



## A Structural Equation Modeling Approach to Assessing the Impact of Ship Characteristics and Operational Parameters on Ballast Water Treatment Efficiency

Ülkü Demirci<sup>1</sup>✉ | Meltem Eken<sup>2</sup> | Mehmet Fatih Can<sup>3</sup>

1. ISTE Center for Science and Technology Studies and Research (ISTE-CSTSR), İskenderun Technical University, İskenderun, Hatay, Türkiye

2. Department of Maritime Transportation and Management Engineering, Barbaros Hayrettin Naval Architecture and Maritime Faculty, İskenderun Technical University, İskenderun, Hatay, Türkiye.

3. Department of Water Resources Management and Organization, Marine Science and Technology Faculty, İskenderun Technical University, İskenderun, Hatay, Türkiye

### Article Info

#### Article type:

Research Article

#### Article history:

Received: 14 August 2025

Revised: 28 September 2025

Accepted: 09 February 2026

#### Keywords:

*Treatment performance*

*Invasive species*

*Adenosine triphosphate*

*Marine pollution*

### ABSTRACT

The global spread of invasive aquatic organisms via ballast water discharge poses significant ecological and economic risks. Although various ballast water treatment systems (BWTS) are designed to mitigate this threat, the influence of ship-specific and operational parameters on treatment performance remains insufficiently understood. This study applies Structural Equation Modeling (SEM) to evaluate relationships among ship characteristics (gross tonnage, length, width), treatment system operational parameters (rated capacity, retention time, flow rate, total volume), and biological outcomes (concentrations of viable organisms  $\geq 50 \mu\text{m}$  and 10–50  $\mu\text{m}$ ). Data were obtained from 59 International Maritime Organization (IMO)-compliant commissioning test reports collected during discharge via dedicated sample ports under IMO G2 guidelines. Organism concentrations were determined using second-generation Adenosine triphosphate (ATP) analysis, with thresholds aligned to the IMO D-2 standard.

Initial one-way ANOVA tests revealed no significant differences in organism concentrations across ship types or treatment technologies. Multiple regression analyses identified modest linear relationships between certain ship or operational variables and biological outcomes but also showed inter correlations among predictors that could obscure their individual effects. To address these dependencies and investigate potential indirect pathways, SEM was employed. The final model achieved good fit and indicated that larger ships generally possessed greater treatment and operational capacity, which was associated with reduced concentrations of organisms in the 10–50  $\mu\text{m}$  size class. No significant effect was observed for organisms  $\geq 50 \mu\text{m}$ . These results highlight the need to align BWTS capacity and hydraulic exposure with vessel scale, while suggesting that supplementary strategies may be required to effectively control larger organisms.

**Cite this article:** Demirci, Ü., Eken, M., & Fatih Can, M. (2026). A Structural Equation Modeling Approach to Assessing the Impact of Ship Characteristics and Operational Parameters on Ballast Water Treatment Efficiency. *Pollution*, 12(1), 342-350. <https://doi.org/10.22059/poll.2025.400685.3078>



© The Author(s).

Publisher: The University of Tehran Press.

DOI: <https://doi.org/10.22059/poll.2025.400685.3078>

## INTRODUCTION

Ballast water, ships use to maintain stability, is routinely transferred between ports and has become a major pathway for the global spread of aquatic invasive species (IMO, 2004, 2008). A well-known case is the comb jelly *Mnemiopsis leidyi*, introduced into the Black Sea in the 1980s, which caused the collapse of local fisheries and economic losses exceeding USD 250 million annually (Sergeeva & Zaika, 1990; Shiganova et al., 2001). Such examples highlight

\*Corresponding Author Email: [ulku.demirci@iste.edu.tr](mailto:ulku.demirci@iste.edu.tr)

the severe ecological and economic risks of ballast water-mediated invasions (Doğru et al, 2021). Globally, an estimated 7,000–10,000 species are transported daily in ballast tanks (Satir, 2014; Vural & Yönsel, 2017; Yazır & Gedik, 2022; Chen et al, 2023).

To address this, the International Maritime Organization (IMO) adopted the Ballast Water Management Convention (BWM-2004), effective since 2017, which requires treatment systems to meet the D-2 standard for viable organism concentrations (Güney, 2018; Saenz Alcantara, 2018; Chen et al 2023; Feng, 2023). Various technologies are approved, including filtration, UV radiation, chemical disinfection, deoxygenation, and electrochlorination (Tsolaki & Diamadopoulou, 2010; Sayınlı et al., 2022). Despite this, treatment effectiveness varies with environmental conditions, system capacity, and operational factors (Özdemir, 2023).

Most performance assessments focus on  $\geq 50 \mu\text{m}$  and 10–50  $\mu\text{m}$  organism size classes. Recent advances in adenosine triphosphate (ATP) analysis allow rapid and reliable compliance monitoring, particularly for medium-sized organisms (Peperzak, 2023; Peperzak et al., 2024). ATP-based thresholds aligned with the D-2 standard enable fast evaluations of treatment efficiency (IMO, 2018, 2019).

To better understand how ship features and operational parameters influence biological outcomes, this study applies Structural Equation Modeling (SEM). Unlike traditional regression, SEM accounts for interdependencies and indirect effects, offering a systems-level view of performance drivers (Fernandes et al., 2018). Using 59 IMO-compliant commissioning test reports, this research investigates the relationships between vessel characteristics, treatment capacity, and organism concentrations, providing insights for optimizing ballast water management under real-world conditions.

Therefore, the aim of this study is to evaluate the extent to which ship characteristics and operational parameters influence the treatment performance of ballast water treatment systems, thereby providing evidence-based insights to improve compliance with international standards and support sustainable maritime operations.

## MATERIAL & METHODS

Ballast water samples were collected from 59 vessels during discharge, following the IMO G2 Guidelines (IMO, 2008, 2015). Sampling was performed through dedicated discharge ports by an accredited service provider, ensuring standardized collection and handling procedures. The dataset included fishing vessels ( $n=2$ ), container ships ( $n=9$ ), bulk carriers ( $n=34$ ), and tankers ( $n=14$ ). All samples were protected from sunlight and analyzed within 3–4 hours to maintain integrity, with required volumes adjusted according to organism size class (Bailey et al., 2022).

Treatment performance was assessed using second-generation adenosine triphosphate (ATP) analysis. ATP, the universal energy carrier in living cells, was quantified through a luciferase–luciferin bioluminescence reaction, with emitted light proportional to intracellular ATP concentration. Second-generation methods specifically measure ATP in viable cells, reducing interference from debris, dissolved substances, and extracellular ATP released by dead organisms. This approach enables rapid and reliable assessments of ballast water treatment system performance under real-world conditions (IMO, 2018).

Acceptance thresholds for ATP concentrations were based on IMO (2019) guidance, corresponding to fewer than 150,000 pg ATP/ $\text{m}^3$  for organisms  $\geq 50 \mu\text{m}$ , fewer than 500 pg ATP/mL for organisms 10–50  $\mu\text{m}$ , and fewer than 1,000 pg ATP/100 mL for bacteria. These limits align with the D-2 standard of  $<10$  viable organisms/ $\text{m}^3$ ,  $<10/\text{mL}$ , and low concentrations of indicator microbes (*Vibrio cholerae*, *Escherichia coli*, intestinal enterococci). In 2013, an independent laboratory investigation utilizing ballast water samples from the Kiel Canal and the Baltic Sea provided further validation of ATP as a reliable indicator. The study demonstrated

that an ATP concentration of approximately 700 pg/mL corresponded to a bacterial abundance of 1,000 CFU per 100 mL, thereby confirming a strong correlation between ATP levels and culturable bacterial counts (IMO, 2019).

Validation of treatment efficacy followed IMO guidance under BWM.2/Circ.70/Rev.1 (Guidance for the commissioning testing of ballast water management systems). Each commissioning test report was signed by the accredited test facility, confirming adherence to this protocol and certifying that the reports contained no known errors, omissions, or false statements.

For statistical evaluation, one-way ANOVA was first used to test differences in organism concentrations across ship types and treatment technologies, but no significant effects were observed ( $p > 0.05$ ). To illustrate the findings, the outcomes of the one-way ANOVA comparing organism concentrations across different ballast water treatment technologies and across ship types are summarized in Table 1 and Table 2, respectively.

To adequately address the question of why variability in organism concentrations occurs across different ship types and treatment technologies, it is necessary to employ an alternative statistical technique that accounts for the full range of available variables. Due to correlations among predictors, Structural Equation Modeling (SEM) was employed to jointly examine ship characteristics (gross tonnage, length, width), operational parameters (rated capacity, retention time, flow rate, total volume), and biological outcomes (organisms  $\geq 50 \mu\text{m}$  and  $10\text{--}50 \mu\text{m}$ ). SEM allowed simultaneous estimation of direct, indirect, and mediated effects (Civelek, 2018; Kline 2023). In this framework, measurement models linked observed variables to latent constructs, while structural models captured the hypothesized relationships among those constructs (Finch & French, 2015; Fan et al., 2016). The variables included in the SEM analysis, along with their definitions and measurement units, are summarized in Table 3.

**Table 1.** One-way ANOVA results for organism concentrations by treatment technology

	Technology			
	F	df1	df2	p
Org50	0.321	2	56	0.727
Org10_50	2.225	2	56	0.118

**Table 2.** One-way ANOVA results for organism concentrations by ship type

	Ship Type			
	F	df1	df2	p
Org50	2.36	3	55	0.082
Org10_50	2.15	3	55	0.104

**Table 3.** Input variables: Definitions and units

Variable	Acronym
Gross tone (GT)	GT
Ship length (m)	Length
Ship width (m)	Width
Treatment rated capacity in $\text{m}^3/\text{hr}$	TRC
Time ballast water is held in ballast tank(s) prior to de-ballasting (hr)	HoldTime
Deballast flow rate ( $\text{m}^3/\text{hr}$ )	FlowRate
Deballast total volume ( $\text{m}^3$ )	Volume
Organism $\geq 50 \mu\text{m}$ ( $\text{pg}/\text{m}^3$ )	Org50
Organism $\geq 10\text{--}50 \mu\text{m}$ ( $\text{pg}/\text{mL}$ )	Org10_50

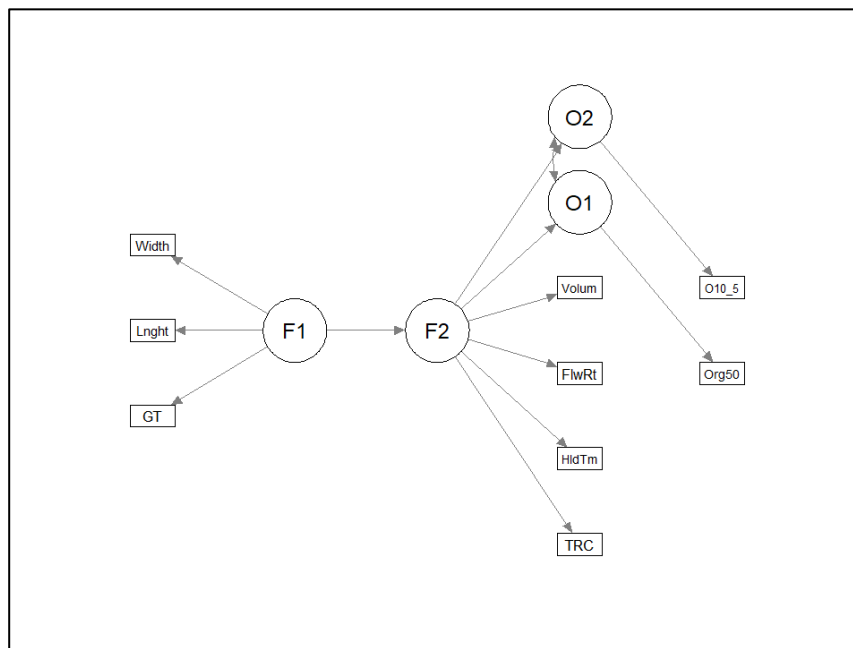


Fig. 1. The conceptual SEM model

Table 4. Classification of variables according to factor structures

Latent Variable	Observed Variables	Explanations
F1: Ship Features	Gross Tonnage, Ship Length, Ship Width	Physical and structural attributes of the vessel
F2: Treatment & Operational Capacity	Treatment Rated Capacity, Ballast water hold time, Deballast Flow Rate, Deballast Total Volume	Operational capacity and process variables related to treatment and ballast water management
O1: Biological Outcome-1	Organism $\geq 50 \mu\text{m}$	Outcome variable indicating treatment efficiency for organisms larger than $50 \mu\text{m}$
O2: Biological Outcome-2	Organism $\geq 10 - < 50 \mu\text{m}$	Outcome variable indicating treatment efficiency for organisms in the $10 - 50 \mu\text{m}$ size range

In this study, two groups of hypotheses were formulated. First, structural relationships were proposed between latent constructs: ship features (F1) were expected to influence treatment and operational capacity (F2), which in turn was hypothesized to affect organism concentrations in the  $\geq 50 \mu\text{m}$  (O1) and  $10 - 50 \mu\text{m}$  (O2) size classes. Second, measurement relationships were specified to define how latent constructs are represented by observed variables: F1 was measured through gross tonnage, length, and width; F2 through treatment rated capacity, holding time, flow rate, and volume; O1 through viable organisms in the  $\geq 50 \mu\text{m}$  class; and O2 through viable organisms in the  $10 - 50 \mu\text{m}$  class. Together, these structural and measurement hypotheses provided the conceptual basis for the SEM analysis.

The conceptual model illustrated in Figure 1 was tested using SEM to evaluate the effects of ship characteristics and treatment-related operational parameters on organism concentrations in ballast water.

In the conceptual model, it is hypothesized that ship characteristics (F1) influence operational and treatment capacity (F2), which in turn affects the biological outcomes O1 and O2. The latent factors and their associated observed variables included in the model are summarized in Table 4.

Model parameters were estimated using the Maximum Likelihood method with robust

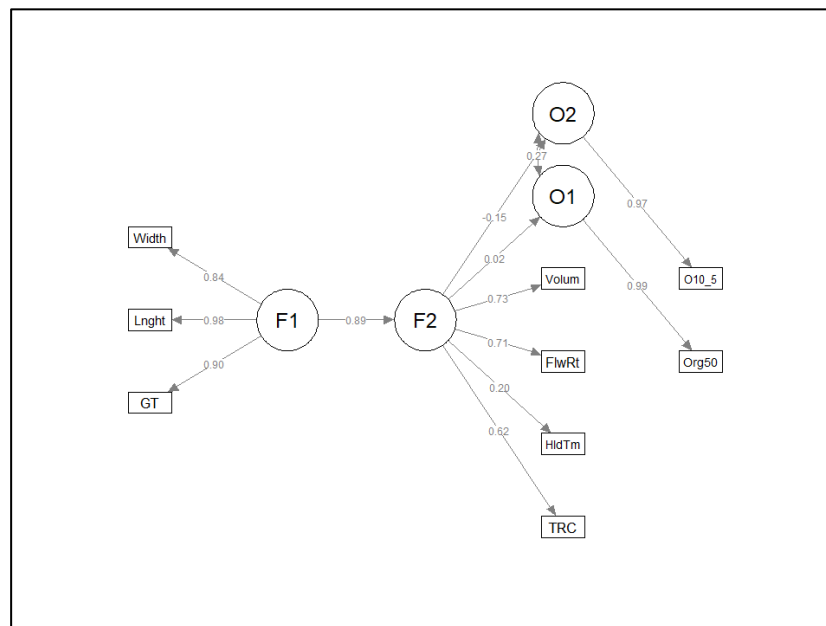


Fig. 2. The final SEM model

corrections for small sample size (Finch & French, 2015; Fan et al., 2016), and all calculations and simulations were conducted using R (R Core Team, 2022), Jamovi (The jamovi project, 2025), and Microsoft Excel software.

## RESULTS AND DISCUSSION

The structural equation model was estimated using the robust ML method with the Satorra-Bentler mean-adjusted correction for small sample size ( $N = 59$ ). The model convergence was achieved in 33 iterations, with 29 free parameters (Finch & French, 2015; Fan et al, 2016).

The structural relationships among ship characteristics, treatment capacity, and organism concentrations (along with model fit indices, measurement model, structural model, explained variances, and direct effects for the final SEM model) are presented in Figure 2.

Model fit indices indicated an acceptable to good model fit. The scaled chi-square test was not statistically significant,  $\chi^2(25) = 36.2$ ,  $p = 0.069$ , suggesting a satisfactory model-data fit. Although the classical chi-square was significant,  $\chi^2(25) = 47.5$ ,  $p = 0.004$ , this result was interpreted with caution due to the sensitivity of the test to sample size. Comparative fit indices supported this interpretation: CFI = 0.961, TLI = 0.944, and NNFI = 0.944, all exceeding the recommended threshold of 0.90 (Finch & French, 2015). The RMSEA was 0.087 (scaled), with a 90% confidence interval of [0.011, 0.139], and an associated p-value of 0.143, indicating reasonable error of approximation. The SRMR value was 0.068, supporting good fit (Fan et al, 2016).

All observed variables loaded significantly onto their respective latent constructs:

- F1 (Ship Feature) was defined by GT ( $\beta = 0.904$ ,  $p < 0.001$ ), Length ( $\beta = 0.983$ ,  $p < 0.001$ ), and Width ( $\beta = 0.845$ ,  $p < 0.001$ ).
- F2 (Treatment Capacity) was defined by TRC ( $\beta = 0.832$ ,  $p = 0.007$ ), HoldTime ( $\beta = 0.273$ ,  $p = 0.020$ ), FlowRate ( $\beta = 0.960$ ,  $p < 0.001$ ), and Volume ( $\beta = 0.991$ ,  $p < 0.001$ ).
- Output latent variables O1 and O2 were measured by Org50 ( $\beta = 1.000$ ,  $p < 0.001$ ) and Org10\_50 ( $\beta = 1.000$ ,  $p < 0.001$ ), respectively.

The path from F1 to F2 was statistically significant ( $\beta = 0.664$ ,  $z = 5.477$ ,  $p < 0.001$ ),

**Table 5.** Indirect effect estimates in the SEM

Label	Description	Parameter	Estimate	SE	95% CI		$\beta$	z	p
					Lower	Upper			
IE1	F1 $\Rightarrow$ F2 $\Rightarrow$ O1	p10*p11	0.016	0.084	-0.148	0.181	0.016	0.195	0.845
IE2	F1 $\Rightarrow$ F2 $\Rightarrow$ O2	p10*p12	-0.131	0.055	-0.238	-0.024	-0.128	-2.39	0.017

indicating that larger ship features predicted higher treatment capacity.

The direct effect of F2 on O1 (Organisms  $\geq 50 \mu\text{m}$ ) was positive but non-significant ( $\beta = 0.025$ ,  $p = 0.846$ ), while F2 had a significant negative effect on O2 (Organisms 10–50  $\mu\text{m}$ ) ( $\beta = -0.193$ ,  $z = -2.671$ ,  $p = 0.008$ ). This suggests that increased treatment capacity significantly reduced the presence of mid-size organisms but had no effect on larger organisms.

$R^2$  values indicated that the latent constructs explained high variance in their respective indicators: GT ( $R^2 = 0.818$ ), Length (0.967), Width (0.714), TRC (0.693), FlowRate (0.922), and Volume (0.982). HoldTime showed relatively low explained variance ( $R^2 = 0.074$ ). The model accounted for 44.1% of the variance in F2, but only 0.04% in O1 and 3.7% in O2, suggesting weak prediction of biological outputs.

The indirect effect of F1 on O1 through F2 (IE1) was not significant ( $\beta = 0.016$ ,  $p = 0.845$ ). However, the indirect effect of F1 on O2 through F2 (IE2) was statistically significant ( $\beta = -0.128$ ,  $p = 0.017$ ), indicating a mediated negative relationship: larger ships predicted higher treatment capacity, which in turn reduced organism concentration in the 10–50  $\mu\text{m}$  size class (shown in Table 5).

A significant positive covariance was found between O1 and O2 ( $\beta = 0.274$ ,  $p = 0.045$ ), indicating shared variance between the two organism types. Among measurement variables, significant variance was found for HoldTime ( $\beta = 0.926$ ,  $p < 0.001$ ) and TRC ( $\beta = 0.307$ ,  $p = 0.013$ ).

The multivariate analysis conducted in this study revealed substantial variability among sample vessels in both structural features (F1) and operational parameters of their BWTS (F2). Gross tonnage, length, and width (F1) exhibited wide distributions, as did the operational parameters comprising F2—rated treatment capacity, flow rate, total tank volume, and retention time. Coefficients of variation exceeded 30% for several variables, indicating high heterogeneity within the dataset. This variability was also reflected in the biological outcomes, particularly for the  $\geq 50 \mu\text{m}$  organism group, where high variance and outliers highlighted the necessity of applying a multivariate modeling framework such as SEM to capture complex interrelationships.

The structural equation model developed in this study achieved an acceptable level of fit according to multiple indices. Although the Satorra–Bentler corrected chi-square test was marginally non-significant ( $p = 0.069$ ), other statistics (CFI = 0.961, TLI = 0.944, RMSEA = 0.087, and SRMR = 0.068) met or approached commonly recommended thresholds for adequate model fit (Finch & French, 2015). These results indicate that the specified model structure appropriately captures the relationships among F1, F2, and biological outcomes, despite constraints in sample size.

The measurement model results confirmed the statistical robustness of both latent factors. Observed variables representing F1 loaded strongly (0.84–0.98) on their latent construct, while F2 displayed high loadings for flow rate and total tank volume. Retention time contributed less strongly to F2 ( $\beta = 0.273$ ,  $p = 0.020$ ), a finding likely explained by its dependence on voyage duration and operational practices rather than on system design capacity. Moreover, ballast water often undergoes pre-treatment at intake, which may limit the additional impact of extended retention time on organism reduction.

Structural model results indicated a strong and significant influence of F1 on F2 ( $\beta = 0.664$ ,  $p < 0.001$ ), suggesting that larger and more structurally advanced vessels tend to be equipped

with higher-capacity treatment systems. However, the direct effect of F2 on  $\geq 50$   $\mu\text{m}$  organism concentrations was not statistically significant ( $\beta = 0.025$ ,  $p = 0.846$ ). This supports existing literature suggesting that the UV-based treatment technologies predominant in this dataset may be less effective against larger organisms, which often exhibit greater resistance to UV irradiation (Bradie et al., 2018).

In contrast, a significant negative direct effect was observed between F2 and the 10–50  $\mu\text{m}$  organism group ( $\beta = -0.193$ ,  $p = 0.008$ ), indicating that higher treatment/operational capacity is associated with lower concentrations in this size class. This is consistent with studies showing that medium-sized planktonic organisms are generally more susceptible to physical and UV-based treatments (Peperzak, 2023). Additionally, a significant indirect effect was detected from F1 to the 10–50  $\mu\text{m}$  group via F2 ( $\beta = -0.128$ ,  $p = 0.017$ ), implying that larger vessels can indirectly reduce the abundance of these organisms by virtue of having more powerful treatment systems.

No significant indirect effect was found for  $\geq 50$   $\mu\text{m}$  organisms, reinforcing the conclusion that current UV-based systems are less effective for larger planktonic organism groups. Given the ecological importance of the 10–50  $\mu\text{m}$  group—which includes numerous organism groups with high invasive potential (Peperzak et al., 2024)—the indirect pathway from F1 through F2 to biological reduction highlights the role of vessel design and capacity optimization in enhancing ballast water management effectiveness. This finding also supports the continued refinement of IMO D-2 compliance strategies (IMO, 2004, 2019) to ensure effective management across all organism size classes.

## CONCLUSION

This study applied structural equation modeling to examine how vessel structural features (F1: gross tonnage, length, width) and operational treatment parameters (F2: rated capacity, flow rate, total volume, retention time) influence the effectiveness of ballast water treatment systems in reducing viable organism concentrations in the  $\geq 50$   $\mu\text{m}$  and 10–50  $\mu\text{m}$  size classes. Larger vessels generally operate higher-capacity systems, with varying effectiveness across organism size classes.

By combining vessel-level and operational parameters in a single analytical framework, and grounding the analysis in real-world operational data collected from ships, this research offers a more integrated and practice-oriented perspective than many previous studies, which often examine treatment technologies under controlled or experimental conditions without accounting for ship-specific factors. This approach provides new insights into the operational realities of ballast water management and emphasizes the need to match treatment strategies to both vessel characteristics and target organism size classes.

The predominance of UV-based systems may limit effectiveness against larger organisms, highlighting the need for complementary treatment methods. These constraints suggest that the observed patterns may vary under different technological or environmental contexts. Addressing these limitations presents opportunities for future work: incorporating a wider range of treatment methods, collecting data across diverse seasons and uptake environments, and including long-term operational monitoring could yield a more comprehensive understanding of system performance.

Such expanded datasets would also allow for the evaluation of hybrid or multi-stage treatment approaches, which may be necessary to achieve consistent reductions in  $\geq 50$   $\mu\text{m}$  organisms. Moreover, integrating real-time monitoring technologies with adaptive operational controls could help optimize parameters such as flow rate and total tank volume, improving system responsiveness to varying biological loads.

By linking its recommendations directly to the study's constraints, this work highlights

specific pathways for advancing ballast water treatment effectiveness. The findings support the development of vessel-specific strategies and technology upgrades that not only meet the IMO D-2 standard but also contribute to the long-term protection of marine ecosystems against invasive species.

## ACKNOWLEDGMENT

This study is a part of the Doctoral Thesis titled “Evaluation of operational risks and treatment performance in ship ballast water treatment systems” of Ülkü Demirci, which is being prepared at the institute of graduate studies, maritime transportation engineering program, from İskenderun Technical University. Additionally, the authors would like to express their sincere gratitude to “Kent Asbest” for providing access to ballast water analysis reports, including organism concentration data from 59 different vessels, which formed the basis of this study.

## GRANT SUPPORT DETAILS

The present research did not receive any financial support.

## CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

## LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

## REFERENCES

- Bailey, S. A., Brydges, T., Casas-Monroy, O., Kydd, J., Linley, R. D., Rozon, R. M., & Darling, J. A. (2022). First evaluation of ballast water management systems on operational ships for minimizing introductions of nonindigenous zooplankton. *Marine Pollution Bulletin*, 182; 2022, 113947.
- Bradie, J., Gianoli, C., He, J., Curto, A. L., Stehouwer, P., Veldhuis, M., & Bailey, S. (2018). Detection of UV-treatment effects on plankton by rapid analytic tools for ballast water compliance monitoring immediately following treatment. *Journal of Sea Research*, 133; 177-184.
- Chen, Y., Xue, J., Feng, W., Du, J., and Wu, H. (2023). Bloom forming species transported by ballast water under the management of D-1 and D-2 standards—Implications for current ballast water regulations. *Marine Pollution Bulletin*, 189; 115391.
- Civelek, M. E. (2018). Essentials of structural equation modeling. Zea E-Books. 64.
- Doğru, M., Demirci, S. M. E., Canımoğlu, R., & Elçiçek, H. (2021). An overview of environmental impacts and treatment systems of ship ballast waters. *Journal of Marine and Engineering Technology*, 1(1); 13-23.
- Fan, Y., Chen, J., & Shirkey, G., (2016). Applications of structural equation modeling (SEM) in ecological studies: an updated review. *Ecological Processes*, 5(19); 1-12.
- Feng, W., Chen, Y., Zhang, T., Xue, J., & Wu, H. (2023). Evaluate the compliance of ballast water management system on various types of operational vessels based on the D-2 standard. *Marine Pollution Bulletin*, 189; 115381.
- Fernandes, A., Ferreira, A., Sanches Fernandes, L., Cortes, R., & Pacheco, F. (2018). Path modelling analysis of pollution sources and environmental consequences in river basins. *WIT Transactions on Ecology and the Environment*, 228; 79–87.

- Finch, W. H., & French, B. F. (2015). *Latent variable modeling with R*. Routledge, New York.
- Güney, C. B. (2018). Ballast water management on ships according to the IMO Ballast Water Convention and current changes, *GIDB Journal*, 12; 21-36.
- IMO. (2004). International Convention for the Control and Management of Ships' Ballast Water and Sediments. International Maritime Organization, London, UK.
- IMO. (2008). Guidance on ballast water sampling (G2). Resolution MEPC.173(58). International Maritime Organization, London, UK.
- IMO. (2015). Guidance on ballast water sampling and analysis for trial use in accordance with the BWM Convention and Guidelines (G2). BWM.2/Circ.42/Rev.1. International Maritime Organization, London, UK.
- IMO. (2018). Code for approval of ballast water management systems (BWMS Code). MEPC.300(72). International Maritime Organization, London, UK.
- IMO. (2019). Revised guidance on ballast water sampling and analysis. PPR 7/INF.4. International Maritime Organization, London, UK.
- IMO. (2020). Guidance on ballast water sampling and analysis for trial use in accordance with the BWM Convention and Guidelines (G2). BWM.2/Circ.42/Rev.2. International Maritime Organization, London, UK.
- Kline, R. B. (2023). *Principles and practice of structural equation modeling*. Guilford publications.
- Larson, M. G. (2008). Analysis of variance. *Circulation*, 117(1); 115-121.
- Özdemir, Ü. (2023). A quantitative approach to the development of ballast water treatment systems in ships. *Ships and Offshore Structures*, 18(2); 177-192.
- Peperzak, L. (2023). The critical adenosine triphosphate (ATP) concentration in treated ballast water. *Marine Pollution Bulletin*, 187; 114506.
- Peperzak, L., Casas-Monroy, O., & Bailey, S. A. (2024). Validation of an adenosine triphosphate (ATP) model for 10–50 µm plankton. *Marine Pollution Bulletin*, 189; 116066.
- R Core Team (2022) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Saenz Alcantara, E. (2018). Comparative study of approved IMO technologies for treatment of ballast waters. Universitat Politècnica de Catalunya (Master's thesis).
- Satir, T. (2014). Ballast water treatment systems: design, regulations, and selection under the choice varying priorities. *Environmental Science and Pollution Research*, 21; 10686–10695.
- Sayinli, B., Dong, Y., Park, Y., Bhatnagar, A., & Sillanpää, M. (2022). Recent progress and challenges facing ballast water treatment—a review. *Chemosphere*, 291(2); 2022, 132776.
- Sergeeva, P. G., & Zaika, V. E. (1990). Feeding of *Mnemiopsis leidyi* in the Black Sea. *Ekologiya Morya*, 35; 18-22.
- Shiganova, T., Mirzoyan, Z., Studenikina, E., (2001). Population development of the invader ctenophore *Mnemiopsis leidyi*, in the Black Sea and in other seas of the Mediterranean basin. *Marine Biology*, 139; 431–445.
- The Jamovi Project (2025). *Jamovi (Version 2.4) [Computer Software]*. (Accessed 30 May 2025)
- Tsolaki, E., & Diamadopoulos, E. (2010). Technologies for ballast water treatment: a review. *Journal of Chemical Technology & Biotechnology*, 85(1); 19-32.
- Vural, G. & Yönsel, F. (2017). Application of key performance indicators (KPI) to the selection of ballast water treatment systems. *Gemi ve Deniz Teknolojisi*, (208); 5-30.
- Yazır, D., & Gedik, D. (2022). Selection of Ballast Water Treatment System for Ships with a Ballast Pumping Capacity of 500-1500 m<sup>3</sup>/h Using the Analytic Hierarchy Process and Fuzzy Analytic Hierarchy Process Methods. *Mersin University Journal of Maritime and Logistics Research*, 4(2); 129-162.