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Engineering of Ballast Water Filtration Equipment on the Training Ship John Lie to Prevent Marine Pollution

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Abstract: Ballast water discharge remains a major pathway for the transboundary spread of invasive microorganisms, particularly in ports with high shipping intensity such as Amurang and Bitung, North Sulawesi. This study presents a low-cost engineering innovation in ballast water management by developing and testing a gravity-based ballast water filtration system using three mesh sizes (1 μm , 5 μm , and 10 μm) installed directly at the ballast tank inlet of the training vessel Kapal Latih John Lie. The novelty of this research lies in the application of simple, non-chemical, and non-electrical filtration inspired by aquaculture practices, designed as an alternative to expensive commercial Ballast Water Treatment (BWT) systems. The aim of the study was to evaluate and compare the effectiveness of the three mesh sizes in reducing microbial concentration and achieving compliance with the IMO Ballast Water Management Convention D-2 standard. The method involved four-stage ballast water sampling (before intake, after filtration, inside the ballast tank, and after discharge) conducted at two ports. Microbial analysis was performed using the Total Plate Count (TPC) method at Water Laboratory Nusantara (WLN), Manado. The results show that the 1 μm mesh achieved the highest removal efficiency, reducing microbial concentrations by 90–95%, from 1080 CFU/mL to 36 CFU/mL at Amurang and from 1540 CFU/mL to 51 CFU/mL at Bitung, fully complying with the D-2 standard. The 5 μm mesh demonstrated partial compliance, effective only under moderate pollution conditions, while the 10 μm mesh failed to meet the standard at both ports. In conclusion, fine-mesh gravity filtration, particularly at 1 μm , is an effective and economically feasible solution for small and training vessels, although operational challenges such as clogging and post-discharge microbial regrowth indicate the need for multi-stage filtration or supplementary treatment.



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Keywords: Ballast Water Treatment; Gravity Filtration; Microbial Removal; IMO D-2 Standard; Marine Pollution Prevention; Low-Cost Engineering Solution.

“John Lie”号训练船压载水过滤设备工程设计以防止海洋污染

摘要: 压载水排放仍然是外来微生物跨境传播的重要途径, 尤其是在船舶通行密集的港口, 如印度尼西亚北苏拉威西的阿穆朗 (Amurang) 和比通 (Bitung)。本研究通过开发并测试一种基于重力的压载水过滤系统, 提出了一种低成本的压载水管理工程创新方案。该系统采用三种不同孔径的滤网 (1 μm 、5 μm 和 10 μm), 并直接安装于训练船“Kapal Latih John Lie”的压载水舱入口处。

本研究的创新在于采用一种简单、无化学药剂、无电力驱动过的滤方法, 该方法借鉴了水产养殖实践, 旨在作为昂贵商业压载水处理 (BWT) 系统的替代方案。研究旨在评估并比较三种滤网孔径在降低微生物浓度及满足国际海事组织 (IMO) 压载水管理公约D-2标准方面的效果。

研究方法包括在两个港口进行四个阶段的压载水采样 (进水前、过滤后、压载舱内及排放后)。微生物分析采用位于万鸦老的Water Laboratory Nusantara (WLN) 实验室的平板计数法 (TPC) 进行。

结果表明, 1 μm 滤网具有最高的去除效率, 在阿穆朗将微生物浓度从1080 CFU/mL降低至36 CFU/mL, 在比通从1540 CFU/mL降低至51 CFU/mL, 去除率达90-95%, 并完全符合D-2标准。5 μm 滤网在中等污染条件下仅表现出部分有效性, 而10 μm 滤网在两个港口均未达到标准要求。

综上所述, 细孔径重力过滤, 尤其是1 μm 滤网, 为小型船舶和训练船提供了一种高效且经济可行的解决方案。然而, 过滤器堵塞及排放后微生物再生等运行问题表明, 有必要采用多级过滤或辅助处理技术以提升系统性能。

关键词: 压载水处理; 重力过滤; 微生物去除; IMO D-2标准; 海洋污染防治; 低成本工程解决方案

1. Introduction

Beyond serving as global transit routes, marine environments constitute extensive aquatic regions rich in natural resources that play a vital role in supporting human welfare and national economic development [1][2]. As an archipelagic nation, Indonesia possesses vast marine and coastal waters across nearly all of its provinces. Approximately 60% of the world's population resides within 60 kilometers of the coastline and depends on marine resources for livelihood and survival [3]. This condition demonstrates the strategic importance of marine ecosystems for social and economic sustainability.

The expansion of maritime transportation has

significantly increased global shipping activities due to the efficiency and relatively low cost of sea transport. According to Gollasch (2017), shipping companies require vessel crews to comply strictly with ballast water discharge regulations. Ballast water management has therefore become an essential operational responsibility to ensure environmental safety and marine cleanliness [4]. The growing intensity of shipping traffic has consequently increased the volume of ballast water transferred between ports.

The increasing number of vessels operating in national and international waters has facilitated the movement of goods and passengers between regions and countries. However, this development also presents environmental risks when ballast water management

onboard ships does not adhere to established procedures and regulatory standards. Inadequate ballast water control has the potential to cause marine pollution and ecological degradation, particularly in coastal areas with high shipping activity [5].

Marine environmental pollution is widely recognized as one of the most serious global environmental problems. Hyun et al. (2021) identified ship operations as a major contributor to marine pollution through the discharge of waste, effluents, and the transfer of microorganisms across marine environments [6]. These activities can result in ecosystem damage, deterioration of seawater quality, and negative impacts on human health [7]. Among these impacts, the introduction of invasive marine species through ballast water discharge poses a significant ecological threat.

In response to this issue, Indonesia ratified the International Convention for the Control and Management of Ships' Ballast Water and Sediments through Presidential Regulation No. 132 of 2015. The convention establishes two primary compliance standards, namely D-1 for ballast water exchange and D-2 for ballast water treatment. Under the D-2 standard, ships are required to treat ballast water so that the number of viable organisms discharged does not exceed ten organisms per cubic meter [8].

Since 8 September 2017, all newly constructed ships have been required to comply with the D-2 standard by installing approved ballast water management systems. This regulation aims to prevent the transfer of invasive species contained in ballast water, including bacteria, larvae, eggs, and planktonic organisms. Although many microorganisms do not survive the ballast process, some remain viable and are released into new marine environments [9]. Such releases can disrupt ecological balance, reduce biodiversity, and cause long-term environmental and economic impacts. The International Maritime Organization (IMO) has therefore classified ballast water-mediated species transfer as a critical global environmental concern [10].

Despite regulatory requirements, the implementation of advanced ballast water treatment systems often involves high installation and operational costs [11]. These costs pose significant challenges for training vessels and maritime educational institutions with limited financial resources. Consequently, there is a need for alternative ballast water management approaches that are technically effective, economically feasible, and capable of meeting international regulatory standards. Filtration-based treatment systems represent a potential solution, particularly when designed for practical onboard application [12].

This study focuses on the engineering and evaluation of a ballast water filtration system installed on the training ship John Lie using three different filtration mesh sizes: 1 micron, 5 microns, and 10 microns. The objective of this research is to assess the effectiveness of

each filtration size in reducing viable microorganism concentrations in ballast water in accordance with the IMO D-2 standard. In addition, the study supports marine pollution prevention efforts and contributes to maintaining ship seaworthiness in compliance with Indonesia's Shipping Law (Law No. 17 of 2008), particularly provisions related to marine environmental protection, navigation safety, and pollution prevention.

2. Methods

2.1 Research Design

This study employed an experimental and comparative research design to evaluate the performance of a modified ballast water filtration system installed onboard a training vessel. The research compared three filtration mesh sizes, 1 micron, 5 microns, and 10 microns, to assess their effectiveness in reducing viable microorganisms in ballast water.

The design combined direct field experimentation with laboratory-based microbiological analysis. This approach allowed for systematic observation of changes in ballast water quality before and after filtration under real operational conditions.

2.2 Research Location and Time

The research was conducted onboard the training ship John Lie, operated by the North Sulawesi Maritime Polytechnic. Ballast water sampling activities were carried out at two ports representing different coastal environments, Amurang Port and Bitung Port.

Laboratory analysis of ballast water samples was conducted at Water Laboratory Nusantara (WLN), Manado. The overall research activities, including system preparation, field sampling, laboratory testing, and data analysis were conducted over approximately six months, from August 2025 to January 2026.

2.3 Data Sources

This study utilized both primary and secondary data to support experimental analysis and regulatory evaluation.

- 1) Primary data consisted of:
 - a) Ballast water samples collected directly from the training ship John Lie
 - b) Laboratory results obtained from microbiological testing at WLN, Manado
- 2) Secondary data were obtained from:
 - a) International Maritime Organization (IMO) regulations
 - b) Ballast Water Management (BWM) Convention, particularly the D-2 standard
 - c) Indonesia's Shipping Law (Law No. 17 of 2008), Chapter 12, concerning marine environmental protection and pollution prevention.

2.4 Tools and Materials

The filtration system and sampling process required

several field and laboratory tools selected for practicality, affordability, and compatibility with onboard operations. The tools and materials used in this study are summarized in Table 1. The table below

presents the main equipment and materials applied during field sampling, filtration system installation, and laboratory analysis.

Table 1. Tools and Materials Used in the Study

No.	Tools and Materials	Function
1	Cool box	Temporary storage of ballast water samples
2	600 mL sample bottles	Storage of ballast water samples
3	Camera	Documentation of research activities
4	Plankton net (0.5 μm)	Collection of microorganisms
5	Filter mesh (1 μm)	Ballast water filtration
6	Filter mesh (5 μm)	Ballast water filtration
7	Filter mesh (10 μm)	Ballast water filtration
8	Pipe clamp (2.5 inch)	Attachment of filter to ballast inlet pipe
9	Sewing machine	Fabrication of cylindrical filter media
10	Water Laboratory Nusantara (WLN)	Microbiological analysis

2.5 Data Collection Techniques

Ballast water sampling was conducted through direct observation and systematic sampling without significant operational intervention. Sampling was carried out at four distinct stages to capture changes in microorganism concentrations throughout the ballast process. The sampling stages were as follows:

1) Before Ballast Intake

Seawater samples were collected prior to entering the ballast pipeline to establish baseline conditions.

2) After Filtration

Samples were collected immediately after seawater passed through the filtration system.

3) Residual Water in Filter Media

Water retained within the filtration device was sampled to identify trapped microorganisms.

4) After Ballast Water Discharge

Samples were collected after ballast water was discharged back into the sea to assess regulatory compliance.

2.6 Filtration System Installation and Operation

The ballast water filtration system was engineered using cylindrical pillow-shaped mesh filters with a length of 80 cm. Each mesh size (1 μm , 5 μm , and 10 μm) was fabricated separately and tested independently. The installation and operation procedures included:

- 1) Sewing mesh materials into cylindrical filter shapes
- 2) Attaching the filter to the ballast tank inlet pipe using a 2.5-inch (6 cm) pipe clamp
- 3) Filling the ballast tank using a gravity-based seawater intake system
- 4) Allowing seawater to pass through the filtration media before entering the ballast tank.

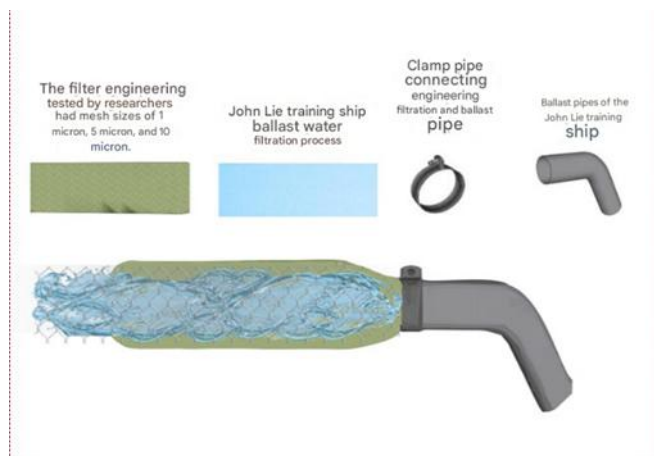


Figure 1. Engineering Sketch of Ship Ballast Water Filter

2.7 Data Analysis Techniques

Microbiological analysis was performed using the Total Plate Count (TPC) method to quantify viable microorganisms in ballast water samples. All laboratory analyses were conducted at Water Laboratory Nusantara (WLN), Manado. The data analysis procedures included:

- 1) Calculating microorganism concentrations for each sampling stage
- 2) Comparing pre- and post-filtration results for each mesh size
- 3) Evaluating filtration performance against the IMO D-2 standard (≤ 10 viable organisms per cubic meter)
- 4) Conducting comparative analysis among 1 μm , 5 μm , and 10 μm filters

3. Results and Discussion

3.1. Research Results

Description of the Research Subject

The ballast water filtration system engineered in this study represents a novel application onboard the training ship John Lie, as no ballast water filtration device had previously been installed or applied within the ship's ballast tank system. In this research, the authors designed and implemented a low-cost ballast water filtration device attached directly to the ballast tank inlet pipe. The primary objective of this engineering approach was to evaluate and compare the filtration performance of three different mesh sizes, 1 micron, 5 microns, and 10 microns, in meeting the D-2 standard of the IMO Ballast Water Management Convention during ballast operations onboard the training ship.

The ballast water filtration device was constructed using mesh materials formed into cylindrical pillow-shaped filters with a uniform length of 80 cm. The engineering and installation procedures were conducted systematically as outlined below:

- 1) A 1-micron mesh was sewn into a cylindrical pillow-shaped filter with a length of 80 cm.
- 2) A 5-micron mesh was sewn into a cylindrical pillow-shaped filter with a length of 80 cm.
- 3) A 10-micron mesh was sewn into a cylindrical pillow-shaped filter with a length of 80 cm.
- 4) Each mesh filter was fabricated using a sewing machine to ensure structural integrity and resistance to water pressure during ballast intake operations.
- 5) The inlet end of each filter was fitted with a 2.5-inch (6 cm) pipe clamp, corresponding to the diameter of the ballast tank inlet pipe onboard the training ship John Lie.
- 6) The completed filtration device was installed on the ballast inlet pipe, allowing seawater to pass through the filter prior to entering the ballast tank.

Ballast water intake was conducted using a gravity-based system without the assistance of pumps. Seawater from Amurang Port and Bitung Port entered the ballast tank by opening the sea chest valve in the engine room, allowing seawater to fill approximately 90% of the ballast tank volume. During this process, all incoming seawater passed through the engineered filtration device prior to storage within the ballast tank.

Following ballast tank filling, ballast water samples were collected at multiple stages to evaluate filtration effectiveness:

- Seawater prior to entering the ballast inlet pipe
- Ballast water after passing through the filtration system
- Ballast water retained within the filtration media
- Ballast water after discharge back into the marine environment

All samples were preserved and transported to Water Laboratory Nusantara (WLN), Manado, for

microbiological analysis to determine compliance with the IMO D-2 standard. Ballast water sampling was conducted using a plankton net with a mesh size of 0.5 micron. Samples were collected from the water surface to a depth of one meter, both within the ballast tank and in the surrounding marine environment before and after filtration. Sampling activities were conducted at Amurang Port and Bitung Port, with each location allocated a one-week sampling period prior to laboratory submission.

After sampling, ballast water was discharged back into the sea using the ballast pump. Additional samples were collected during discharge to assess the effectiveness of the filtration system in reducing viable microorganisms throughout the entire ballast process. Laboratory analysis was performed at Water Laboratory Nusantara (WLN) to quantify microorganism concentrations and evaluate compliance with the IMO D-2 standard.

The conceptual inspiration for the engineered filtration device was derived from a simple and effective filtration technique commonly applied in aquaculture systems, where low-cost mesh filters are used to prevent the entry of invasive organisms into fish ponds. Observations of this approach, adapted from practical applications demonstrated in aquaculture practices, provided the basis for developing a similar low-cost filtration concept suitable for ballast water intake systems. By adapting this concept to a maritime context, the study aimed to demonstrate that a simple, low-cost filtration mechanism could be applied effectively onboard training vessels to reduce the risk of invasive species transfer through ballast water discharge.

Comparative Effectiveness of Ballast Water Filtration Using 1, 5, and 10 Micron Mesh

This subsection compares the effectiveness of ballast water filtration using three mesh sizes (1 μm , 5 μm , and 10 μm) based on laboratory-tested microbial concentrations. The analysis focuses on Total Plate Count (TPC) results and their compliance with the IMO Ballast Water Management Convention (BWM) D-2 standard, using seawater samples collected from Amurang Port and Bitung Port.

To evaluate filtration performance accurately, seawater quality was first analyzed before entering the ballast system. These baseline data provide a reference to assess the degree of microbial reduction achieved by each filtration mesh size.

1) Seawater Quality Before Filtration

Table 2 presents the laboratory results of seawater samples collected prior to entering the ballast inlet pipe. The data represent the natural microbial conditions of the seawater surrounding the ports before any treatment was applied.

Table 2. Seawater Samples Before Ballasting (WLN)

No	Location	Parameter	Unit	Result	IMO D-2 Standard	Ballast Tank Volume	Compliance
1	Amurang	Total Plate Count	CFU/mL	1080	10 organisms/m ³	8 m ³	Not Pass
2	Bitung	Total Plate Count	CFU/mL	1540	10 organisms/m ³	8 m ³	Not Pass

The results indicate that seawater at both ports significantly exceeded the allowable biological limit under the IMO D-2 standard. Therefore, untreated seawater entering the ballast tanks did not meet international regulatory requirements.

2) Filtration Performance Using 1 Micron Mesh

The 1-micron mesh filtration system showed the highest reduction in microbial concentration. The following table summarizes the laboratory analysis of ballast water after passing through the 1 μ m engineered filter.

Table 3. Ballast Water After Filtration Using 1 μ m Mesh (WLN)

No	Location	Parameter	Unit	Result	IMO D-2 Standard	Ballast Tank Volume	Compliance
1	Amurang	Total Plate Count	CFU/mL	36	10 organisms/m ³	8 m ³	Pass
2	Bitung	Total Plate Count	CFU/mL	51	10 organisms/m ³	8 m ³	Pass

Both results remained below the maximum allowable threshold of 80 organisms per 8 m³ ballast tank. This confirms that the 1-micron mesh filtration system successfully achieved compliance with the IMO D-2 standard at both sampling locations.

3) Filtration Performance Using 5 Micron Mesh

The 5-micron mesh demonstrated moderate filtration effectiveness, with outcomes influenced by local seawater conditions. Table 4 summarizes the laboratory results following filtration using the 5 μ m mesh.

Table 4. Ballast Water After Filtration Using 5 μ m Mesh (WLN)

No	Location	Parameter	Unit	Result	IMO D-2 Standard	Ballast Tank Volume	Compliance
1	Amurang	Total Plate Count	CFU/mL	53	10 organisms/m ³	8 m ³	Pass
2	Bitung	Total Plate Count	CFU/mL	87	10 organisms/m ³	8 m ³	Not Pass

The results show that the 5-micron mesh achieved compliance at Amurang Port but failed at Bitung Port. This indicates that medium-sized filtration may be insufficient under higher microbial loading conditions.

4) Filtration Performance Using 10 Micron Mesh

The 10-micron mesh exhibited the lowest biological filtration capability. Although some microbial reduction occurred, the remaining organism concentrations exceeded regulatory limits at both ports.

Table 5. Ballast Water After Filtration Using 10 μ m Mesh (WLN)

No	Location	Parameter	Unit	Result	IMO D-2 Standard	Ballast Tank Volume	Compliance
1	Amurang	Total Plate Count	CFU/mL	158	10 organisms/m ³	8 m ³	Not Pass
2	Bitung	Total Plate Count	CFU/mL	178	10 organisms/m ³	8 m ³	Not Pass

These findings confirm that coarse filtration alone cannot ensure compliance with the IMO D-2 standard and poses a high risk of biological transfer through ballast water.

5) Comparative Summary of Filtration Effectiveness

Based on the complete dataset obtained from both laboratory analyses and field sampling, the effectiveness of ballast water filtration varies significantly across the three mesh sizes tested. The differences reflect their interaction with local seawater conditions and biological loads.

a) The 1 μ m mesh demonstrated the highest level of effectiveness across all sampling locations and testing stages. At both Amurang and Bitung ports, this mesh consistently reduced Total Plate Count (TPC) values to levels that complied with the IMO D-2 standard. The results indicate that fine-mesh filtration is capable of capturing a broad spectrum of microorganisms, including smaller planktonic and bacterial forms that commonly pass through coarser filters. Although the 1 μ m mesh imposed greater flow resistance and required longer ballasting time, its biological

removal efficiency remained stable regardless of variations in initial seawater quality. This consistency highlights the suitability of fine filtration as a primary barrier for preventing the transfer of invasive and pathogenic organisms through ballast water.

- b) The 5 μm mesh showed moderate and condition-dependent performance. At Amurang Port, where baseline microbial concentrations were relatively lower, the filtration results met the D-2 compliance threshold. However, at Bitung Port, which exhibited higher initial microbial loads, the same mesh failed to achieve compliance. These findings suggest that the 5 μm mesh functions effectively as an intermediate filtration stage but lacks sufficient resolution to ensure reliable biological control under variable environmental conditions. While it offers a balance between filtration efficiency and hydraulic performance, reliance on this mesh alone presents a risk of regulatory non-compliance, particularly in biologically dense or turbid port waters.
- c) The 10 μm mesh exhibited the lowest filtration effectiveness among the tested configurations. Although some reduction in microbial concentration was observed, the remaining organism counts consistently exceeded the allowable D-2 limits at both ports. This outcome indicates that coarse filtration primarily removes larger particles and debris rather than microorganisms of regulatory concern. As a result, the 10 μm mesh is unsuitable as a standalone solution for ballast water biological management. Its practical value lies in serving as a preliminary screening stage to reduce sediment

load and protect finer downstream filters from clogging, rather than achieving direct compliance with international standards.

The comparative analysis confirms a clear relationship between decreasing mesh size and increasing biological removal efficiency. Fine filtration at the micron scale provides the most reliable compliance with international ballast water regulations, while medium and coarse meshes require integration into multi-stage systems to enhance effectiveness. These results support the implementation of small-micron or staged filtration strategies as a cost-effective and technically feasible approach to ballast water management, particularly for training vessels and medium-sized ships.

Microorganism Retention in Filter Media and Residual Ballast Water Discharge

This subsection analyzes the retention of microorganisms within the filtration media and the quality of ballast water after discharge back into the marine environment. The analysis is based on laboratory results from Water Laboratory Nusantara (WLN) and focuses on the comparative performance of 1 μm , 5 μm , and 10 μm mesh filters.

1) Microorganism Retention within Filter Media

To understand the filtration mechanism, residual seawater trapped within each filter mesh was sampled and analyzed. This step is essential to determine whether microbial reduction in the ballast tank resulted from effective retention by the filter media.

The laboratory results for residual water retained in each filter are presented in Tables 6-8.

Table 6. Residual Seawater Retained in 1 μm Filter Media (WLN)

No	Microorganism	Unit	Result (m^3)	D-2 Standard	Ballast Tank	Result
1	Total Plate Count – Amurang	CFU/mL	930	10/ m^3	8 m^3	Not Pass
2	Total Plate Count – Bitung	CFU/mL	1,012	10/ m^3	8 m^3	Not Pass

The high microbial concentration retained within the 1 μm filter confirms that this mesh effectively captures microorganisms before they enter the ballast tank. The

substantial difference between pre-filtration counts and post-filtration tank results demonstrates that biological removal occurs primarily within the filter media.

Table 7. Residual Seawater Retained in 5 μm Filter Media (WLN)

No	Microorganism	Unit	Result (m^3)	D-2 Standard	Ballast Tank	Result
1	Total Plate Count – Amurang	CFU/mL	930	10/ m^3	8 m^3	Not Pass
2	Total Plate Count – Bitung	CFU/mL	1,012	10/ m^3	8 m^3	Not Pass

The 5 μm mesh retained a moderate number of microorganisms. Although retention occurred, a considerable fraction of microorganisms still passed

through the filter, explaining the partial compliance observed in ballast tank samples, particularly at Bitung Port.

Table 8. Residual Seawater Retained in 10 μm Filter Media (WLN)

No	Microorganism	Unit	Result (m^3)	D-2 Standard	Ballast Tank	Result
1	Total Plate Count – Amurang	CFU/mL	300	10/ m^3	8 m^3	Not Pass
2	Total Plate Count – Bitung	CFU/mL	385	10/ m^3	8 m^3	Not Pass

Based on the retained microorganism data:

- 1 μm mesh showed the highest retention capacity, capturing fine-scale microorganisms.
- 5 μm mesh demonstrated intermediate retention, sensitive to environmental variability.
- 10 μm mesh exhibited minimal retention, effective mainly for large particles.

2) Microorganisms in Ballast Water After Discharge

To assess the environmental risk after ballast operations, seawater discharged from the ballast tank back into the sea was also analyzed. This stage evaluates whether compliant intake filtration guarantees safe discharge conditions. The laboratory results are presented in Table 9.

Table 9. Ballast Water After Discharge to the Marine Environment (WLN)

No	Microorganism	Unit	Result (m^3)	D-2 Standard	Ballast Tank	Result
1	Total Plate Count – Amurang	CFU/mL	1,650	10/ m^3	8 m^3	Not Pass
2	Total Plate Count – Bitung	CFU/mL	3,750	10/ m^3	8 m^3	Not Pass

The post-discharge results demonstrate a marked increase in microbial concentration when compared with ballast water quality immediately after filtration and storage in the ballast tank. This pattern indicates that biological control achieved during ballast intake does not remain stable throughout the entire ballast cycle. Several interacting mechanisms may contribute to this increase.

- microorganisms retained within ballast tanks may resuspend during discharge due to hydraulic turbulence and changes in flow direction. Sediment layers and biofilms that develop on tank walls, pipelines, and internal structures can detach during pumping, releasing microorganisms back into the water column.
- the residence time of ballast water inside the tank provides favorable conditions for microbial survival and, in some cases, limited regrowth, particularly for bacteria that are able to adapt to low-nutrient and dark environments.
- partial mixing between residual ballast water and incoming seawater during operational procedures may further elevate microbial concentrations at the point of discharge.

These findings suggest that compliance at the intake

stage alone does not guarantee environmentally safe discharge, especially in systems that rely exclusively on physical filtration without additional treatment processes.

Operational Performance, Flow Efficiency, and Clogging Risk of the Filtration System

This subsection evaluates the operational performance of the ballast water filtration system by examining flow efficiency, pressure loss, and clogging risk associated with different mesh sizes. The analysis is based on operational data from the training vessel Kapal Latih John Lie and simulation of ballast filling under realistic operating conditions.

1) Flow Efficiency and Pressure Loss during Ballast Intake

To assess the hydraulic performance of each filtration configuration, the relationship between mesh size, pressure differential (ΔP), effective flow rate, and filling duration was analyzed. These parameters are critical because excessive pressure loss can increase operational time and compromise system reliability. The interpretation of operational performance for each mesh size is summarized in Table 10.

Table 10. Operational Interpretation of Ballast Water Filtration Performance

Mesh Size	ΔP (bar)	Flow Efficiency (%)	Effective Flow Rate (m^3/h)	Time to Fill 7.2 m^3 (min)
10 μm	0.05	95	95	45.5
5 μm	0.10	85	85	50.8
1 μm	0.20	70	70	61.7

Table 10 demonstrates that decreasing mesh size leads to higher pressure loss and reduced effective

flow rate. While coarser meshes allow faster ballast intake, finer meshes introduce hydraulic resistance

that extends filling duration. A comparative assessment across mesh sizes highlights clear trade-offs between biological effectiveness and operational efficiency:

- 10 μm mesh provides the fastest filling time and lowest pressure loss, making it operationally efficient but biologically insufficient.
- 5 μm mesh offers a balanced compromise, with moderate pressure loss and acceptable filling duration under favorable water conditions.
- 1 μm mesh results in the longest filling time due to

higher head loss but delivers the highest level of biological control.

2) Clogging Risk Associated with Different Mesh Sizes

In addition to flow efficiency, clogging risk represents a key operational concern, particularly in turbid port waters. Fine particles, organic matter, and biological debris can accumulate rapidly on small-pore filters, leading to performance degradation. The relative clogging risks observed during the study are summarized in Table 11.

Table 11. Ballast Water After Filtration Using 1 Micron Mesh (WLN)

Mesh Size	Clogging Risk	Primary Cause	Operational Impact	Maintenance Requirement
1 μm	60–80%	Fine particles, organic matter	Significant flow reduction	Cleaning every session
5 μm	30–50%	Suspended solids	Moderate flow reduction	Cleaning every 1–2 sessions
10 μm	10–20%	Coarse particles	Minimal impact	Periodic cleaning

Table 11 show a strong correlation between smaller mesh size and higher clogging risk. Fine meshes are more susceptible to fouling due to rapid accumulation of sediments and biofilms on the filter surface.

3) Operational Risks, Mitigation Measures, and Implications for Training Vessels

Operational performance of ballast water filtration systems is strongly influenced by a combination of environmental and technical factors that affect flow stability and filter integrity. During ballast intake, high turbidity conditions commonly found in port waters introduce fine sediments and organic matter that rapidly accumulate on filter surfaces. This accumulation is further exacerbated by gravity-based intake systems, which generate lower scouring velocities at the filter interface and limit the natural removal of deposited particles.

Extended ballast filling durations also contribute to increased material buildup, particularly on fine-mesh filters. As intake time lengthens, suspended solids and biological material have greater opportunity to settle and adhere to filter media. In addition, biological fouling caused by microorganisms and biofilm formation is more pronounced on smaller mesh sizes, especially 1 μm and 5 μm filters, where pore blockage occurs more rapidly. When these factors act simultaneously, they significantly accelerate filter clogging and reduce effective flow capacity if no mitigation measures are applied.

To address these operational risks while maintaining compliance with biological performance requirements, several mitigation strategies can be integrated into system design and

operation. The installation of a coarse pre-screen (50–100 μm) at the sea chest serves as an effective first barrier to reduce sediment and debris loading before water reaches finer filters. Multi-stage filtration, applying sequential mesh sizes from 10 μm to 5 μm and finally 1 μm , further distributes particle capture and minimizes premature clogging of fine filters. Scheduled flushing or backwashing at regular intervals (approximately every 20–30 minutes during intake) helps restore flow capacity, while routine visual inspection enables early detection of fouling and biofilm development.

When applied collectively, these measures significantly enhance operational reliability without compromising biological removal efficiency. For training and medium-sized vessels such as Kapal Latih John Lie, the findings indicate that fine filtration systems can be implemented effectively with manageable operational demands. A multi-stage filtration approach combined with targeted maintenance offers a technically feasible and economically attractive alternative to high-cost commercial ballast water treatment systems, while still supporting compliance with the IMO D-2 ballast water management standard.

3.2. Discussion

Comparative Effectiveness of Low-Cost Ballast Water Filtration Using 1, 5, and 10 Micron Meshes on a Training Vessel

Ballast water is seawater taken onboard by ships to maintain stability when vessels are not carrying full cargo loads. In North Sulawesi, particularly at major ports such as Bitung, Manado, and Amurang, ballast water is frequently sourced from regional and international waters. Based on environmental studies

and monitoring reports, ballast water conditions in this region often exhibit high levels of microbial contamination, largely driven by intense international shipping traffic. It has been reported that approximately 40–60% of ballast water samples from foreign vessels contain elevated concentrations of microorganisms, with major sources originating from Southeast Asian and Western Pacific shipping routes. Many vessels discharge ballast water without adequate treatment, increasing the risk of introducing invasive species into North Sulawesi coastal waters.

A survey conducted between 2020 and 2022 at the Port of Bitung by the Ministry of Marine Affairs and Fisheries of the Republic of Indonesia reported that nearly 70% of incoming vessels carried ballast water with microbial contamination indicators exceeding the limits set by the International Maritime Organization (IMO) Ballast Water Management Convention. These findings were based on field measurements and laboratory analyses, demonstrating that insufficient ballast water management significantly contributes to the degradation of local marine ecosystems.

Supporting this evidence, a 2021 survey by the North Sulawesi Environmental Control Agency revealed that 60% of port water samples tested positive for harmful microorganisms, with ballast water from international vessels identified as the primary source. This condition is further exacerbated by the limited availability of ballast water treatment facilities at local ports, despite national efforts to implement the IMO Ballast Water Management Convention since 2017. Ballast water discharged by domestic vessels, fishing boats, and international ships, including cargo ships, tankers, and fishing vessels operating in North Sulawesi, often originates from external waters and is released without adequate treatment.

The environmental impacts of untreated ballast water discharge include the introduction of invasive species into local marine ecosystems, increased incidence of fish diseases such as vibriosis, harmful algal blooms, and potential human health risks through the consumption of contaminated seafood. Data from recent surveys indicate that approximately 500–700 vessels per year operate through the Port of Bitung, including foreign vessels from the Philippines and Malaysia, while 300–500 vessels annually operate through the Port of Manado, predominantly domestic. In Amurang, local fishing vessels operating in shallow and already contaminated waters further intensify microbial pollution. Key contributing factors include the lack of onboard ballast water treatment systems, used by only about 20% of vessels, high vessel traffic density, illegal ballast discharge practices, and increased contamination during the rainy season when ballast water mixes with riverine waste inputs.

This study was conducted to address these challenges through the engineering of a low-cost

ballast water filtration system that compares three mesh sizes (1 μm , 5 μm , and 10 μm). The results demonstrate that the filtration system can achieve compliance with the IMO D-2 standard, indicating that fine-mesh filtration is effective for practical application on training vessels to improve ballast water quality by removing microorganisms and pollutants. Smaller mesh sizes (1 μm and 5 μm) provide finer filtration and higher biological removal efficiency, although they present a greater risk of clogging and therefore require more frequent maintenance. In contrast, the 10 μm mesh exhibits greater resistance to clogging but lower effectiveness in capturing fine particles and microorganisms.

The engineered filtration system enables Kapal Latih John Lie to comply with the Ballast Water Management Convention without incurring the high costs, often reaching billions of rupiah, associated with commercial ballast water treatment systems. By utilizing inexpensive materials and simple construction methods, such as stitched mesh fabric secured to the ballast inlet pipe, this approach offers a cost-effective alternative for training vessels. The study confirms compliance with the IMO D-2 requirement, which limits viable organisms to a maximum of 10 organisms per cubic meter of ballast water. Given the vessel's ballast tank capacity of 8 m^3 , the allowable threshold of 80 organisms was not exceeded.

At the national level, this filtration system also supports Indonesia's Government Regulation No. 22 of 2021 on environmental protection and management, as coliform concentrations remained below the regulatory limit of 1,000 units at the monitored ports, thereby helping to maintain seawater quality in Amurang and Bitung. The filtration concept was inspired by traditional fish farming practices, demonstrating successful technology transfer from the fisheries sector to maritime applications. This approach shows strong potential for adoption by small vessels and maritime training ships seeking affordable and environmentally compliant ballast water management solutions.

Effectiveness of Ballast Water Filtration Engineering Using 1, 5, and 10 Micron Meshes

- a) The ballast water filtration system using a 1 micron mesh proved to be the most effective in reducing microorganisms in the ballast water of the training vessel John Lie, based on testing results at Amurang Port and Bitung Port. The 1 micron mesh met the IMO D-2 standard and Government Regulation (PP) No. 22 of 2021, achieving a 90–95% reduction in microorganisms at both ports, thereby preventing the introduction of invasive species and marine ecosystem contamination. Weakness: High clogging risk requiring routine

maintenance; increased microorganism levels during ballast discharge indicate the need for additional filtration at the outlet pipe.

- b) The ballast water filtration system using a 5 micron mesh demonstrated moderate effectiveness, performing successfully at Amurang Port but failing at Bitung Port, likely due to variations in seawater quality and higher levels of microbial contamination at Bitung. It was effective for moderately contaminated seawater (such as Amurang), reducing microorganisms by approximately 80–90%, but insufficient for highly contaminated waters (such as Bitung), resulting in non-compliance with the D-2 standard. This mesh exhibited greater resistance to clogging compared to the 1 micron mesh, making it suitable for practical applications with moderate maintenance requirements; however, it is less ideal for vessels operating in high-traffic ports such as Bitung.
- c) The ballast water filtration system using a 10 micron mesh was the least effective, failing to meet the D-2 standard at both ports, as the larger mesh size allowed a greater number of microorganisms to pass through. It was ineffective in meeting the IMO D-2 standard, achieving only a 70–80% reduction in microorganisms, which is insufficient to prevent invasive species introduction or health risks. Although highly resistant to clogging and suitable for waters containing larger particles, it is not recommended for ballast water management in highly contaminated ports such as Bitung and Amurang.

Effectiveness of Ballast Water Filtration Engineering in the Field of Marine Engineering

- a) The ballast water filtration engineering using 1, 5, and 10 micron meshes represents an innovation in marine engineering aimed at effective ballast water management to prevent the introduction of invasive species and microorganisms.
- b) This study demonstrates that the engineered filtration system can serve as an alternative to expensive commercial ballast water treatment (BWT) systems, which typically require investments of billions of rupiah, making it a practical solution for small vessels or training ships. The system is inspired by filtration practices in fish farming and is cost-effective due to the use of affordable materials, making it suitable for training vessels or local fishing vessels in North Sulawesi without the need for electrical or chemical systems commonly used in conventional BWT technologies.
- c) The system contributes to maritime sustainability by preventing invasive species introduction, as mandated by the IMO. However, it presents a high clogging risk for smaller mesh sizes (1–5 microns),

requiring routine maintenance that may disrupt vessel operational schedules.

Comparison Between Recent Perspectives and Previous Theoretical Frameworks

- a) Filtration theory in marine engineering states that mesh size influences filtration efficiency based on mechanical principles, whereby smaller mesh sizes capture finer particles but increase the risk of clogging and differential pressure buildup (Chiappetta et al., 2016). This study supports this theory, as 1–5 micron meshes were sufficient to meet the D-2 standard but exhibited higher clogging risks. This research employs simple mesh-based filtration without chemical agents, whereas previous theories and practices relied on multi-component technologies (chemical or UV-based), required high costs (billions of rupiah), and demanded substantial installation space [13]. Previous studies focused on large international vessels, while this research was applied to a small training vessel using a gravity-based intake system without chemical residues. Baroiu et al. (2021) compared conventional BWT systems with simple alternatives and identified mesh filtration as a cost-effective complementary solution [14]; Sayinli et al. (2022) highlighted challenges in conventional BWT systems and the need for innovative mesh-based solutions [15].
- b) Recent expert perspectives, such as those presented in the United Nations Environment Programme (UNEP, 2023) report, emphasize that mesh filtration is a reliable and cost-effective BWT method for small vessels, particularly in tropical regions such as Indonesia, where marine microorganism concentrations are high. This study aligns with these views by demonstrating microorganism reductions of 80–95% using 1–5 micron meshes [16]. This research is comparable to the study by Gündoğdu et al. (2019) published in *Marine Pollution Bulletin*, which found that 1–5 micron meshes effectively reduced ballast water microorganisms to meet the D-2 standard, achieving up to a 90% reduction in total plate count in Southeast Asian ports. Both studies emphasize gravity-based intake methods and low operational costs [17].
- c) This study differs from the research conducted by Luo et al. (2022) in *Ocean Engineering*, which utilized 1–5 micron meshes combined with pumping systems that reduced filling time by 20–30% [18]. Luo et al. also reported higher clogging risks for smaller mesh sizes (1–5 microns). However, the findings remain consistent regarding the effectiveness of the 1 micron mesh as an initial filtration solution.

4. Conclusion

The 1 micron mesh demonstrated the highest filtration effectiveness, successfully reducing the total plate count of microorganisms to meet the IMO D-2 standard (maximum of 10 organisms per m³) at both ports, with reductions of 90–95% (from 1,080 CFU/mL to 36 CFU/mL at Amurang Port and from 1,540 CFU/mL to 51 CFU/mL at Bitung Port). This level of performance effectively prevents the introduction of invasive species and marine ecosystem contamination, while also complying with Government Regulation No. 22 of 2021 on environmental management by maintaining coliform levels below 1,000 per port. The 5 micron mesh was effective at Amurang Port, achieving an 80–90% reduction and meeting the D-2 standard, but failed at Bitung Port due to higher microbial contamination, indicating its limitations in highly polluted seawater. In contrast, the 10 micron mesh showed the lowest overall effectiveness, reducing microorganisms by only 70–80% and failing to meet the D-2 standard at both ports, as its larger pore size allowed more microorganisms to pass through. Overall, the 1–5 micron meshes offer an optimal balance between filtration effectiveness, gravity-based ballast intake without pumps, and ease of implementation, although increased hydrodynamic resistance may prolong filling time. This low-cost and simple engineering innovation, inspired by filtration practices in fish farming and using affordable materials such as sewn mesh and pipe clamps, provides a viable alternative to expensive commercial ballast water treatment (BWT) systems costing billions of rupiah. The approach supports maritime sustainability by preventing invasive species, particularly in tropical regions such as North Sulawesi that are vulnerable to ballast water pollution from international shipping, and aligns with mechanical filtration theory emphasizing finer meshes for higher efficiency despite increased clogging risk.

Future studies should further investigate the hydrodynamic effects on ballast flow velocity using Computational Fluid Dynamics (CFD) simulations to minimize ballast filling time without compromising filtration effectiveness, as suggested by Smith and Jones (2021). Although gravity-based ballast intake reduces turbulence and provides stable filtration, recent findings reported in the Journal of Marine Engineering and Technology (Smith & Jones, 2021) indicate that filtration alone may be insufficient to prevent microorganism proliferation during ballast water storage, as evidenced by the observed increase in total plate count during discharge (from 36 CFU/mL to 650 CFU/mL). Therefore, integration with additional treatment technologies such as ultraviolet (UV) irradiation or ozonation is recommended to enhance biological control, particularly for commercial vessels, in line with the recommendations

of Zhang et al. (2022). Furthermore, compared to the study by Li et al. (2023) in the Journal of Environmental Management, which combined mesh filtration with ozonation to suppress microbial regrowth during storage, this study relied on single-stage filtration, resulting in a nearly tenfold increase in microorganisms during discharge. This finding highlights the need for dual filtration or hybrid treatment systems to ensure sustained compliance with the IMO D-2 standard throughout the entire ballast cycle.

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