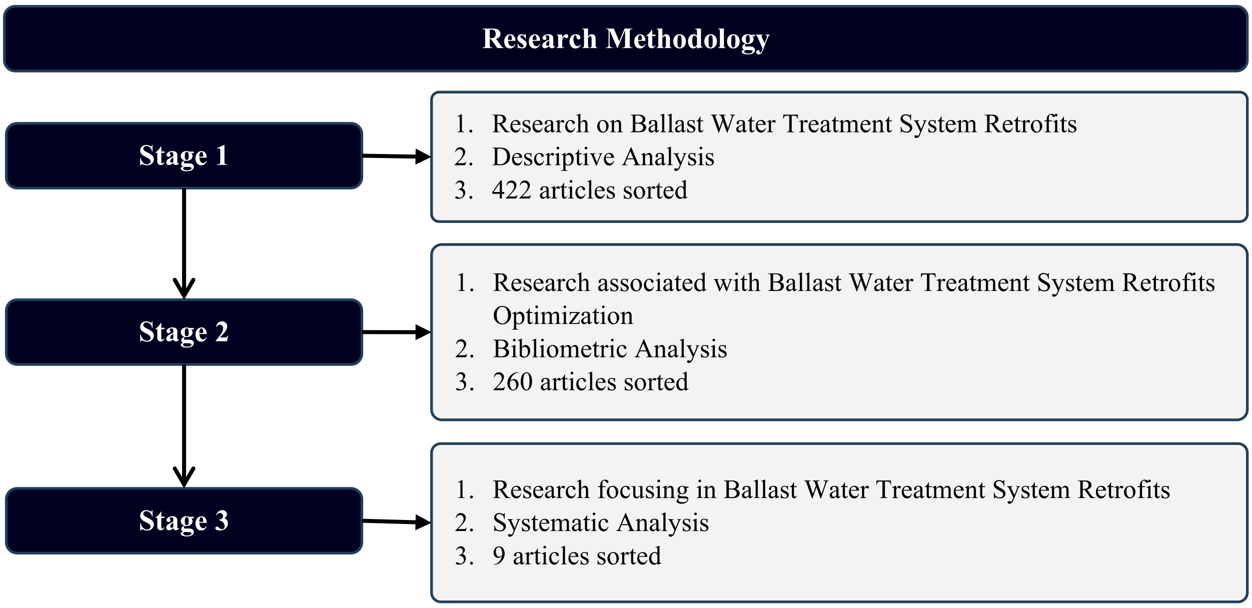

Figure 2 Research methodology framework for Ballast Water Treatment System Retrofit review.

The second stage refines the scope to 260 articles for bibliometric analysis, focusing on intellectual structures, collaboration networks, and thematic development in the BWTS retrofit field. The final stage narrows this to 9 rigorously selected articles for systematic thematic synthesis. This staged approach, which begins with descriptive analysis and continues through bibliometric mapping before reaching thematic synthesis, ensures a comprehensive and structured understanding of the research landscape while facilitating targeted insights into technological and operational optimizations for BWTS retrofitting. The novelty of this study lies in the sequential and iterative integration of these stages. Descriptive analysis provides the broad context, bibliometric analysis identifies intellectual foundations and thematic clusters, and the synthesis stage enables a nuanced, theory-informed interpretation of findings. To maintain clarity and focus, 9 representative studies that best addressed the seven key retrofit criteria were selected for detailed evaluation in the subsequent sections. This methodological synergy elevates the review beyond a descriptive summary into a robust framework for identifying underlying patterns and future research trajectories. The overall research framework and three-stage process are illustrated in **Figure 2**.

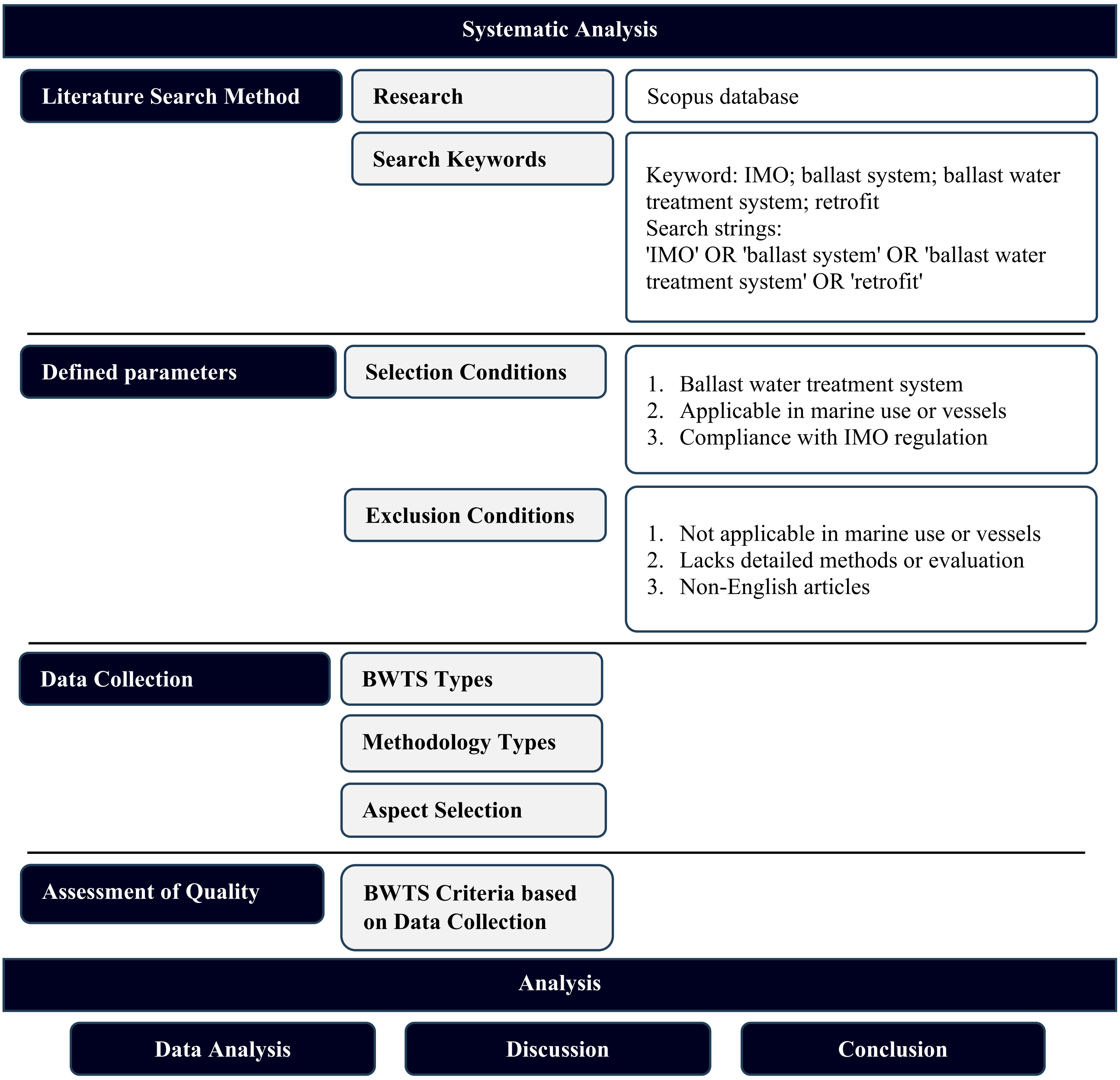

Figure 3 Systematic analysis process framework for literature selection and evaluation.

The systematic analysis stage follows a structured framework adapted from Sari and Gunawan (2024), based originally on PRISMA methodology by Page et al. (2020, 2021) to ensure a rigorous and reproducible literature review. Articles were retrieved primarily from the Scopus database using carefully selected keywords and search strings such as "IMO," "ballast system," "ballast water treatment system," and "retrofit". The inclusion criteria focused on studies relevant to ballast water treatment systems applicable to marine vessels and compliant with IMO regulations. Specifically, the systematic analysis rigorously examined how selected studies addressed adherence to the D-2 performance standard, as well as the implementation and verification processes stipulated by the IMO's BWMS Code (MEPC.300(72)). IMO regulations, including the BWMS Code, stipulate that systems must undergo comprehensive testing at land-based facilities and onboard ships to verify their ability to meet the D-2 performance standard and to ensure they do not cause unreasonable risk to the ship, crew, environment, or public health. This also includes verification that the BWMS installation has been carried out in accordance with technical specifications and relevant operating manuals, while excluding non-English papers and those lacking detailed methods or evaluations. Detailed data extraction encompassed BWTS types, methodological approaches, and retrofit-specific considerations. Quality assessment was conducted by evaluating the methodological rigor, compliance with regulatory standards, and relevance to retrofit scenarios. The systematic evaluation process and key steps for literature search, selection, and analysis are presented in **Figure 3**. The collected data were then synthesized through analysis, discussion, and concluding remarks to highlight trends, challenges, and future directions in BWTS retrofits. This systematic framework provides clarity, transparency, and replicability in evaluating BWTS retrofit research, facilitating the identification of knowledge gaps and best practices for technological and operational improvements.

Figure 4 and **Table 2** present the structured stages of consideration for retrofitting BWTS onboard ships. These stages are synthesized from the thematic synthesis conducted in the final stage of this study and adapted from the framework proposed by Sari and Gunawan (2024). The structure also integrates regulatory guidelines drawn from the BWM Convention (IMO, 2018b), along with critical technical standards outlined in the MEPC.169(57) Guidelines for Approval of Ballast Water Management Systems (G8) and MEPC.300(72) (IMO, 2008, 2018a), which amended and enhanced compliance obligations under the BWM Convention. For instance, the regulatory compliance stage incorporates procedures related to approval documentation, crew training, and system verification, as required under MEPC.169(57) and reaffirmed in MEPC.300(72). Similarly, the selection of BWTS method stage aligns with the D-2 discharge standards set by the BWM Convention by emphasizing compatibility with ship design and operational effectiveness.

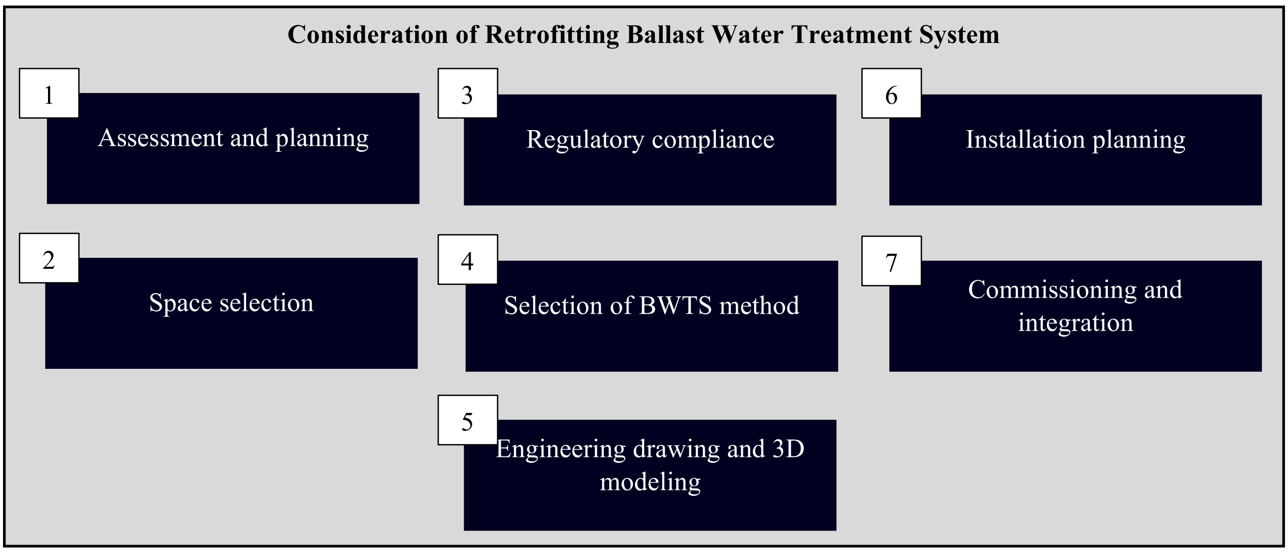

Figure 4 Stage of consideration for retrofitting Ballast Water Treatment System (BWTS).

The flow depicted in **Figure 4** divides the retrofit process into seven sequential phases: assessment and planning, space selection, regulatory compliance, BWTS method selection, engineering drawing and 3D modeling, installation planning, and commissioning and integration. Each of these stages reflects not only technical execution, but also the regulatory expectations of the IMO. For instance, the regulatory compliance stage incorporates procedures related to approval documentation, crew training, and system verification, as required under MEPC.169(57) and reaffirmed in MEPC.300(72). This stage critically evaluates the varying requirements across different regulatory bodies, such as the IMO and the USCG, highlighting the complexities shipowners face in global compliance. Similarly, the selection of BWTS method stage aligns with the D-2 discharge standards set by the BWM Convention by emphasizing compatibility with ship design and operational effectiveness.

Table 2 Explanation of consideration for retrofitting BWTS.

No.	Stage	Description
1	Assessment and planning	This initial phase involves a detailed evaluation of the retrofit needs, including ballast tank dimensions, pipe layout, and ship-specific requirements. It lays the foundation for informed decision-making and efficient project planning.
2	Space selection	Based on the previous assessment, appropriate space within the vessel is chosen to install the BWTS. The placement must be optimized to avoid interference with existing systems while maintaining operational integrity.
3	Regulatory compliance	The selected area must meet regulatory requirements set by the IMO and environmental authorities. This includes securing administrative approvals, ensuring system testing, crew training, and fulfilling safety and maintenance protocols. It also encompasses navigating varied requirements across international and national jurisdictions (e.g., IMO vs. USCG), which can significantly impact approval processes and operational flexibility.
4	Selection of BWTS method	The most suitable BWTS method is selected according to predefined criteria like ship size, system capacity, and operational characteristics. The goal is to ensure compliance while maximizing treatment efficiency.
5	Engineering drawing and 3D modeling	A technical drawing and 3D model of the retrofit system are created to visualize how the BWTS will be integrated into the existing infrastructure. This minimizes design errors and aids smooth execution during installation.
6	Installation planning	Based on the design, installation planning begins with prefabrication of system components like piping. These are then installed on the ship in accordance with the layout and operational requirements. Space limitations on active ships are carefully considered.
7	Commissioning and integration	This final and crucial phase ensures the BWTS operates according to the manufacturer's specifications and complies with regulatory standards. Successful commissioning confirms system readiness for operational use.

By adopting this structured approach, the retrofit process is positioned to achieve efficiency, regulatory conformity, and technical precision. The inclusion of advanced engineering tools, such as 3D modeling and prefabricated installation planning, addresses common challenges faced during retrofitting on existing ships with spatial and operational limitations. **Table 2** further elaborates on each of the seven stages, providing clear and operationally grounded explanations to support shipowners, naval architects, and regulatory assessors throughout the BWTS retrofit lifecycle.

3. Results and discussion

3.1 Descriptive analysis in BWTS study

The literature search for this stage was conducted using the Scopus database with the query proposed in the methodology above, used to gather relevant studies to comprehensively analyze trends in Ballast Water Treatment System (BWTS) retrofit research. **Figure 5** presents the annual number of publications within this ten-year period from 2015 to 2025. The publication trend shows fluctuations over the years, with a peak in 2015, where 35 articles were published. A slight decline is observed in 2016, with 15 publications, followed by a steady increase, reaching 31 publications, in 2019. The year 2020 witnessed a significant drop to 13 publications, likely influenced by global disruptions. However, a resurgence occurred in the subsequent years, with publications stabilizing around 25 - 30 annually, and a moderate decline in 2024 and 2025 to 18 and 15 publications, respectively, respectively. It should be noted that the 2025 publication count may increase, as the search query was performed around mid-year, and additional articles are expected to be published later in the year. This trend indicates a sustained academic interest in BWTS retrofits, reflecting ongoing technological advancements and regulatory developments in the field.

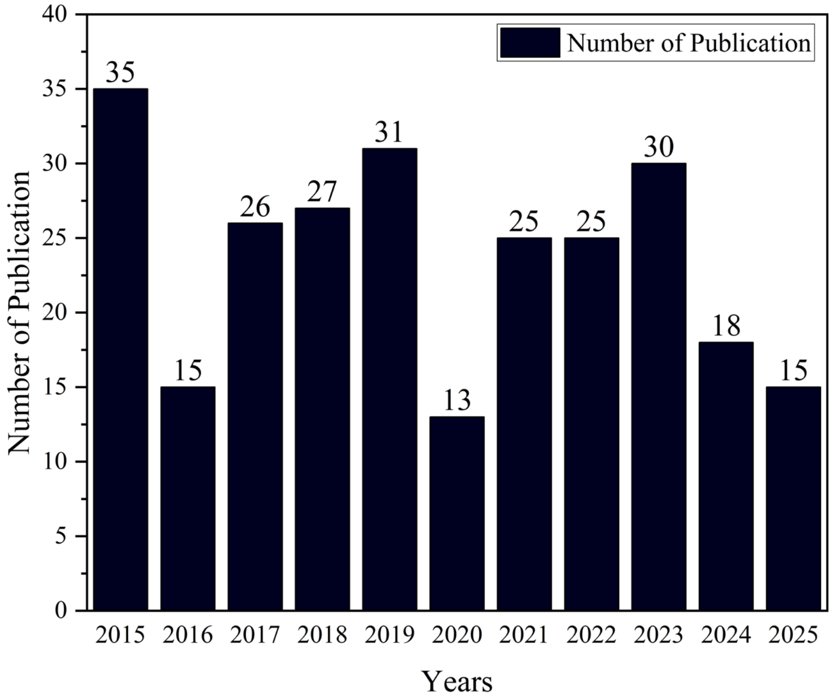

Figure 5 Annual publication trends on Ballast Water Treatment Systems (BWTS) from 2015 to 2025.

To further understand the research focus, **Figure 6** categorizes publications by research area. The results highlight the multidisciplinary nature of BWTS research. Environmental Science leads with 236 publications, underscoring the ecological importance of ballast water management. Engineering follows with 166 publications, highlighting technical innovations and system designs. Agricultural and Biological Sciences contributes 107 publications, and Earth and Planetary Sciences has 66 publications, reflecting interdisciplinary approaches to biological invasions and environmental impact assessment. Other notable areas include Chemistry, with 49 publications, Chemical Engineering, with 37 publications, Social Sciences, with 35 publications, Materials Science, with 20 publications, Energy, with 20 publications, and Biochemistry, Genetics, and Molecular Biology, with 18 publications. This distribution demonstrates the multifaceted nature of BWTS research, encompassing environmental, engineering, biological, and social dimensions.

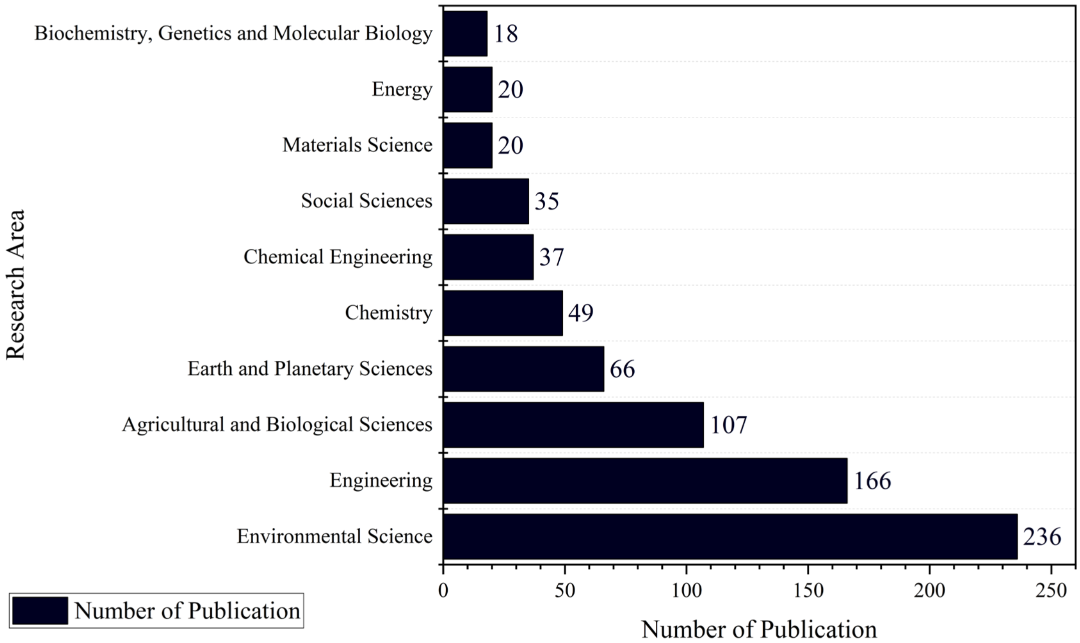

Figure 6 Research areas contributing to Ballast Water Treatment System (BWTS) studies.

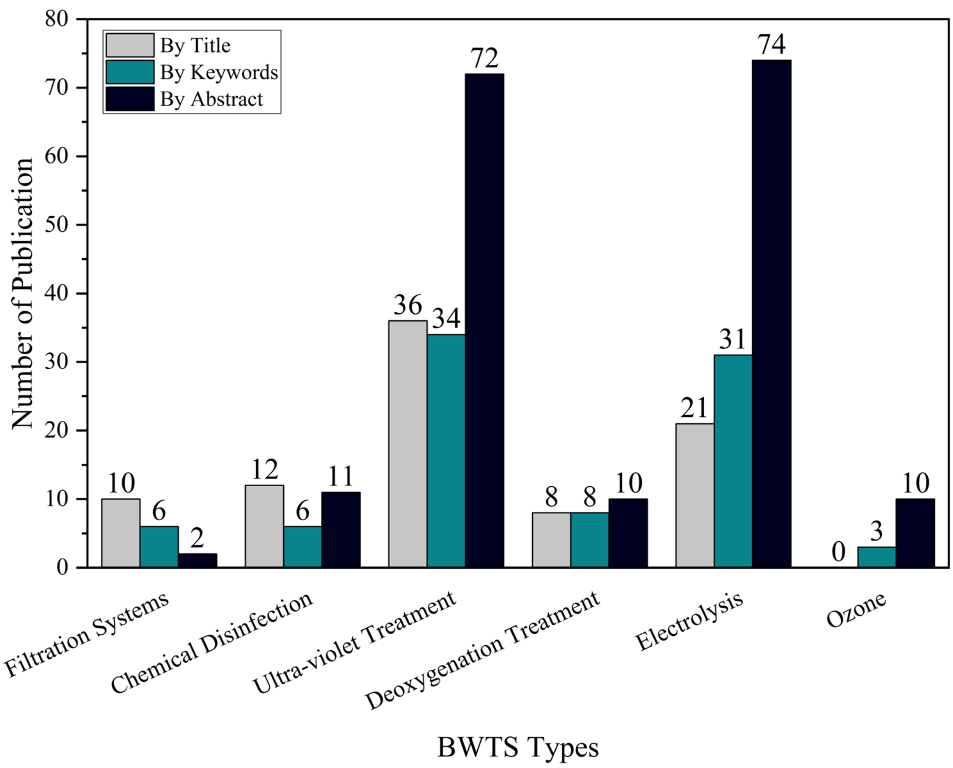

Figure 7 Distribution of publications by BWTS types.

Taking this analysis a step further from the 422 articles identified by the initial search, **Figure 7** illustrates the distribution of publications according to six BWTS types, as classified by Sari and Gunawan (2024), filtered by title, keywords, and abstract. Ultra-violet treatment emerges as the most studied method, with 36 publications by title, 34 by keywords, and a notably higher number of 72 by abstract, indicating its prominence in research discussions. Electrolysis is the second most frequently researched type, with 21 publications by title, 31 by keywords, and 74 by abstract, reflecting growing interest in this technology. The high prominence of UV treatment in abstract discussions suggests its widespread practical application and ongoing research into its efficacy and cost-effectiveness for retrofitting. For engineers, this indicates a mature and well-documented technology with significant operational data. For academics, it points to continued opportunities for optimizing UV systems, especially concerning diverse water quality parameters and long-term biological effectiveness, informing the development of more resilient treatment models. The growing interest in electrolysis, as evidenced by its abstract counts, highlights an emerging area for both practical implementation and further theoretical exploration regarding its energy efficiency and byproduct management. Filtration Systems and Chemical Disinfection show moderate attention, with 10 and 12 publications by title, respectively, and fewer counts by keywords and abstract. Deoxygenation Treatment and Ozone have relatively fewer publications, suggesting emerging or less widespread research focus areas. The disparity in counts between title, keyword, and abstract filtering highlights the varying degrees of emphasis placed on these BWTS types in different sections of the literature. Overall, the descriptive analysis reveals sustained and diverse research activity in BWTS retrofits over the past decade, with significant focus on environmental and engineering aspects, and growing interest in ultraviolet and electrolysis treatment technologies.

3.2 Bibliometric analysis in BWTS study

The bibliometric analysis presented in this section provides a comprehensive examination of the Ballast Water Treatment System (BWTS) retrofit research landscape. This analysis was conducted using the VOSviewer tool, which is designed for visualizing and analyzing networks of scientific papers, authors, journals, and keywords (Kundori & Suganjar, 2025). The primary aim of this analysis is to uncover trends in research, highlight the most influential works, reveal patterns of collaboration, and explore the thematic evolution within the BWTS field. The analysis includes both citation networks and co-authorship networks, as well as keyword co-occurrence analysis to identify key topics and their relationships (Jin et al., 2023; Özkan et al., 2023).

Figure 8 represents the citation network of the most influential academic works in BWTS retrofitting research. This analysis is based on the citation analysis type, with the unit of analysis as documents. The fractional counting method was applied to assign proportional weight to co-authored papers, ensuring that the influence of each paper is fairly represented based on its citation impact. Only documents with a minimum of 5 citations were included in this analysis to highlight the most significant contributions to the field. The figure highlights several papers that stand out due to their high citation counts. While **Figure 8** is presented as a density map, the brighter, denser areas implicitly represent clusters of highly influential and frequently cited academic works, thereby indicating the intellectual backbone of the field. For instance, the prominent bright concentration around Shah et al. (2015), with 199 citations, Pelorus and Karahalios (2017), with 116 citations, and Jiang et al. (2015), with 83 citations, highlights their significant foundational role and widespread impact on subsequent research. These works, along with Gonsior et al. (2015), with 72 citations, and Stehouwer et al. (2015), with 69 citations, form the core intellectual base, frequently referenced together or in similar research contexts, signifying their importance in driving conceptual and technical understanding of BWTS.

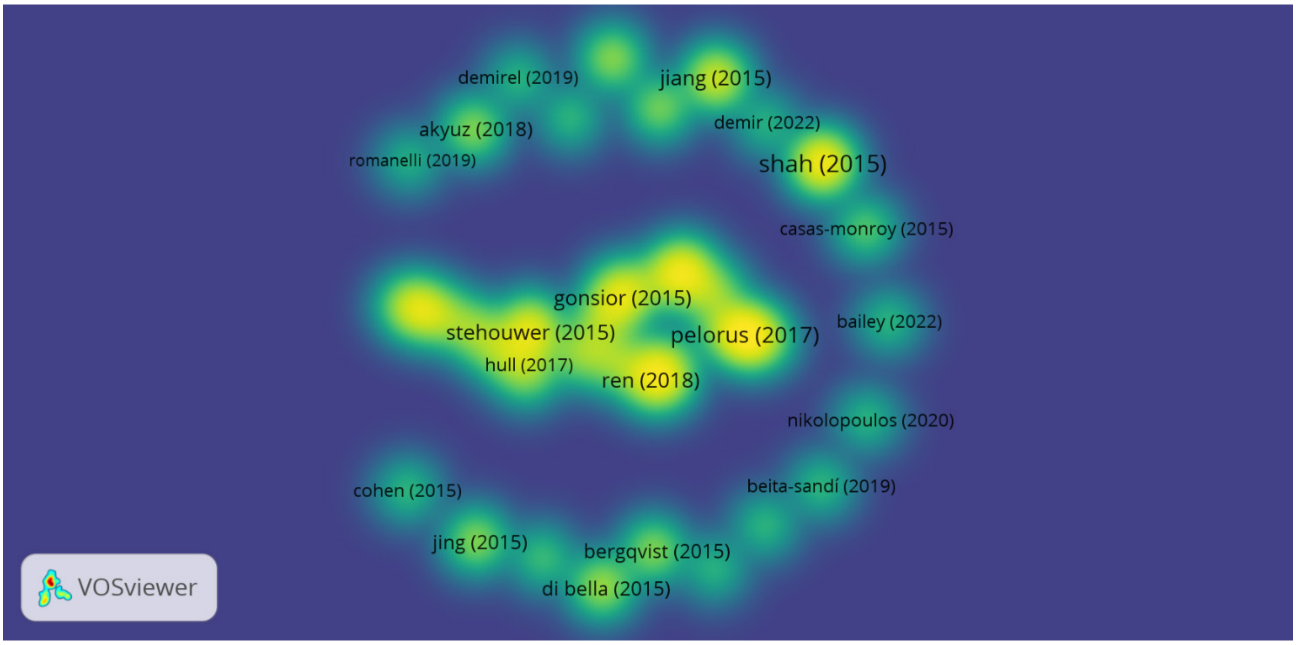

Figure 8 Citation network of most influential academic works in BWTS retrofits.

These bright regions represent the magnitude of influence and interconnection among the most frequently cited studies, emphasizing their centrality in the BWTS research network. Larger and brighter clusters, such as those encompassing Shah et al. (2015) and Pelorus and Karahalios (2017), indicate stronger scholarly impact and conceptual reach across multiple studies, showing that researchers frequently rely on these works for theoretical or methodological guidance. For example, Pelorus and Karahalios (2017) introduced a combined AHP-TOPSIS methodology for ship operators to evaluate BWTS, focusing on cost-benefit analysis and expert judgment for selection. This methodological innovation provides a concrete decision-making tool for engineers navigating complex retrofit choices, offering a framework for optimizing system selection based on quantified operational and environmental trade-offs. Similarly, Shah et al. (2015) extensively investigated the chemical behavior of peracetic acid (PAA) in saline waters for ballast water treatment, detailing the formation of secondary oxidants and disinfection byproducts, which is crucial for understanding the environmental safety and efficacy of chemical treatment methods. This foundational chemical analysis contributes significantly to the theoretical understanding of active substance treatments, providing academics with critical data for predicting environmental impacts and developing safer chemical alternatives.

Jiang et al. (2015) presented a self-powered electrochemical water treatment system leveraging triboelectric nanogenerators for sterilization and algae removal, showcasing innovative solutions for energy efficiency in BWTS. This work exemplifies a pioneering contribution to sustainable BWTS technologies, offering practical avenues for reducing operational energy costs and theoretical insights into novel energy harvesting applications in maritime systems. Gonsior et al. (2015) focused on the formation of brominated disinfection by-products from electrochemical ballast water disinfection in estuarine water, highlighting potential environmental concerns that need further characterization. Their findings are crucial for informing regulatory frameworks and guiding engineers in selecting treatment methods with minimized ecological footprints, while simultaneously posing new research questions for academics on byproduct mitigation and long-term environmental effects. The cluster formed by Hull et al. (2017), and Stehouwer et al. (2015) specifically reflects a body of research focused on theoretical and technological advancements in BWTS. Furthermore, the presence of more recent works like Ren (2018) and Bailey et al. (2022) in connected or emerging clusters demonstrates the evolving trends, with increasing focus on long-term operational efficiency and regulatory compliance. Ren (2018) developed a multi-attribute decision analysis approach for ranking ballast water treatment technologies, integrating subjective and objective weighting methods, which contributes to more robust decision-making for stakeholders.

Although direct citation lines are not displayed, the proximity and clustering of authors/works within these dense areas indirectly reveal thematic relationships and interdependencies. For example, the close proximity of Gonsior et al. (2015), Stehouwer et al. (2015), and Hull et al. (2017) suggests a high level of interconnection and overlapping research themes within their respective areas of study, highlighting shared objectives in advancing BWTS technology and environmental safety. This density map serves as a valuable tool for identifying key players and central themes dominating the BWTS literature, thus revealing the intellectual structure and thematic evolution in the field despite the absence of explicit citation lines. Notable works include Stehouwer et al. (2015), with 69 citations, holding a prominent position in the network, underlining its foundational role in BWTS research. Gonsior et al. (2015), with 72 citations, are also central to the citation network, indicating their significant contributions to the theoretical and technological advancements in BWTS. The clustering observed in the citation network highlights the intellectual structure of the field, where prominent works are linked together based on shared references and themes. For instance, the cluster formed by Gonsior et al. (2015), Hull et al. (2017), and Stehouwer et al. (2015) reflects a body of research that has driven forward the conceptual and technical understanding of BWTS technologies. Additionally, recent Works, such as Pelorus and Karahalios (2017) and Ren (2018), demonstrate the evolving trends in BWTS research, focusing on long-term operational efficiency and regulatory compliance. The citation network thus illustrates how earlier influential studies laid the foundation for subsequent technological investigations and global implementation efforts.

Figure 9 showcases the co-occurrence of keywords in BWTS research, highlighting the key themes and their interrelationships. This analysis, based on co-occurrence analysis, uses author keywords as the unit of analysis, applying the fractional counting method to avoid overrepresentation of frequently occurring keywords (Narong & Hallinger, 2023). Only keywords that appeared 5 times or more across the research documents were considered. The results reveal the most central and frequently discussed topics in BWTS research, including ballast water, with 71 occurrences. This keyword stands out as the most frequently used, reflecting the central role of ballast water in BWTS research. It is the focal point of many studies exploring how ballast water management can prevent the spread of invasive species and pathogens. Invasive species, with 22 occurrences, and phytoplankton, with 17 occurrences, are keywords that emphasize the ecological challenges associated with ballast water. Invasive species, in particular, are a critical concern, as they can disrupt marine ecosystems and biodiversity. Ballast water treatment, with 39 occurrences, and ballast water management, with 19 occurrences, are terms central to the technological aspects of BWTS, focusing on the methods and systems designed to treat ballast water before its discharge. Zooplankton, with 6 occurrences, microalgae, with 6 occurrences, and shipping, with 7 occurrences, are keywords indicating the biological and operational considerations in ballast water management. Zooplankton and microalgae represent important ecological groups impacted by ballast water discharge, while shipping highlights the logistical context in which BWTS operates. Beyond descriptive counts, the pattern shows that ecological risks, such as invasive species, phytoplankton, and zooplankton, formed the backbone of early BWTS research, but over time the focus has shifted toward compliance-driven technological development, indicating the maturation of the field. The relatively lower presence of risk assessment, with 5 mentions, and inactivation, with 6 mentions, highlights methodological niches that remain underexplored and provide opportunities for future research.

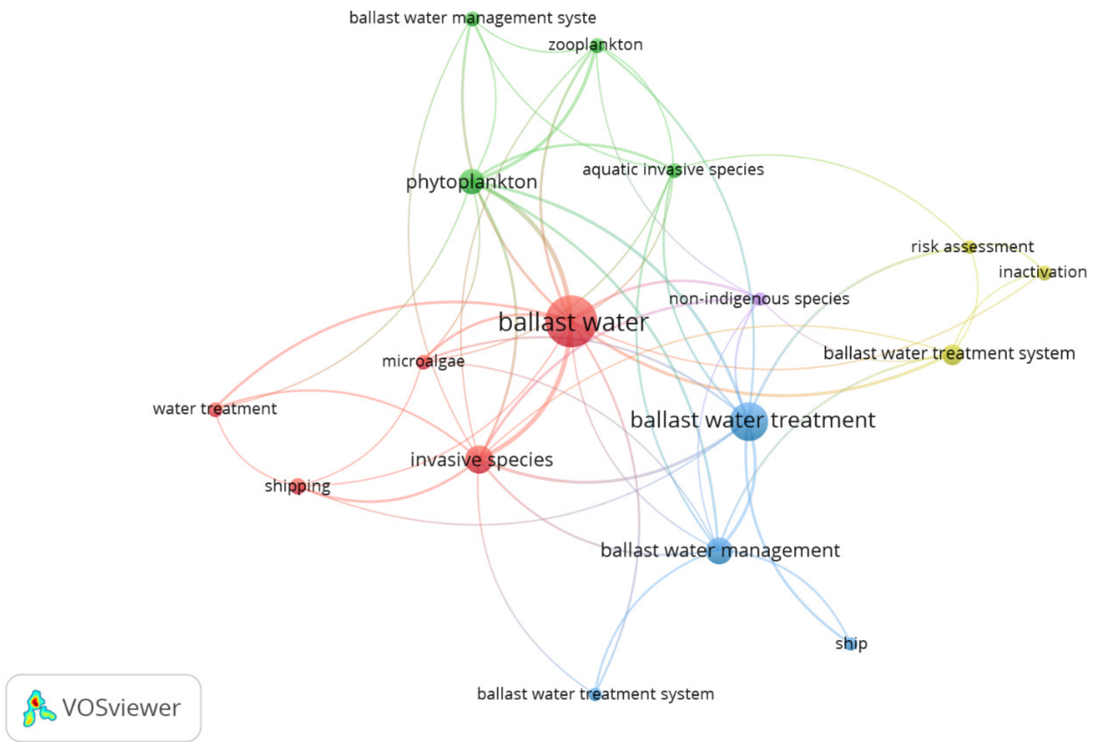

Figure 9 Co-occurrence of keywords in BWTS research.

The co-occurrence network visualized in **Figure 9** shows how these themes are interconnected, with clusters representing related areas of study. For example, the cluster around ballast water is tightly linked to invasive species and phytoplankton, reflecting the importance of managing ballast water in preventing the spread of harmful organisms. This connection underscores the critical ecological driver for BWTS development, guiding engineers to prioritize systems with proven efficacy against these biological threats, and prompting academics to investigate the long-term ecological impacts and adaptive strategies of invasive species post-treatment. Meanwhile, the connection between ballast water treatment and management keywords suggests an increasing focus on developing and implementing treatment systems to meet regulatory standards. This highlights the practical imperative for compliance-driven solutions, offering a clear signal to engineers regarding market demand and to academics for research into the socio-economic aspects of regulatory enforcement and technology adoption. Based on **Figure 9** keyword statistics such as ballast water, with 71 occurrences, and invasive species, with 22 occurrences, reveal a thematic evolution where early ecological concerns, including invasive species, phytoplankton, and zooplankton, progressively converged with operational and regulatory themes, such as ballast water treatment and ballast water management. This indicates that research has shifted from identifying ecological risks toward engineering and management solutions, suggesting a maturation of the field. The relatively lower occurrence of terms like risk assessment, with 5 mentions, and inactivation, with 6 mentions, highlights methodological niches that remain underdeveloped and provide opportunities for future research. This co-occurrence analysis highlights the interdisciplinary nature of BWTS research, where biological, environmental, and engineering concerns are interwoven, pointing to the complex challenges in managing ballast water effectively. This interdisciplinary nature necessitates collaborative research frameworks that integrate biological monitoring, environmental risk assessment, and advanced engineering solutions to achieve truly sustainable marine operations. For instance, linking bibliometric keyword evolution with publication outlets in **Figure 10** shows that, while Marine Pollution Bulletin has historically anchored ecological studies, the rise of Environmental Science and Technology from 2021 onwards reflects growing attention to technological innovations and regulatory science. This thematic transition underscores how ecological awareness is increasingly translated into engineering design and compliance mechanisms, aligning publication trends with the keyword clusters identified in **Figure 9**.

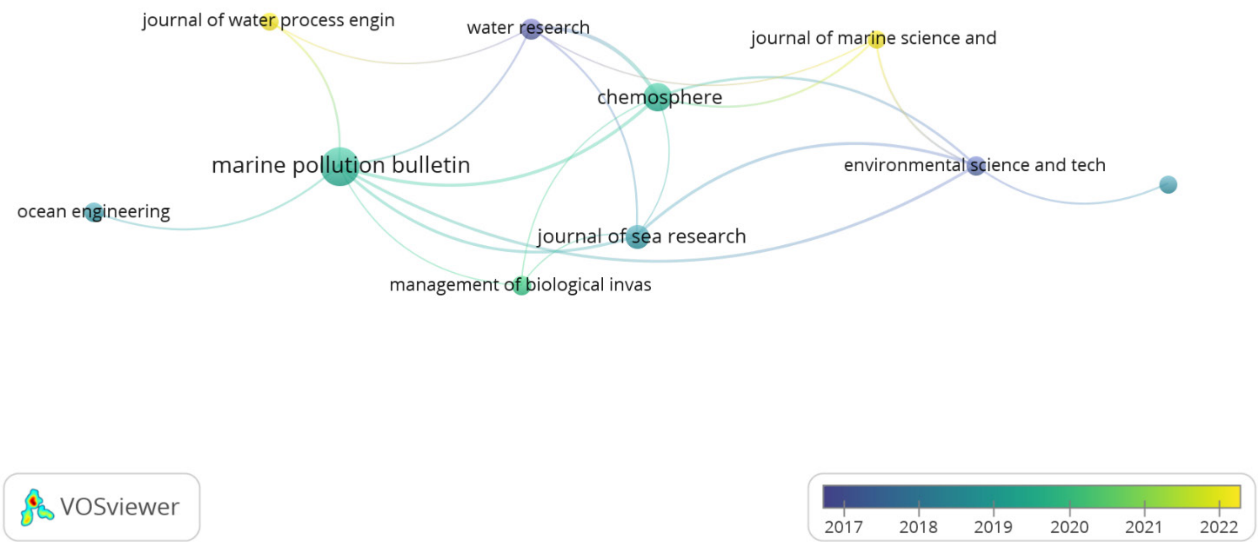

Figure 10 Publication outlets based on citation timeline.

Figure 10 presents the publication outlets based on the citation timeline, particularly journals that have been publishing significant works in the field of BWTS research. This analysis uses citation as the analysis type, with sources from journals as the unit of analysis. The overlay visualization technique is employed, allowing for the representation of the temporal development of citation patterns. The figure highlights the journals that have been the primary outlets for influential BWTS research, showing the increasing prominence of certain publications over time. The use of minimum 1 document and 5 citations thresholds ensures that only journals with meaningful contributions are represented. The figure highlights several journals that have consistently been important in BWTS research. Marine Pollution Bulletin stands out as a central journal, reflecting its sustained influence in the field. Water Research, Journal of Marine Science and Technology, and Chemosphere are also key contributors to the academic discourse on BWTS, underscoring their role in publishing high-impact research. The figure also shows the emergence of Environmental Science and Technology, which has become increasingly prominent in recent years, particularly starting from 2021 and 2022. This indicates the growing importance of journals focusing on environmental science and technology in addressing BWTS-related challenges, including technological advancements and regulatory issues. The consistent prominence of Marine Pollution Bulletin and the rising influence of Environmental Science and Technology suggest a dual focus in BWTS research: addressing immediate environmental concerns (pollution) and pursuing deeper technological and scientific advancements. For researchers, this trend signifies the increasing value of interdisciplinary studies that bridge engineering innovations with ecological impact assessments, guiding publication strategies towards journals that prioritize integrated solutions and rigorous scientific contributions. This timeline trend indicates that BWTS research initially relied on pollution-oriented journals to establish ecological concerns but, since 2020, there has been a notable shift toward interdisciplinary and technology-driven journals. The rising prominence of Environmental Science and Technology illustrates a growing demand for studies that connect environmental regulation with engineering innovation, reflecting a forward-looking research trajectory. Together with the keyword evolution, these journal shifts confirm that the BWTS field is progressing toward solution-oriented, technology-driven, and policy-relevant studies.

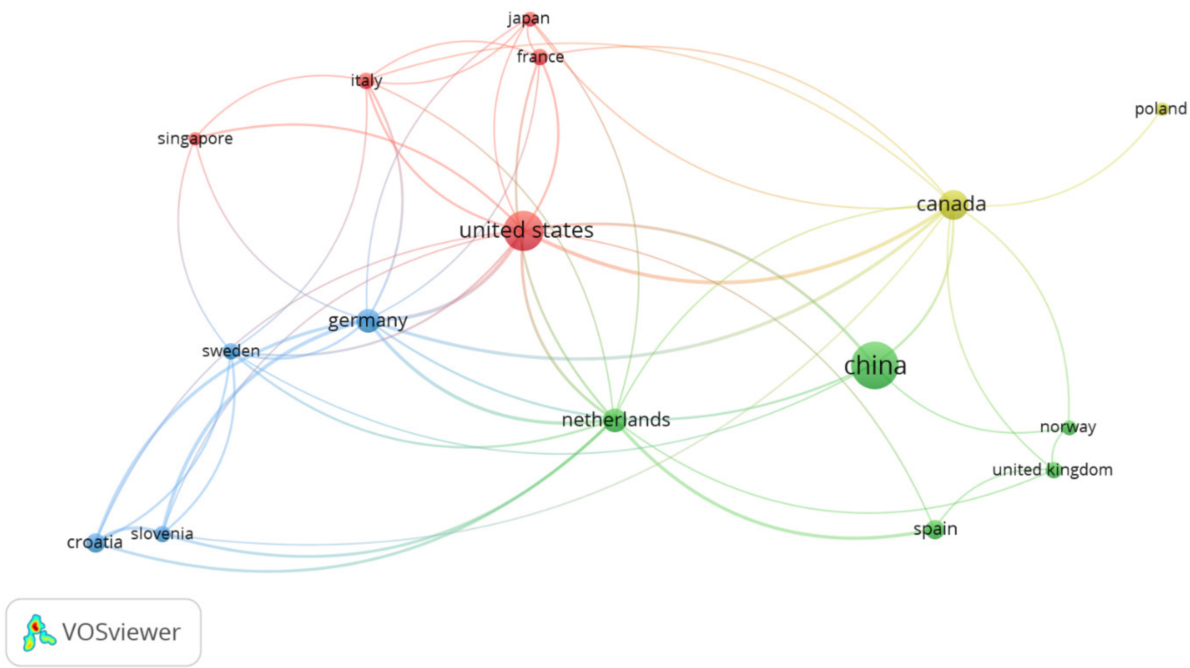

Figure 11 Co-authorship network by countries.

Figure 11 represents the co-authorship network by countries, showing the global collaboration in BWTS research. This figure considers countries with at least 5 documents in the field. The co-authorship analysis indicates how countries collaborate on BWTS research, with the United States, with 43 documents and 618 citations, being the most prominent, as reflected by its link strength of 117. This signifies the significant role of the United States in both producing research and in collaborating with other countries in this domain. China, with 61 documents and 800 citations, although leading in publication numbers, has a slightly lower link strength of 67, indicating strong contributions to BWTS research, but with fewer international collaborations. This discrepancy suggests that, while China leads quantitatively, the United States maintains stronger influence through collaboration and citation networks, which amplifies its role in shaping research directions.

Other major contributors, such as Germany (15 documents, 421 citations) and Canada (23 documents, 446 citations), exhibit solid citation impacts and collaboration networks. The presence of countries like Slovenia (7 documents, 136 citations) and Croatia (10 documents, 111 citations), though smaller, highlights the broader international engagement in the research community. The figure visualizes how countries with strong collaborative networks, such as United States and Germany, drive forward research trends, while emerging countries contribute to a growing global network. These strong inter-country collaborations are vital for sharing expertise in complex engineering challenges, facilitating data exchange on diverse environmental conditions, and potentially harmonizing regulatory interpretations. For academics, identifying these collaborative hubs can inform strategic partnerships, while for practitioners, it highlights the global effort to develop robust BWTS solutions. The extended co-authorship network in **Figure 12** further demonstrates how new contributors, such as South Korea (22 documents, 180 citations), are bridging

East Asian and Western research clusters, reinforcing the observation that emerging hubs are expanding thematic diversity such as in digital engineering and compliance monitoring, and is predictive of future centers of innovation.

Figure 12 extends the co-authorship network by countries to include countries with a minimum of 2 documents in the field, providing a broader view of global collaboration. The figure highlights how additional countries, like Italy (7 documents, 142 citations), Spain (10 documents, 157 citations), and the United Kingdom (7 documents, 84 citations), are contributing to the growing research in BWTS. South Korea (22 documents, 180 citations) stands out as an emerging contributor with strong academic output, showcasing the increasing importance of research hubs outside of the traditional maritime nations.

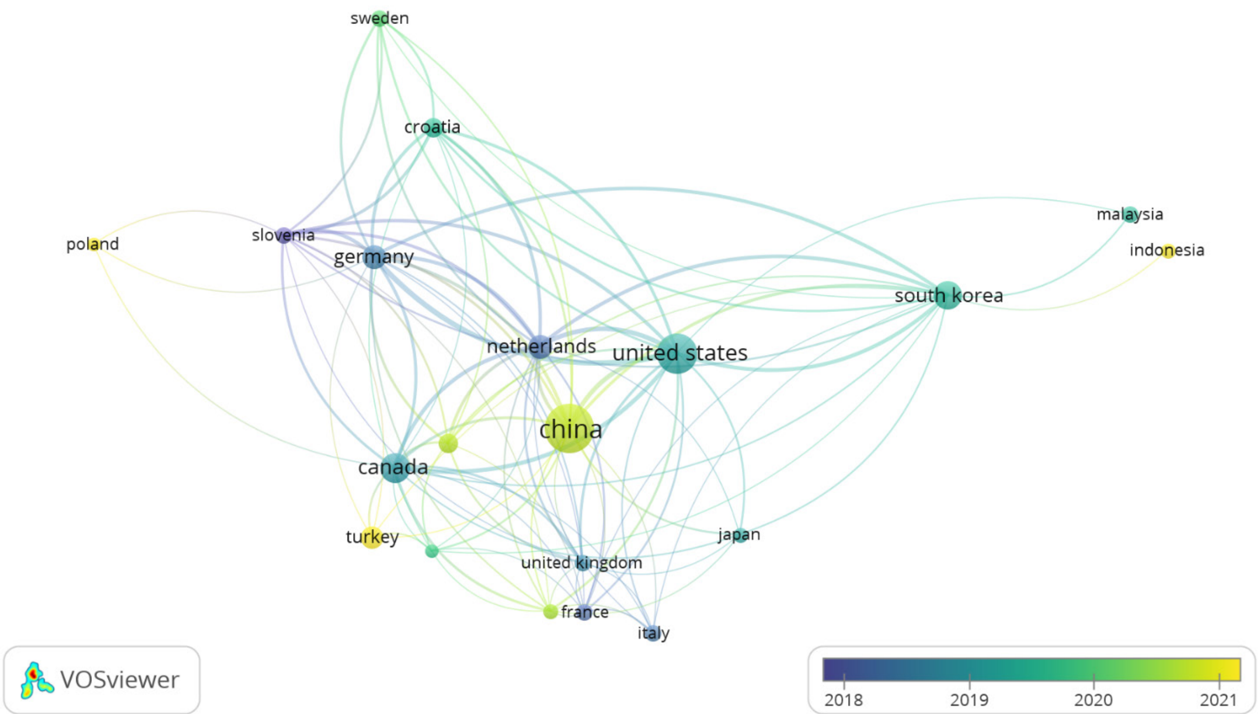

Figure 12 Co-authorship network by countries.

By lowering the threshold to 2 documents per country, the network expands to include a wider range of contributors, revealing the truly global reach of BWTS research. This extended network demonstrates the growing international interest in the field, with countries from multiple continents increasingly addressing ballast water treatment challenges and solutions. The diversification of contributing nations, particularly the emergence of research hubs such as South Korea, reflects a rising global capacity for innovation and problem-solving in BWTS. As a result, the collective intelligence available to tackle the multifaceted challenges of ballast water management has broadened, fostering a more resilient and harmonized approach to marine environmental protection. Moreover, this diversification marks a clear trend: BWTS research is no longer concentrated in a few traditional maritime nations, but is spreading to emerging hubs in Asia and Europe. The rise of South Korea signals a regional shift in which newer research economies are gaining global relevance, especially in areas such as digital engineering and compliance monitoring. Similarly, the inclusion of smaller yet active contributors like Spain and Italy illustrates how BWTS research is becoming increasingly distributed, underscoring the development of a more globally interconnected and collaborative research community.

This bibliometric analysis provides a comprehensive overview of the intellectual structure of BWTS retrofitting research. By incorporating citation networks, keyword co-occurrence analysis, and co-authorship networks, the analysis sheds light on the collaborative dynamics, emerging research trends, and the global spread of BWTS research. The findings highlight the significant contributions from leading countries and journals, as well as the evolving thematic focus of the research community. The increasing global participation and interdisciplinary approach underscore the importance of international collaboration in addressing the challenges of ballast water management and treatment systems.

3.3 Systematic analysis in BWTS study

The systematic analysis stage applies a structured framework in **Figure 3**, grounded in the PRISMA-based methodology proposed by Page et al. (2020, 2021), and adapted by Sari and Gunawan (2024). Evidence from the selected studies was consolidated using predefined evaluation criteria, detailed in **Figure 4** and **Table 2**. These criteria represent seven fundamental aspects of BWTS retrofitting: (1) assessment and planning, (2) space selection, (3) regulatory compliance, (4) selection of BWTS method, (5) engineering drawing and 3D modeling, (6) installation planning, and (7) commissioning and integration. Rapid compliance monitoring devices (CMDs) have become central to pre-arrival screening and port-state triage, although their proxy-based signals (e.g., chlorophyll fluorescence, ATP) often diverge from detailed methods, particularly for UV-treated water. Comparative evaluations of four CMDs against IMO monitoring approaches confirm these systematic differences and emphasize the importance of context-aware interpretation to avoid false non-compliance narratives (Romero-Martínez et al., 2024). The 2025 CMD landscape further extends toward electronic record integration and analytics for targeted oversight (Ndlovu, 2025). To ensure transparency, credibility, and reproducibility, a detailed coding procedure was applied to the 9 rigorously selected articles. Each article was reviewed against the seven predefined criteria, with coding based on explicit mentions or in-depth discussions. A criterion was marked 'O' (considered) if the study provided substantial information, analysis, or data directly related to that aspect, and 'X' (not considered) if it was absent or only superficially addressed. A coding rubric with operational definitions was developed prior to the review to maintain consistency. For example, Assessment and Planning was marked 'O' if a study included ship-specific evaluations, such as ballast tank dimensions, pipe layouts, or risk assessments. Space Selection was marked 'O' if the study discussed optimizing available space for BWTS integration while maintaining system and operational integrity. Regulatory Compliance was marked 'O' when adherence to IMO and national regulations (e.g., USCG), administrative approvals, testing, or crew training were explicitly addressed.

For the Selection of BWTS Method, a mark of 'O' was given if the study detailed the process of choosing a suitable technology based on predefined criteria, such as ship size, capacity, or operational characteristics. Projected demand beyond September 2024 is expected to become more selective and cost-sensitive, as remaining fleets reconcile life-cycle economics with route-specific water quality and verification regimes. Dynamic compliance-cost modeling shows that total ownership cost, including OPEX and verification, significantly influences system choice in this late-phase market (Hardiyanto et al., 2023). In parallel, product-service innovations and the growing evaluation of port-based or ballast-free concepts provide complementary pathways that could divert future demand from onboard retrofits in certain trades (Rivas-Hermann et al., 2015; Srivastava, 2024). Engineering Drawing and 3D Modeling was marked 'O' if a study presented or discussed the creation of technical drawings or 3D models to visualize BWTS integration, aiming to minimize design errors. Installation Planning was marked 'O' if prefabrication and careful placement of components (e.g., piping) within spatial limitations were addressed. Finally, Commissioning and Integration was marked 'O' if the study examined the phase of ensuring the BWTS operated according to manufacturer specifications and complied with regulatory standards. To enhance reliability, the coder conducted a rigorous self-review by revisiting all 9 articles and their assigned categories after the initial coding. This process allowed the identification and correction of inconsistencies or misinterpretations, thereby strengthening the internal validity of the analysis.

For illustrative purposes, Jee and Lee (2017) was marked 'O' for all seven criteria because their comparative feasibility study for retrofitting on a bulk carrier explicitly covered installation considerations, space management, cost analysis, and system performance comparisons, directly aligning with the comprehensive framework. In contrast, Wang and Corbett (2021) was marked 'X' for 'Engineering Drawing and 3D Modeling' and 'Installation Planning'. Their study focused on scenario-based cost-effectiveness analysis of different BWTS strategies under varying regulatory conditions and, while it addressed economic feasibility and regulatory compliance, it did not delve into the granular technical details of design visualization or physical integration processes on the ship. Likewise, Kolios (2024) was marked 'X' for 'Space Selection', as the study developed a comprehensive risk assessment model for environmentally sustainable retrofits, identifying general technical and environmental risks, but did not provide specific details or methodologies for optimizing space for BWTS installation. This rigorous coding approach ensured that the evaluations presented in **Table 3** and **Figure 13** accurately reflect the depth of coverage for each criterion within the reviewed literature. The synthesis of findings from this analysis is presented in **Tables 3 - 4** and **Figure 13**.

Table 3 Evaluation of study in retrofitting BWTS based on criteria consideration.

No. Ref	Author	Criteria consideration						
		1	2	3	4	5	6	7
1	Hasanspahić and Zec (2017)	O	O	O	O	X	O	O
2	Jee and Lee (2017)	O	O	O	O	O	O	O
3	Wang and Corbett (2021)	O	O	O	O	X	X	O
4	da Silva Jorge and Satir (2020)	O	O	O	O	O	O	O
5	Hardiyanto et al. (2023)	O	O	O	O	O	O	O
6	Mahmud et al. (2023)	O	O	O	O	O	O	O
7	Mahmud et al. (2024)	O	O	O	O	O	O	O
8	Kolios (2024)	O	X	O	O	O	O	O
9	Chen et al. (2025)	O	O	O	O	O	O	O

Table 3 details the inclusion of the seven retrofit criteria across nine selected academic studies. Each study is assessed based on its explicit consideration of each criterion. For instance, Jee and Lee (2017) and Mahmud et al. (2023, 2024) comprehensively addressed all seven considerations, demonstrating a thorough methodological approach. In contrast, Wang and Corbett (2021) notably lacked focus on engineering modeling and installation planning, while Kolios (2024) omitted space selection. This variability in **Table 3** highlights which methodological dimensions consistently receive academic attention, and which are often overlooked, in current research. Notably, regulatory compliance and commissioning consistently appear among the most considered stages. This emphasis reflects the critical importance of ensuring legal adherence and operational verification in BWTS retrofits. For engineers, consistent attention to these stages ensures project legitimacy and functional efficacy. For academics, it points to ongoing research needs in refining compliance assessment methodologies and optimizing commissioning protocols to enhance overall system reliability.

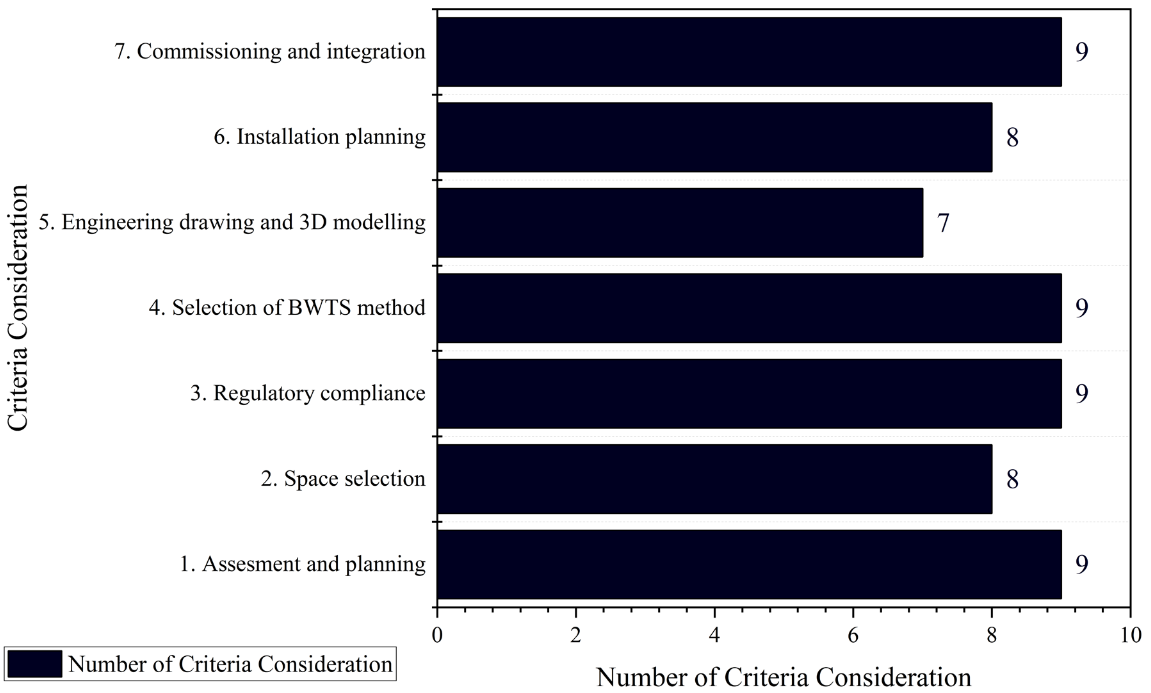

Figure 13 Comparison of number of criteria consideration acceptance from the 9 studies in retrofitting BWTS.

Figure 13 presents a bar chart summarizing the number of criteria addressed by each study. The results from this figure indicate that, out of 9 studies, all include six or more of the criteria, with six studies covering all seven stages of consideration. This suggests a growing trend towards comprehensiveness in recent publications. The chart effectively visualizes gaps in earlier research, emphasizing the evolution in systematic rigor over time. The most commonly omitted criteria in these studies were engineering drawing and 3D modeling and installation planning, highlighting operational areas that require greater integration in future research efforts. The oversight of these critical stages represents a significant gap for practical application, as inadequate engineering visualization and planning can lead to costly errors, installation delays, and suboptimal system integration on complex vessel structures. For engineers, prioritizing research in these areas directly translates to more efficient and less risky retrofit projects. For academics, this gap presents a fertile ground for developing advanced digital twin models, AI-driven planning algorithms, and optimized pre-fabrication strategies that can significantly improve retrofit efficiency and precision. Building upon the insights from **Figure 13**, it is crucial to address System Design Limitations (SDL) as a critical factor in BWTS selection. The IMO BWMS Code (MEPC.300(72)) explicitly defines SDL as water quality and operational parameters (e.g., salinity, temperature, particulate organic carbon, total suspended solids, dissolved organic carbon) for which a BWMS is designed to achieve the D-2 performance standard. These limitations are pivotal for BWTS selection, as different technologies possess inherent operational constraints that dictate their effectiveness under varying environmental conditions. For example, UV treatment efficacy is highly dependent on water clarity and can be significantly reduced by high sediment loads. Similarly, chemical treatments may be affected by water temperature, pH, and organic matter content. Therefore, while not a separate criterion within the initial seven-point evaluation framework, understanding and validating these SDLs is fundamental for ensuring a system's performance in real-world conditions and for proper selection and installation. **Table 4**, below, provides a detailed breakdown of how each study, initially evaluated in **Table 3**, addresses these SDL aspects, based on criteria derived from the IMO BWMS Code (MEPC.300(72)). This table clarifies the specific water quality and operational parameters considered or implied by each paper.

Table 4 Evaluation of System Design Limitations (SDL) discussion in reviewed BWTS retrofitting studies based on IMO BWMS code (MEPC.300(72)).

No. Ref	Author	System Design Limitations (SDL)	
		Water quality parameters	**Operational parameters**
1	Hasanspahić and Zec (2017)	-	BWTS dimensions Power consumption Installation duration
2	Jee and Lee (2017)	Water temperature Water salinity UV Transmission	Voyage duration Power requirements
3	Wang and Corbett (2021)	-	BWTS footprint Necessity to meet stringent numerical standards
4	da Silva Jorge and Satir (2020)	Water type: Fresh (F), brackish (B) and marine (M).	Flow capacity (min/max) Power requested Treatment process adopted
5	Hardiyanto et al. (2023)	Water salinity, Water temperature Water pH Water turbidity	Power requirement Pump rate Available area (footprint) Payload
6	Mahmud et al. (2023)	-	Space availability Structural compatibility Accessibility for maintenance and operation
7	Mahmud et al. (2024)	Ambient temperature range Relative humidity electronics UV Transmission	System weight Vessel stability Flow range Filter and UV capacity System pressure loss Power supply Power requirement Operating hours Fuel consumption Spare parts replacement intervals
8	Kolios (2024)	-	Operational efficiency System compatibility Structural integrity Reliability of new components, unexpected maintenance, delays
9	Chen et al. (2025)	Nuclear contamination, radioactive substances (e.g., tritium, 14C, 125Sb, 137Cs, Sr).	Lack of uniform loading standards for different ship types Low BWMS installation rates Challenges in retrofitting Low coverage of shore-based reception facilities

Future research on BWTS retrofits should explicitly analyze how proposed systems align with the specific SDLs of a vessel's operational routes, thereby providing a more comprehensive assessment of compliance and effectiveness. A systematic understanding of SDLs is essential for guiding practical retrofitting projects and informing policy decisions that promote sustainable marine operations. By incorporating water quality parameters (e.g., salinity, temperature, UV transmission) and operational parameters (e.g., flow capacity, power consumption, available space), engineers can better predict system performance and adapt designs for particular vessel routes, ensuring optimal compliance and efficiency. For academics, this detailed understanding of SDLs provides a foundation for developing advanced multi-criteria decision models, predictive analytics for system degradation, and new material science solutions tailored to extreme operational environments, thus strengthening the theoretical framework for BWTS design and selection. Operational reliability can also be reinforced through data-centric diagnostics. A multi-feature-fusion graph-convolution approach for BWMS fault diagnosis integrates heterogeneous sensor features and their interrelationships, improving anomaly detection and identification under complex shipboard conditions. Embedding such graph-based health monitoring alongside CMD-aware verification and adaptive machine-learning control creates a coherent, post-2024 pathway from retrofit completion to durable performance assurance (Ai et al., 2024).

Connecting this analysis to **Table 5**, which summarizes the assessment quality of studies on BWTS retrofitting based on seven criteria, reveals a nuanced picture of research focus and depth regarding SDLs. Several studies provide detailed empirical evidence that sheds light on the operational and structural constraints of BWTS. Mahmud et al. (2024), for example, report that BWTS contributes only 0.04 % to initial lightship weight, with less than a 2 % effect on overall vessel stability. They also show that treatment at 100 % UV transmission reduces operational costs by half, compared to conditions below 65 % transmission, highlighting the direct influence of UV parameters on SDL evaluation. Decision-support analyses further emphasize how post-deadline selection priorities balance CAPEX/OPEX, capacity, supplier reliability, and integration constraints. For bulk carriers, AHP-TOPSIS results indicate that OPEX (0.315), CAPEX (0.250), and capacity (0.160) are the dominant factors, with BWTS life-cycle CO_2 contributions (~3 %, ≈456.5 t) underscoring sustainability trade-offs (Ejder et al., 2024). Complementary frameworks, such as DEMATEL-ANP and FAHP-TOPSIS, confirm that operator priorities (technical status, space availability, vendor reliability) can shift rankings, often elevating ozone systems. These findings demonstrate the importance of structured, objective weighting in guiding upgrades and replacements beyond 2024 (Chen et al., 2023; Özdemir, 2023).

Jee and Lee (2017) provide empirical data on energy consumption across BWTS types, showing that UV systems require 30 kilowatts, while ozone-based systems demand up to 199 kilowatts. Their study also reports pressure loss measurements (0.5 bar for UV systems) and examines how water temperature and salinity affect electrolysis efficiency. The influence of UV transmission on UV system performance is further analyzed, directly addressing SDLs related to water quality. Similarly, Da Silva Jorge and Satir (2020) apply a fuzzy logic approach to system optimization, explicitly incorporating SDL-related parameters such as flow capacity (m^3/h) and power demand (kW), thereby integrating operational SDLs into system design. Hardiyanto et al. (2023) focus on regulatory compliance costs, modeling SDLs through variables such as ship deadweight tonnage (DWT), flow rate, ballast tank volume, power demand, and available onboard space. Their regression models link flow rate to BWTS cost, power usage, and equipment weight, while also correlating DWT with installation and fabrication costs. Although SDLs are not the primary focus, these variables form critical elements of both design and operational constraints. Other studies address SDLs from a more conceptual perspective. Mahmud et al. (2023) highlight the advantages of high-fidelity 3D scanning for retrofitting, enabling clash-free layouts, accelerated multi-party decisions, and measurable reductions in schedule and cost at the yard interface. Case-specific integration analyses also indicate negligible weight or stability penalties and cost benefits when UV transmittance is high, emphasizing the importance of condition-aware technology selection post-2024 (Mahmud et al., 2024). Digital engineering further strengthens execution through case-based design and hydraulic calculations, which reveal hidden integration constraints, such as insufficient pump head for UV trains, early enough to de-risk yard windows (Čurovas, 2025). Where UV performance is limited by low transmittance, owners increasingly adopt condition-aware configurations or alternative chemistries. Recent Galápagos design work demonstrates chemical-dosing variants and the operational limits of hydrocyclones and UV in turbid waters, underscoring that post-2024 retrofits are fewer, but more tailored (Townsend et al., 2024).

Looking forward, digital engineering links retrofit planning to durable operational performance. A 2024 container-ship case study shows how 3D laser scanning and model-based design streamline spatial integration, reduce rework, and compress yard schedules, while confirming spatial compatibility and minimal impacts on lightship weight and stability. Under high UV-transmittance conditions, operating costs were also favorable (Mahmud et al., 2024). At the downstream stage, CFD-assisted optimization reduces inter-reactor distribution errors to ~7 - 8.5 % in constrained machinery spaces, stabilizing UV dose delivery and lamp wear (Rak et al., 2025). At the downstream stage, CFD-assisted optimization reduces inter-reactor distribution errors to ~7 - 8.5 % in constrained machinery spaces, stabilizing UV dose delivery and lamp wear (Thach & Van Hung, 2024). Beyond CFD and model-based engineering, adaptive control is emerging. An online machine-learning architecture ingests ship and port sensor streams, updating predictive models continuously or at thresholds to forecast BWMS performance under varying UV-T, turbidity and flow conditions. These adaptive pipelines, which include monitoring, model switching, and retraining triggers, mitigate model drift, support predictive maintenance, and reduce verification risk. Together with CMD-aware verification and 3D/CFD-driven layout accuracy, they provide a coherent pathway for sustaining compliance as retrofit volumes taper (Iftikhar et al., 2024). These tools align with systematic retrofit frameworks that emphasize assessment and planning, space selection, engineering drawing and 3D modeling, installation planning, and commissioning/integration as interdependent levers for compliance assurance (Jee & Lee, 2017; Sari & Gunawan, 2024). Hasanspahić and Zec (2017) examine broader market conditions and retrofitting feasibility, noting the influence of BWTS dimensions and energy demands, which suggest underlying SDLs. Wang and Corbett (2021) model cost-effectiveness under varying regulatory conditions, recognizing that stricter standards necessitate advanced technologies, though without exploring specific BWTS operational parameters. Kolios (2024) proposes a risk assessment model for sustainable retrofits, identifying general technical and environmental risks aligned with SDLs that relate on electrification. Chen et al. (2025) highlight a critical limitation of current BWMS, namely, their inability to treat radioactive contaminants, which underscores a significant technological shortcoming despite the absence of detailed operational SDL data.

Table 5 presents a detailed matrix combining three key dimensions for each study: the types of BWTS evaluated, the methodological approach employed, and the retrofit aspect selection. This assessment reveals rich methodological diversity. Techniques range from comparative feasibility analyses, life cycle costing, and 3D scanning with CAD modeling, to fuzzy logic frameworks and Failure Mode, Effects, and Criticality Analysis (FMECA).

When evaluating these studies against **Table 5**, studies like Jee and Lee (2017) and Mahmud et al. (2024), which cover all seven core criteria comprehensively (as indicated by 'O' for all 7 criteria in **Table 3** of the main document), also provide the most concrete data points for SDLs. This suggests a correlation: studies that adopt a holistic assessment approach (covering all seven criteria) are more likely to delve into the specific operational and environmental parameters that define SDLs. Conversely, studies that omit certain core criteria (e.g., engineering drawing & 3D modeling and installation planning, as seen in Wang and Corbett (2021)) may also implicitly show less empirical data regarding SDLs, as these aspects are often interconnected. Therefore, a comprehensive assessment quality, as outlined in **Table 5**, appears to be a good indicator of the depth with which

SDLs are implicitly or explicitly addressed in BWTS retrofit research. Studies employing methodologies, such as detailed comparative feasibility analyses, life cycle costing, and 3D scanning with CAD modeling (e.g., Jee and Lee (2017); Mahmud et al. (2024)), consistently provide more concrete empirical data on SDLs. This suggests that, for engineers seeking granular data for system design and optimization, these methodological approaches are highly valuable. For academics, this correlation indicates that future research aiming to contribute detailed insights into SDLs should prioritize methodologies that integrate engineering design tools and empirical performance assessments, thus enriching the theoretical understanding of practical system constraints.

Table 5 Summary of assessment quality of study in retrofitting BWTS.

No. Ref	BWTS types	Methodology types	Aspect selection
1	Filtration Systems Chemical Disinfection	Market analysis methodology: Literature review Qualitative analysis Statistical estimations Comparative analysis	Cost-effective retrofitting Complexity of obtaining type approvals Significant cost Logistical planning required for installation
2	Direct flow electrolysis Side stream electrolysis UV treatment Ozone treatment	Comparative feasibility analysis: Systematic review and description of technologies Cost analysis Installation considerations Operational analysis Comparison of performance and costs	Technology selection Installation space management and planning Cost analysis (CAPEX and OPEX) Microbiological strains Concentration of ballast water contamination
3	Filtration Systems Chemical Disinfection Ultra-violet Treatment	Scenario based cost effectiveness analysis (CEA) with Consistent IMO Regulation: Inconsistent regulation Consistent stricter regulation	Cost analysis Regulatory compliance System size Operational dynamics
4	Electrolysis Electrochlorination UV irradiation Photocatalytic oxidation Electrocatalysis Chlorine dioxide (ClO_2)	Combination of framework development, multicriteria decision-making, and fuzzy logic: Technology screening and ranking System optimization with Fuzzy Inference System (FIS)	Technology selection Installation space Cost analysis (CAPEX and OPEX) Microbiological strains
5	Type A: Filtration + UV Treatment Type B: Filtration + Direct Flow Electrolysis Type C: Filtration + Side-Stream Electrolysis	System Dynamics (SD) and Life Cycle Costing (LCC): Expert judgement Simulation model Testing and validation Policy design and evaluation	Power requirements Installation space Maintenance costs over time

Table 5 (continued) Summary of assessment quality of study in retrofitting BWTS.

No. Ref	BWTS types	Methodology types	Aspect selection
6	Filtration Ultraviolet (UV) treatment	Integration of cutting-edge 3D scanning technology: 3D scanning technology deployment Identification of installation locations Compatibility assessment 3D model simulation Strategic decision-making	Technological selection Installation space management and planning Cost analysis Microbiological strains Compliance with environmental and regulatory standards Operational efficiency
7	Ultraviolet (UV) Radiation + Filtration	Advanced technological assessments: 3D scanning assessment Piping and Instrumentation Diagram (PID) simulation Cost analysis Sensitivity analysis Case study	Technology selection 3D scanning and CAD modeling Cost analysis (CAPEX/OPEX) Microbial inactivation efficiency Impact on lightship weight and stability System power and fuel consumption
8	Not specified	Failure Mode, Effects, and Criticality Analysis (FMECA) approach: Quantitative assessments Qualitative assessments Potential risks evaluation	Environmental protection Compliance with regulatory standards
9	Ultraviolet disinfection Electrolytic devices	Qualitative analysis: Policy Technology Regulatory assessments	Technology selection Regulatory compliance Cost analysis Installation space consideration

3.4 Discussion in findings of BWTS study

The implementation and retrofitting of Ballast Water Treatment Systems (BWTS) represent a pivotal component in global efforts to prevent marine bio-invasions and ensure environmental sustainability in maritime transport. This section consolidates insights from descriptive, bibliometric, and systematic analyses, offering a comprehensive view of technological, regulatory, economic, and ecological dynamics shaping BWTS developments, and critically linking these findings to broader challenges and future directions. Building upon the synthesized evidence, this study proposes a conceptual framework that highlights the critical interplay of “Technological Feasibility,” “Regulatory Harmonization,” and “Operational Resilience” as cornerstones for sustainable BWTS retrofits. This framework serves as a theoretical contribution, providing a structured lens for academics to analyze complex interdependencies and for engineers to strategically plan retrofit projects, recognizing that isolated advancements are insufficient for holistic success. The analysis reveals that successful implementation requires a dynamic balance among these three pillars, with progress in one area often necessitating adjustments in others. For example, the descriptive analysis showed UV treatment's technological dominance, but the systematic analysis indicated challenges in addressing diverse water qualities and emerging contaminants. This demonstrates that, although UV systems remain the most widely adopted technology due to cost-effectiveness and operational simplicity, their limitations under variable water quality conditions reveal a gap between laboratory feasibility and real-world resilience. This explicitly links the bibliometric evidence of UV's prominence with the systematic findings on performance challenges, emphasizing the need for adaptive designs and context-specific engineering solutions.

This tension between technological development and operational resilience directly informs practical design improvements and academic inquiry into adaptive treatment mechanisms. The dominance of UV technology is evident in its research and adoption rates. While UV treatment is a well-established method, with a significant number of publications and approved systems, its adoption is not a one-size-fits-all solution, especially for bulk carriers (Jee & Lee, 2017). A multi-criteria analysis using AHP-TOPSIS for a bulk carrier showed that Operational Expenditure (OPEX) with a priority of 0.315, Capital Expenditure (CAPEX) with 0.250, and Capacity with 0.160 are the dominant factors in system selection (Ejder et al., 2024). The most suitable system, Product G, had a CAPEX of $425,000 and an annual OPEX of $6,200. In contrast, a comparative feasibility study by Jee and Lee (2017) found that, for a bulk carrier, UV systems had the lowest annual operation cost at $6,934, compared to ozone systems at $11,151, and direct flow electrolysis at $9,538. The study also provided a cost estimation for a 27-year project period, showing that UV systems had the lowest total cost. However, practical shipboard studies have shown that UV systems encounter operational challenges under certain conditions. Jang et al. (2020) reported that systems failed in waters with extreme TSS levels due to filter clogging and reduced UV transmission, while Olsen et al. (2021) noted efficiency drops caused by shielding effects from particles and biofouling. Thach and Hung (2023) further emphasized that scaling UV treatment for large vessels often demands multiple high-power lamps, raising both energy use and maintenance costs. These findings reinforce the need to broaden the discussion of BWTS trends beyond UV dominance. The market is increasingly turning to other systems, such as electrolysis, for which research shows a growing interest, with 74 publications by abstract, and ozonation, due to their specific operational characteristics and suitability for diverse ship requirements. Moreover, novel hybrid approaches, such as filtration combined with membrane separation and deoxygenation, have demonstrated effective compliance with IMO D-2 standards in full-scale shipboard trials, offering lower operational complexity and avoiding the production of harmful by-products (Dong et al., 2023). The overall trend in BWTS selection is shaped by a complex interplay of factors, including regulatory compliance, ship size, operational routes, and owner preferences (Feng et al., 2023). For instance, while UV treatment demonstrates strong technological feasibility, its operational resilience is challenged by emerging contaminants like radioactive discharge, underscoring the need for adaptive regulatory frameworks. This finding bridges the descriptive trend of UV adoption with the identified gaps in regulatory scope, guiding engineers towards systems with broader contaminant capabilities and prompting academics to develop more comprehensive risk assessment models for novel pollutants. Such integration moves beyond siloed discussions, offering a holistic perspective to assess current challenges and to guide future strategic planning in the maritime industry. By explicitly connecting findings across descriptive trends, bibliometric structures, and systematic evaluations, this framework provides both a practical roadmap for stakeholders and a robust conceptual tool for advanced research into the complex adaptive systems of global ballast water management. Crucially, the "Regulatory Harmonization" pillar, informed by our systematic evaluation, highlights the pervasive influence of international and national regulations on every stage of BWTS retrofitting, from system selection to post-installation compliance.

This observation is strongly supported by the descriptive analysis presented in **Figure 7**, which shows ultra-violet treatment as the most extensively researched method, with 72 publications by abstract, indicating its prominence in academic discussions and potentially, market adoption. The bibliometric data here not only reflect academic interest, but also mirror practical industry uptake, as seen in regulatory approvals and cost modeling studies**.** The prominence of UV in both descriptive counts and systematic evaluations illustrates how research attention aligns with engineering feasibility and market demand, thereby validating the conceptual framework that technological feasibility serves as a cornerstone for BWTS adoption. This dominance, further detailed by the cost-effectiveness identified by Jee and Lee (2017), underscores its technological feasibility and widespread engineering adoption, serving as a baseline for future system innovation. Their findings showed that UV-based systems yielded the lowest total costs, including capital and operating expenses, especially when compared with ozone and electrolysis systems, making UV treatment particularly advantageous for bulk carrier retrofits. While UV treatment demonstrates strong technological feasibility and cost-effectiveness for certain vessel types, the overall market for BWMS installations is significantly shaped by the adoption of other technologies, such as electrolysis, for which research shows a growing interest, and ozonation, due to their specific operational characteristics and suitability for diverse ship requirements and water conditions. The selection of BWTS technology often depends on a complex interplay of factors, including regulatory compliance, ship size, operational routes, and owner preferences, leading to a varied market adoption landscape.

Further analysis into the cost components of UV treatment systems indicates that initial capital and installation costs for IMO-compliant BWTS can range from $0.7 million to $1.1 million, with a broader range of $0.2 million to $1.8 million when considering market extremes and various capacities, including those for very large crude carriers (VLCCs) (Wang & Corbett, 2021). For a specific case study, the capital expenditure for a UV-type BWTS on a container vessel was estimated at €255,000 (Mahmud et al., 2024), including hardware, installation, and engineering. Operational costs are significantly influenced by energy consumption and the need for consumables. Power requirements for UV systems can range from 7.6 to 12.7 kWh per 100 m^3 of treated water (Gerhard et al., 2019). Crucially, the efficacy of UV treatment is highly dependent on water quality, particularly UV Transmittance (UVT), with lower UVT levels (e.g., below 65 %) leading to a twofold increase in fuel costs, compared to 100 % UVT scenarios due to higher power consumption (Mahmud et al., 2024). This operational insight connects directly to bibliometric findings where "risk assessment" and "inactivation" appeared as underrepresented keywords suggesting that, while engineering solutions dominate, methodological tools for evaluating real-world variability remain underdeveloped. This disconnect between research emphasis and operational needs highlights a critical area for future interdisciplinary studies, ensuring that bibliometric gaps inform targeted technological innovation. These operational considerations, particularly the influence of water quality on UVT and costs, are a significant aspect of the 'Engineering' research area identified in **Figure 6**, which accounts for 166 publications, reflecting the ongoing focus on optimizing technical and cost performance under diverse environmental conditions. Maintenance expenses are also recurrent, with UV lamps requiring replacement after approximately 8,000 to 12,000 operational hours. Filters, essential for pre-treatment, also necessitate periodic cleaning or replacement, adding to the ongoing operational expenditure. These factors underscore the importance of comprehensive cost analysis beyond initial purchase, encompassing lifecycle expenses driven by operational conditions and component longevity.

However, despite the operational success, ecological concerns remain substantial. Ballast water serves as a primary vector for introducing non-indigenous and potentially pathogenic microorganisms, including bacteria, viruses, protists, and zooplankton, into new marine environments (Outinen et al., 2024; Xiao et al., 2023). Laas et al. (2022) observed that, even after UV treatment, ballast waters retained high concentrations of *Synechococcus sp.*, a pathogenic taxon that poses a risk to marine biodiversity. Furthermore, ballast water can carry pollutants beyond biological organisms. Liu et al. (2024) underscored the rising concern of cross-border nuclear contamination from ballast water following Japan's Fukushima wastewater release. Their study emphasized the urgent need for international legal instruments to address radioactive discharges and ecological vulnerabilities that conventional BWTS are not designed to handle. Additionally, ballast tank sediments and biofilms were shown to act as reservoirs for persistent microbial communities, resisting disinfection and forming long-term ecological threats (Laas et al., 2022).

In terms of regulatory context, the International Maritime Organization (IMO) requires all vessels to meet the D-2 discharge standard by 2024 under the Ballast Water Management Convention (Romero-Martínez et al., 2024; Shomar & Solano, 2023). The D-2 standard mandates that discharged ballast water must contain fewer than 10 viable organisms per cubic meter greater than or equal to 50 µm in minimum dimension, fewer than 10 viable organisms per milliliter between 10 and 50 µm in minimum dimension, and specified concentrations of indicator microbes (Casas-Monroy et al., 2022). Most ships are expected to comply with this standard through the installation of a BWMS. The implementation of D-2 requirements is detailed in the IMO's Code for Approval BWMS Code, Resolution MEPC.300(72), which outlines land-based and shipboard testing procedures to ensure systems meet performance standards. Notably, this Code, effective October 13, 2019, superseded the earlier G8 guidelines (Resolution MEPC.174(58) and MEPC.279(70)), introducing more stringent requirements for type approval and performance testing. Furthermore, commissioning testing of BWMS units became mandatory, effective June 1st, 2022, to ensure correct operation after installation (Outinen et al., 2024). However, implementation is not without hurdles. Jurisdictional ambiguity, particularly in managing radioactive content in ballast discharges, weakens enforcement in international waters. When connected to the bibliometric analysis, this reveals why regulatory harmonization consistently emerges as a high-frequency theme; the data not only map publication counts, but also reflect ongoing structural challenges in aligning IMO and USCG approval frameworks. This demonstrates how bibliometric signals (frequent occurrence of “management,” “compliance,” and “regulation” keywords) are substantiated by systematic evidence of fragmented implementation. As highlighted by Campara et al. (2019) , the United States Coast Guard (USCG) imposes more prescriptive testing and approval processes compared to the IMO, often leading to distinct compliance pathways for global operators. Jurisdictional ambiguity, particularly in managing radioactive content in ballast discharges, weakens enforcement in international waters. For instance, China has launched national monitoring and early-warning systems, but such unilateral initiatives fall short without cross-border cooperation (Liu et al., 2024). Inconsistent certification and inspection protocols among classification societies hinder uniform application of BWTS standards. Synchronization of these protocols is critical to avoid compliance gaps. These regulatory complexities directly underscore the importance of 'Regulatory compliance' as a fundamental consideration in BWTS retrofitting, as consistently addressed by all nine studies in this systematic analysis, seen **Figure 13** and **Table 3**, yet also reveal ongoing challenges in achieving harmonization. Additionally, Jiang et al. (2023) utilized evolutionary game theory to model regulator-carrier interactions, suggesting that introducing public oversight and financial incentives significantly improves compliance motivation, particularly in high-cost scenarios.

From a market and industry perspective, Hasanspahić and Zec (2017) reported a surge in demand for BWTS installations following BWMC enforcement, accompanied by operational bottlenecks such as complex US MARAD (United States Maritime Administration) approval processes and limited shipyard availability. During the initial enforcement surge between 2017 and 2020, limited yard capacity was indeed a constraint; however, as fleets approached and passed the 8 September 2024 D-2 deadline, retrofit demand began to normalize. Compliance datasets from a decade of U.S. EPA reporting indicate generally low non-compliance rates (< 3 % for bacteria; < 10 % for biocides), with the lowest rates recorded in 2020 - 2023, reflecting the operational maturation of BWTS fleets and stronger verification practices (Stehouwer et al., 2025). Comparative evaluations of compliance-monitoring devices (CMDs) further reveal method-dependent outcomes in UV-treated waters, underscoring that today’s operational challenges center more on verification and analytics than on shipyard capacity (Romero-Martínez et al., 2024). In the post-deadline phase, the focus has shifted from yard capacity to in-service performance, commissioning quality, and day-to-day compliance monitoring. Since mid-2022, mandatory commissioning biology tests have already driven improvements, reducing failure rates from ~20 % to ~6 - 7 %, with residual non-compliance concentrated in the ≥ 50 µm size class (Drillet et al., 2023). Operational uptake-discharge sampling also shows high treatment efficacy, with ≥ 98 % organism reductions and consistent achievement of D-2 standards in the small-size class; exceedances in the large-size class are linked to uptake loads and filter mesh selection (Casas-Monroy et al., 2025; Feng et al., 2023).

With D-2 compliance universal since 8 September 2024, the emphasis now lies in commissioning quality, monitoring fidelity, and context-aware system operation, rather than yard scarcity (Berestovoi, 2024b, 2024a). In the United States, BWTS approvals are overseen by the U.S. Coast Guard (USCG) under a type-approval regime that differs in scope and methodology from IMO pathways, reinforcing that, post-2024, operational challenges are primarily regulatory and operational, rather than capacity-related (Campara et al., 2019). Such practical challenges, particularly regarding space limitations on existing vessels, are implicitly reflected in the 'Installation planning' and 'Space selection' criteria within the result of systematic analysis in **Table 3** and **Figure 13**, confirming their significance in real-world retrofitting. These findings highlight the continuing need for regulatory harmonization and capacity planning to support retrofitting efforts. Projected demand beyond September 2024 is expected to decline as fleets complete mandatory installations, with residual demand focusing on replacements (e.g., systems mismatched to local UV-T or pump head), reliability upgrades, and verification-driven optimization. Production-engineering evidence shows that perceived yard bottlenecks can be mitigated through process optimization; a maintenance-shipyard study using discrete-event simulation demonstrated throughput improvements from 23 to 41 BWTS units per year (~78 % productivity gain) after targeted interventions (Mentes et al., 2025) . At the ship level, constraints are shifting from berth slots to integration details; for instance, the Mintis project identified inadequate ballast pumps for the selected UV system head-loss, requiring impeller changes and flow adjustments typical of the post-deadline retrofit tail (Čurovas, 2025). At a portfolio level, mass, dimensional, and energy characteristics have become increasingly important as owners prioritize OPEX and operational fit. UV systems are compact, but may require nearly double the power of electrolysis for the same flow, while electro-chlorination systems are heavier and larger, factors that shape residual retrofit choices beyond 2024 (Berestovoi, 2024b).

In parallel, digital engineering reduces rework and schedule risk; 3D scanning-driven retrofit planning cut project time by ~25 % and total costs by ~15 % in shipyard execution (Mahmud et al., 2023), while a container-ship case showed minimal stability/lightship impact (BWTS ≈0.04 % of lightship; < 2 % stability effect) and favorable costs under high UV-transmittance conditions (Mahmud et al., 2024). This trend toward digital engineering is implicitly supported by the increasing prominence of journals like 'Journal of Marine Science and Technology' and 'Environmental Science and Technology' in **Figure 10**, which often publish research on advanced engineering tools and methodologies for maritime applications, including 3D scanning and modeling for retrofit projects. Wang and Corbett (2021) contrasted onboard BWTS with barge-based systems, concluding that, while onboard systems are generally more affordable globally, regional policies may favor port-based systems under certain compliance frameworks. In a related study, da Silva Jorge and Satir (2020) proposed a fuzzy logic model that enables multi-criteria BWTS selection based on factors such as vessel type, feasibility, and technical compatibility. This is particularly useful for tankers and specialized fleets. From a lifecycle economics perspective, Hardiyanto et al. (2023) developed a dynamic cost model to assess long-term BWTS investments. Their analysis concluded that filtration-UV combinations (Type A systems) were the most cost-effective option for small tankers over a 12-year horizon, aligning technical efficiency with financial planning. Expanding beyond cost modeling, Kolios (2024) applied failure-mode risk analysis to eco-retrofitting, emphasizing the importance of resilient BWTS designs that anticipate both operational failures and environmental contingencies. Similarly, Chen et al. (2025) reinforced this argument by emphasizing the ecological threats from nuclear wastewater in ballast flows, underscoring that compliance must now encompass emerging non-biological risks.

Monitoring and compliance technologies have also advanced significantly. Ndlovu (2025) noted that rapid-result Compliance Monitoring Devices (CMDs) are now essential tools for port authorities, enabling pre-arrival assessments and real-time enforcement of D-2 standards. Complementing this development, Cho et al. (2025) optimized the DPD colorimetric method using phosphate-iodide-sulfuric acid reagents, which improved the accuracy of residual oxidant detection under dynamic ballast conditions. The emphasis on advanced monitoring aligns with the "Commissioning and integration" criterion in **Table 3** and **Figure 13**, underscoring the critical role of post-installation verification for ensuring BWTS efficacy and compliance with international standards such as D-2. However, performance inconsistencies still exist. Casas-Monroy et al. (2022) found fluctuating results when evaluating indicative analysis devices for organisms in the 10 - 50 μm size range under natural UV-treated conditions. Similarly, Outinen et al. (2024) reported that nearly half of tested vessels exceeded allowable organism concentrations, reinforcing the need for more robust verification and biological detection systems. Residual and emergent risks also sustain ongoing demand for system upgrades and verification. The "Better Ballast Water Discharge Initiative," for instance, identified a nuclear-contamination vector in ballast water, and called for enhanced monitoring, record-keeping, and reception facilities across high-traffic corridors, measures likely to drive targeted system and protocol adjustments rather than wholesale retrofits (Chang et al., 2024). As molecular techniques evolve, the use of genetic tools, such as 16S rRNA sequencing, is expected to strengthen microbial profiling and compliance assurance (Laas et al., 2022). In summary, BWTS has evolved beyond being a simple compliance instrument; it now represents a complex engineering, ecological, and policy system that requires continuous innovation and cross-sectoral coordination. Achieving sustainable ballast water management will depend on integrative strategies that combine robust system design, real-time monitoring, regulatory harmonization, and adaptive risk governance. Collaboration among regulators, shipowners, researchers, and equipment developers is, therefore, essential to advance both the science and the implementation of BWTS worldwide.

4. Conclusions

Retrofitting Ballast Water Treatment Systems (BWTS) remains a pivotal challenge for the maritime industry, requiring both technological innovation and regulatory coordination. Through a three-stage integrated methodology consisting of descriptive, bibliometric, and systematic analyses, this study has provided a comprehensive overview of the retrofit landscape, highlighting interdependencies across technical, economic, ecological, and policy dimensions. Beyond classification of existing studies, the analysis offers a conceptual framework that identifies "Technological Feasibility," "Regulatory Harmonization," and "Operational Resilience" as the cornerstones of sustainable BWTS implementation. The overarching trend in ballast water treatment is moving toward greater stability, lower operational costs, and improved ease of operation and maintenance, rather than relying on a single, superior technology. While ultraviolet (UV) treatment is a prominent technology, favored for its cost-effectiveness and operational simplicity, its limitations, such as high energy consumption and sensitivity to water quality, have prompted increased attention to other systems, like electrolysis and ozonation. The retrofit market is shaped by a diverse array of systems, each with distinct operational strengths and limitations. In addition to these, hybrid approaches, such as filtration combined with membrane separation and deoxygenation, have emerged as promising alternatives, reflecting the industry's shift toward solutions that prioritize operational resilience, adaptability to diverse water qualities, and sustainability. Despite its widespread adoption, UV treatment faces ongoing concerns about its ability to eliminate all harmful organisms and its vulnerability to water quality variations, while broader ecological threats, such as radioactive contaminants in ballast discharge, remain unresolved. Regulatory divergence further complicates adoption, with the IMO's global standards under the Ballast Water Management Convention

(BWMC) differing from the more prescriptive United States Coast Guard (USCG) framework. These discrepancies in definitions, testing protocols, and monitoring requirements create compliance uncertainty for globally operating fleets. Although adoption rates are rising, evidence that less than 2 % of monthly ballast water discharge volume in the United States was treated underscores the gap between installation and effective compliance.

Future research should expand the use of digital engineering tools, such as digital twins, AI-driven simulations, and virtual reality. These technologies can enhance retrofit planning, minimize design errors, and improve spatial efficiency, particularly for older vessels with limited space. Empirical studies that quantify reductions in project time and cost, as well as integration with real-time operational data for predictive maintenance, will strengthen the evidence base. For researchers, this opens opportunities to design predictive models and expand digital twin applications. Practitioners such as engineers and shipowners will obtain practical guidance to reduce CAPEX and OPEX, while improving technical integration, and policymakers will have a stronger case for embedding digital engineering requirements into compliance frameworks. Advancing adaptive BWTS technologies is equally critical to overcome current limitations, especially in addressing emerging contaminants and ensuring effectiveness under diverse water conditions. Researchers can focus on developing multi-contaminant treatment mechanisms, practitioners will benefit from systems that are more reliable and less maintenance-intensive, and policymakers will gain evidence to justify updating regulations for pollutants such as radioactive discharge or persistent microbial communities. Efforts to achieve regulatory harmonization also remain a priority. Research on models that bridge IMO and USCG requirements will help improve compliance through standardized testing and advanced monitoring technologies. Such work will give researchers relevant case studies in governance and compliance modeling, reduce certification and operational burdens for practitioners, and provide policymakers with evidence-based pathways toward greater regulatory convergence. Life-cycle cost-benefit analyses should be strengthened by including not only financial elements, but also ecological externalities, such as invasive species and radioactive discharges. Establishing standardized methods for monetizing ecological damage will enable researchers to refine integrated economic-environmental models. Practitioners will gain clearer decision-support tools for investment planning, and policymakers will be equipped with monetized impact assessments that justify stricter enforcement. Attention must also be given to human factors and crew training. Human-in-the-loop simulations can identify potential operational errors and optimize training, ensuring better interaction between crews and BWTS technologies. For researchers, this provides new ground for advancing maritime human factors studies. For practitioners, improved training will enhance operational readiness and long-term reliability. For policymakers, standardized training protocols can be mandated across jurisdictions to strengthen compliance consistency. In conclusion, this study not only maps the current BWTS retrofit landscape, but also outlines a forward-looking agenda. By linking technological, operational, and regulatory dimensions with stakeholder-specific benefits, it provides both a conceptual roadmap for academic inquiry and practical guidance for industry and policymakers working toward sustainable ballast water management.

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