International Journal of Sustainable Development and Planning
Vol. 20, No. 12, December, 2025, pp. 5205-5215
Journal homepage: http://iieta.org/journals/ijsdp

Sewage Treatment Model with Friendly Technology on Commercial Ships to Reduce Pollution

Kuncowati[1*], Intan Baroroh[2], Sugeng Marsudi[3], Daryanto[3], Rosario Riyan Putra Hellisa[1]

[1] Ship Operations Engineering Technology Study Program, Vocational Faculty of Shipping, Hang Tuah University, Surabaya 60111, Indonesia
[2] Department of Naval Architecture and Shipbuilding Engineering, Faculty of Engineering and Marine Sciences, Hang Tuah University, Surabaya 60111, Indonesia
[3] Ship Engineering Technology Study Program, Vocational Faculty of Shipping, Hang Tuah University, Surabaya 60111, Indonesia

Corresponding Author Email: kuncowati@hangtuah.ac.id

https://doi.org/10.18280/ijsdp.201215

Received: 16 September 2025
Revised: 25 November 2025
Accepted: 19 December 2025
Available online: 31 December 2025

Keywords:
sewage processing, Annex IV of MARPOL 1973/1978, marine pollution, commercial ships, environmentally friendly technology

ABSTRACT

Sewage disposal from ships, including fecal waste, urine, and medical waste, remains a critical maritime environmental issue. Improper discharge without adequate treatment contributes to marine pollution and violates Annex IV of MARPOL 1973/1978 regulations. In addition to its environmental impact, sewage treatment processes may expose crew members to disinfectants, potentially causing health and safety risks. This study aims to develop an analysis model for sewage treatment using environmentally friendly technology on commercial ships to minimize pollution. Quantitative approach using Structural Equation Modeling (SEM) analysis with SmartPLS software (SmartPLS-SEM). The results show that the implementation of Annex IV MARPOL 1973/1978, processing technology, and the application of occupational health and safety procedures significantly influence the effectiveness of sewage treatment systems, with a moderate effect of 60.1%. The model also shows a positive and significant indirect effect (0.092) of Annex IV implementation on environmentally friendly sewage treatment through crew safety and health. This model provides practical insights for improving shipborne sewage management and supports the development of safer, environmentally sustainable maritime transportation.

1. INTRODUCTION

Nowadays, the maritime industry is growing rapidly, both in terms of size, shape, and type of ship [1]. Marine pollution is caused by the impact of shipping, generating large waste with improper disposal [2]. The management of sewage sourced from ships is a critical problem due to the impact of unprocessed sewage [3]. An effective treatment system is essential for reducing pollution and complying with regulations. Sewage treatment can improve ship efficiency and support marine health [4]. The waste content of ships has an impact on the environment, organisms, and waste treatment methods used [5]. Sewage discharged into the sea from domestic vessels was detected to have ecological risks [6]. A waste discharge monitoring mechanism is needed to optimize monitoring [7].

MARPOL (Marine Pollution) annex IV 1973/1978, aims to ensure that sewage disposal from ships is treated first, and port authorities ensure safety management systems to comply with marine protection policies [8]. MARPOL regulations regulate the disposal of sewage from ships, requiring maintenance before being disposed of in designated areas [9]. Annex IV MARPOL1973/1978 defines sewage as waste from toilets, urinals, and waste from medical facilities. These regulations are essential for protecting marine ecosystems, but some ship operators dispose of untreated sewage [10]. In special areas, passenger ships are prohibited from disposing of marine waste, and ports must provide adequate facilities [11]. Crew training is important to ensure compliance with MARPOL regulations [12].

Environmentally friendly sewage treatment technology on ships refers to systems that comply with IMO Resolution MEPC.227(64), which regulates effluent standards for BOD, COD, TSS, coliform, and nutrient concentrations. Modern treatment units commonly integrate ultraviolet (UV) disinfection, biological treatment processes, or membrane bioreactor (MBR) systems that reduce the use of chemicals and minimize environmental impacts. These technologies are widely adopted because they meet international discharge requirements and enhance the safety of shipboard operations [5, 13].

Based on the opinion and results of previous research, the implementation of Annex IV of MARPOL 1973/1978, processing technology, and occupational health safety, is suspected to affect the processing of environmentally friendly sewage on commercial ships. So, the urgency of the research is important to prevent marine pollution from sewage sourced from ships because there is still sewage disposal without processing to reduce pollution, to support the safety of environmentally friendly sea transportation.

The formulation of the problem is that the development of the maritime industry has an impact on the environment [1]. Although there is an annex IV MARPOL regulation on the prevention of pollution from ship sewage, there is still sewage that is dumped into the sea without going through processing, and has an impact on pollution and the safety of crew health during its processing [10]. Therefore, an analysis model of sewage processing with environmentally friendly technology on commercial ships is needed to reduce pollution. The purpose of the research is to obtain an analysis model of sewage treatment with environmentally friendly technology on commercial ships to reduce pollution.

Previous research related to environmentally friendly sewage treatment [14], environmentally friendly waste, which is treated with advanced methods, has been applied to industry and cities. This is a gap in current research in the treatment of ship waste. Advanced treatment systems can purify vessel wastewater [15]. This technology is adopted on cruise ships, which becomes a loophole in the proposed research, so that this technology is also applied to all types of ships. However, most previous studies address general wastewater treatment without specifying compliance with IMO sewage effluent standards. This study defines environmentally friendly technology based on compliance with MEPC.227(64) using UV, MBR, or biological treatment systems, ensuring objectivity in assessing vessel sewage management.

Research related to the prevention of marine pollution conducted by the head of the research proposal showed that safety culture and work environment have an effect on waste separation on passenger ships [16]. The awareness of the community towards the environment is influenced by their knowledge of national and international regulations in preventing marine pollution [17]. Awareness and perception affect solid waste management on ships [18]. Implementation of the Garbage Management Plant on ships [19]. Solid waste processing has an impact on injuries. Waste management on commercial ships refers to regulations [20].

To prevent marine pollution in support of the sustainability of the maritime environment and the safety of environmentally friendly sea transportation, based on previous research [1, 14, 15, 18, 20]. There is a gap in developing research that not only solid waste and sewage treatment of cruise ships, but it is also important to develop a sewage treatment model with environmentally friendly technology applied to all ships.

The novelty of this study lies in the development of an environmentally friendly sewage treatment construct based on internationally recognized technical standards. Unlike previous studies that discussed general ‘green’ technologies, this study objectively defines environmentally friendly technology as shipboard sewage treatment systems that comply with MEPC.227(64) and utilize UV disinfection, biological processes, or membrane bioreactor (MBR) technology.

2. METHODOLOGY

The quantitative research method uses SEM analysis with SmartPLS software to obtain an analysis model of sewage treatment with environmentally friendly technology on commercial ships to reduce pollution based on the implementation of Annex IV MARPOL 1973/1978, the application of occupational health safety procedures, and sewage processing technology. SmartPLS-SEM was chosen because it is suitable for predictive and exploratory models, accommodates complex structural relationships, and does not require normally distributed data. The model estimation was conducted using the PLS algorithm with a path-weighting scheme. SmartPLS software was employed to run the analysis.

With the quantitative research method, the number of samples is determined based on the number of indicators in all research variables. The indicators of this study total 20 indicators, namely the implementation variables annex IV of MARPOL 1973/1978, amounting to 4 indicators, the variables of the implementation of occupational health safety procedures amounting to 4 indicators, the processing technology variables 4 indicators, the safety and health variables 4 indicators, and the variables of environmentally friendly sewage treatment amounting to 4 indicators. So the number of samples set for quantitative analysis of SmartPLS-SEM amounted to 150 crew members. he recommended sample size for SmartPLS-SEM ranges from 100 to 200, depending on the number of indicators and model complexity [21]. Samples were obtained by a random sampling method on the crew of commercial ships in Indonesian waters. The number of samples in this study is 150 ship crews, consisting of commercial ship crews, including passenger ship crews and cargo ship crews (general cargo ships, container ships, bulk carriers, tanker ships) in June, July, and August 2025.

This research consists of 5 research variables, consisting of exogenous variables, namely the implementation of annex IV of MARPOL 1973/1978, sewage processing technology, the application of occupational health safety procedures, and endogenous variables, including crew safety and health, and environmentally friendly sewage processing. The research questionnaire with scoring according to the Likert scale was distributed to 30 crew members first to be tested for validity and reliability with the IBM SPSS program. Statistics. These validity and reliability tests served as preliminary instrument screening, while the main validity and reliability assessments were conducted through the SmartPLS-SEM outer model analysis using outer loadings, composite reliability, rho_A, Average Variance Extracted (AVE), discriminant validity with three approaches, namely the Fornell-Larcker criteria, cross-loading, and Heterotrait-Monotrait ratio (HTMT).

Variables, indicators, and results of the validity test of research instruments are shown in Table 1.

Based on Table 1 of the results of the validity test of the research instrument, it can be explained that all variable indicators of sewage treatment research with environmentally friendly technology on commercial ships to reduce pollution obtained the results of the Pearson correlation value or r calculation ≥ r table. The number of respondents was 30 (N) with a table r value of 0.361, so that all indicators of the research instrument were declared valid because the Pearson correlation value or r was calculated ≥ r table and p value < 0.05. After the validity test of the research instrument was carried out, a reliability test was also carried out, the results of which are shown in Table 2. In the SmartPLS-SEM stage, reliability was further confirmed using composite reliability and rho_A, which are more appropriate for SmartPLS-SEM measurement models.

Table 1. Results of the validity test of sewage treatment research instruments with environmentally friendly technology on commercial ships to reduce pollution

Variables and Indicators	Research Instruments	Pearson Correlation	P-Value
X1: Implementation of Annex IV MARPOL 1973/1978			
X1.1 Regulatory compliance	The sewage treatment on the ship where I work is in accordance with the provisions of annex IV MARPOL 1973/1978 (The ship uses a sewage treatment system that has been inspected by the administration. Sewage that has not been decontaminated can be discharged at a distance of > 12 NM from the nearest land with a minimum ship speed of 4 knots. Sewage disposal > 3 NM from the nearest land for sewage that has been decontaminated with a minimum ship speed of 4 knots)	0.863	0.000
X1.2 Processing facilities	On the ship where I work, there is a sewage treatment facility in accordance with the provisions of MARPOL 1973/1978	0.920	0.000
X1.3 Port authority supervision	In the processing of sewage on the ship, it is supervised by the Port Authority	0.865	0.000
X1.4 Crew training	The crew of the ship has received training in sewage processing on the ship	0.916	0.000
X2: Sewage treatment technology			
X2.1 Ship size and type	Sewage treatment device technology according to the size and type of vessel	0.836	0.000
X2.2 Rules and regulations	The sewage processing technology on the ship where I work is in accordance with rules and regulations	0.849	0.000
X2.3 Technologies used	The sewage treatment on the ship where I work is highly dependent on the technology used	0.830	0.000
X2.4 Ship operating area	The sewage treatment technology used on the ship depends on the ship's operating area	0.792	0.000
X3: Implementation of occupational health safety procedures			
X3.1 Occupational health safety training	On the ship where I work, K3 training was carried out for sewage treatment on the ship	0.935	0.000
X3.2 Culture of occupational health equity	On the ship where I work, there is a very good K3 culture in sewage processing	0.933	0.000
X3.3 Occupational health safety equipment	In the sewage processing on the ship where I worked, the crew of the ship used K3 equipment	0.819	0.000
X3.4 Safe operating procedures	In the sewage treatment on the ship where I work, according to the safe operational procedures imposed on the ship	0.902	0.000
Y1: Crew safety and health			
Y1.1 Risk of work accidents in sewage processing	Sewage treatment on ships can pose a risk of accidents	0.751	0.000
Y1.2 Risk of exposure to disinfectant materials for crew	In sewage processing on ships, it can pose a risk of exposure to disinfectant materials to the crew	0.856	0.000
Y1.3 Risks of diseases arising	Sewage treatment on ships can cause a risk of disease	0.902	0.000
Y1.4 Ship hygiene and hygiene	The processing of sewage on the ship has an impact on the cleanliness and hygiene of the crew	0.850	0.000
Y2: Sewage treatment with environmentally friendly technology on commercial vessels to reduce pollution			
Y2.1 Sewage treatment free of environmentally harmful substances	Sewage treatment on the ship where I work uses sewage treatment technology that is free from the use of environmentally harmful materials	0.851	0.000
Y2.2 Disposal of sewage into the sea according to regulations	In sewage processing on the ship where I work, technology is used in accordance with regulations so that it is environmentally friendly	0.926	0.000
Y2.3 Environmental impact of sewage disposal	In sewage disposal on the ship where I work, technology is used to reduce the environmental impact of sewage disposal into the sea	0.843	0.000
Y2.4 Innovation in the use of processing technology	Innovation in the use of environmentally friendly sewage treatment technology is needed to reduce marine pollution by sewage sourced from ships	0.817	0.000

Source: Primary data, 2025

Table 2. Results of the reliability test of sewage treatment research instrument with environmentally friendly technology on commercial ships to reduce pollution

Variable	Cronbach's Alpha
Implementation of Annex IV of MARPOL 1973/1978	0.839
Sewage treatment technology	0.822
Implementation of occupational health safety procedures	0.841
Crew safety and health	0.826
Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution	0.831

Source: Primary data, 2025

Based on Table 2, it can be explained that all research variables obtained a Cronbach's Alpha value ≥ 0.70, so that it can be stated that the research instrument is declared reliable. After the research instrument was declared valid and reliable, it was then distributed to the research respondents of 150 merchant ship crews. The answers from the distribution of the questionnaire, which is a quantitative research instrument from 150 merchant ship crews, were then tabulated, including both the characteristics of the respondents, the characteristics of the ships where the respondents worked, to be analyzed with statistical descriptive methods in terms of frequency using the SPSS program. The characteristics of the 150 crew respondents can be shown in Table 3.

Of the 150 research respondents, all worked on commercial ships spread across 10 commercial ships. The characteristics of the commercial ship where the study was conducted, which included the name of the ship, type of ship, shipping area, deadweight ton (DWT), and the number of research respondents taken on the ship, are shown in Table 4.

Furthermore, data from 150 respondents were analyzed using SmartPLS-SEM. The indicators were scored according to the Likert scale, and then the outer and inner models were assessed. The outer model describes how each indicator relates to its latent variable using convergent validity (outer loadings > 0.70, composite reliability ≥ 0.70, rho_A ≥ 0.70, AVE > 0.50) and discriminant validity assessed through Fornell – Larcker criteria and HTMT ratios. The statistical significance of all outer and inner model parameters was evaluated using the bootstrapping procedure with 5,000 subsamples, as recommended in SmartPLS-SEM.

The inner model was evaluated using collinearity statistics (VIF < 5 indicates no multicollinearity), R-squared (0.25 = weak; 0.50–0.75 = moderate; >0.75 = strong), and hypothesis testing based on the significance of path coefficients. All p-values and t-statistics reported in the results section were generated from the SmartPLS bootstrapping procedure.

Table 3. The characteristics of respondents

No.	Respondent Characteristics	Category	Sum	Percentage (%)	Total
1.	Gender	Male	148	98.7	150 (100%)
		Female	2	1.3	
2	Age	20–30 years	67	44.7	150 (100%)
		30–40 years	48	32.0	
		> 40 years	35	23.3	
4	Sailing experience	< 5 years	43	28.7	150 (100%)
		5–10 years	59	39.3	
		> 10 years	48	32.0	
5	Onboard positions	Master	10	6.7	150 (100%)
		Deck Officer	34	22.7	
		Boatswain (Deck)	4	2.7	
		Quarter Master	18	12	
		Marine engineer	43	28.6	
		Boatswain (Engine)	6	4	
		Oiler	35	23.3	

Source: Primary data, 2025

Table 4. Boat characteristics

No.	Ship Name	Types of Vessels	Cruise Area	DWT	Number of Respondents
1	MV.MM	Container Ship	Domestic Voyage	> 10000	15
2	MV.LB	Container Ship	Domestic Voyage	< 5000	15
3	MT. AL	Tanker Ship	Domestic Voyage	< 5000	15
4	MV.EB	Passenger Ship	Domestic Voyage	< 5000	15
5	MV.AT	General Cargo Ship	Domestic Voyage	< 5000	15
6	MV.NGP	General Cargo Ship	Domestic Voyage	< 5000	15
7	MV.ET	General Cargo Ship	Domestic Voyage	< 5000	15
8	MV.SN	Passenger Ship	Domestic Voyage	< 5000	15
9	MV.NS	Bulk Carrier	Domestic Voyage	< 5000	15
10	MV.TS	General Cargo Ship	Domestic Voyage	< 5000	15

Source: Primary data, 2025

3. RESULTS

From the results of the distribution of questionnaires to 150 merchant ship crews, an outer model test was then carried out with SmartPLS-PLS analysis. The first outer model test was carried out by carrying out a validity test whose results were the validity test of variable indicators of sewage processing research with environmentally friendly technology on commercial ships to reduce pollution shown in Table 5.

Based on Table 5, it can be explained that the value of outer loadings of all indicators of sewage treatment research variables with environmentally friendly technology on commercial ships to reduce pollution is valid, this is shown by the value of all research variable indicators > 0.70. Indicators of the environmentally friendly technology construct (Y2) reflect the application of UV-based disinfection, membrane bioreactor systems, and biological processes that comply with MEPC.227(64). These indicators align with IMO standards and demonstrate that the measurement model captures objective technological characteristics rather than subjective environmental perceptions. In addition, to find out the value of validity and reliability, it can be shown by the value of construct reliability and validity shown in Table 6.

Table 5. Outer loadings

Variables and Indicators	Outer Loadings
X1: Implementation of Annex IV of MARPOL 1973/1978	
X1.1 Regulatory compliance	0.880
X1.2 Processing facilities	0.895
X1.3 Port authority supervision	0.858
X1.4 Crew training	0.877
X2: Sewage treatment technology	
X2.1 Ship size and type	0.878
X2.2 Rules and regulations	0.842
X2.3 Technologies used	0.829
X2.4 Ship operating area	0.818
X3: Implementation of occupational health safety procedures	
X3.1 Occupational health safety training	0.849
X3.2 Occupational health safety culture	0.865
X3.3 Occupational health safety equipment	0.831
X3.4 Safe operating procedures	0.795
Y1: Crew safety and health	
Y1.1 Risk of work accidents in sewage processing	0.849
Y1.2 Risk of exposure to disinfectant materials for crew	0.865
Y1.3 Risks of diseases arising	0.844
Y1.4 Ship hygiene and hygiene	0.838
Y2: Sewage treatment with environmentally friendly technology on commercial vessels to reduce pollution	
Y2.1 Sewage treatment is free of environmentally harmful substances	0.887
Y2.2 Disposal of sewage into the sea according to regulations	0.888
Y2.3 Environmental impact of sewage disposal	0.870
Y2.4 Innovation in the use of processing technology	0.871

Source: Primary data, 2025

Table 6. Construct reliability and validity

Construct	Cronbach's Alpha	Rho_A	Composite Reliability	Average Variance Extracted (AVE)
Implementation of Annex IV of MARPOL 1973/1978	0.901	0.901	0.931	0.771
Sewage treatment technology	0.864	0.877	0.907	0.709
Implementation of occupational health safety procedures	0.856	0.859	0.902	0.698
Crew safety and health	0.871	0.872	0.912	0.721
Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution	0.902	0.903	0.932	0.773

Source: Primary data, 2025

Table 7. Cross loading

	Y1	X1	X3	X2	Y2
X1.2	0.586	0.895	0.473	0.441	0.572
X1.3	0.561	0.858	0.366	0.443	0.559
X1.4	0.577	0.877	0.398	0.480	0.593
X2.1	0.601	0.500	0.257	0.878	0.559
X2.2	0.396	0.426	0.131	0.842	0.385
X2.3	0.531	0.449	0.331	0.829	0.450
X2.4	0.434	0.407	0.270	0.818	0.547
X3.1	0.466	0.443	0.849	0.282	0.481
X3.2	0.452	0.363	0.865	0.254	0.512
X3.3	0.386	0.383	0.831	0.227	0.410
X3.4	0.502	0.411	0.795	0.237	0.420
Y1.1	0.849	0.552	0.439	0.520	0.584
Y1.2	0.865	0.528	0.474	0.520	0.613
Y1.3	0.844	0.604	0.536	0.503	0.578
Y1.4	0.838	0.582	0.388	0.471	0.540
Y2.1	0.629	0.582	0.503	0.497	0.887
Y2.2	0.615	0.601	0.533	0.469	0.888
Y2.3	0.562	0.537	0.433	0.572	0.870
Y2.4	0.592	0.608	0.455	0.524	0.871
X1.1	0.616	0.880	0.444	0.503	0.601

Source: Primary data, 2025

Based on Table 6, it can be explained that the research variables are all research variables consisting of Implementation of Annex IV of MARPOL 1973/1978, Sewage Processing Technology, Implementation of Occupational Health Safety Procedures, Crew Safety and Health and Sewage Processing with environmentally friendly technology on commercial ships to reduce pollution obtained a Cronbach's Alpha value of more than 0.6, had a Composite reliability value of more than or equal to 0.7 and obtained an AVE value of more than 5. This means that all research variables can be declared valid and reliable, and feasible for internal model testing.

The discriminant validity test uses the cross-loading value; namely, an indicator is declared to meet discriminant validity if the indicator's cross-loading value on its variable is the largest compared to other variables. The Cross Loadings value is shown in Table 7.

Based on Table 7, information is obtained that each research variable indicator has the largest cross-loading value on the variable it forms compared to the cross-loading value on other variables, so it can be stated that the indicators used in this study have good discriminant validity in compiling the variable. Discriminant validity was also carried out using the Fornell-Larcker criteria, where the square root value of the AVE of a construct must be greater than its correlation value with other constructs. The results of the Fornell-Larcker criteria are shown in Table 8.

Table 8. Fornell-Larcker criterion

	Y1	X1	X3	X2	Y2
Y1	0.849				
X1	0.667	0.878			
X3	0.543	0.480	0.836		
X2	0.594	0.533	0.301	0.842	
Y2	0.682	0.663	0.548	0.585	0.879

Source: Primary data, 2025

Based on the results of the Fornell-Larcker test in Table 8, it can be obtained that the square root of the AVE of all constructs is greater than the correlation value with other constructs, so this shows that the discriminant validity requirements have been met. In addition, the discriminant validity test was also carried out with the latest, more recommended criteria, namely the Heterotrait-Monotrait ratio (HTMT) criteria, the results of which are shown in Table 9.

Table 9. Heterotrait-Monotrait ratio (HTMT)

	Y1	X1	X3	X2	Y2
Y1					
X1	0.753				
X3	0.623	0.545			
X2	0.671	0.599	0.340		
Y2	0.768	0.734	0.620	0.653	

Source: Primary data, 2025.

Based on Table 9, it can be explained that all HTMT values are below 0.85, which means that the discriminant validation in the sewage treatment model with technology on commercial ships to reduce pollution is very good and fulfilled. So the inner model test was carried out using the outer VIF and inner VIF criteria; the outer VIF value is shown in Table 10.

Table 10. Outer VIF values

	VIF		VIF
X1.2	2.912	X3.4	1.683
X1.3	2.341	Y1.1	2.132
X1.4	2.565	Y1.2	2.271
X2.1	2.205	Y1.3	2.018
X2.2	2.287	Y1.4	2.059
X2.3	2.027	Y2.1	2.719
X2.4	1.876	Y2.2	2.761
X3.1	2.113	Y2.3	2.502
X3.2	2.292	Y2.4	2.464
X3.3	2.051	X1.1	2.517

Source: Primary data, 2025

Based on Table 10, the outer VIF test can be explained that all indicators are in the range of 1.68-2.91 so that they meet the criteria < 5 which means there are no symptoms of multicollinearity, most of the VIF < 3.3 then the instrument in this environmentally friendly sewage processing model is free from Common Method Bias (CIMB) problems, the model is statistically valid for further analysis, there is no need to delete indicators and the sewage processing model with environmentally friendly technology to reduce this pollution is in the very good category.

After the research data is declared valid and reliable, then an inner model test is carried out which includes Collinearity Statistics (VIF), hypothesis test of the direct influence of exogenous variables implementation of annex IV MARPOL 1973/1978, the application of occupational health safety procedures, sewage processing technology on the variables of crew health safety and sewage processing with environmentally friendly technology on commercial ships to reduce pollution, indirect influence hypothesis test exogenous variables to endogenous variables sewage treatment with environmentally friendly technology on commercial ships to reduce pollution (through variables between crew health safety and R Square test. The results of Collinearity Statistics (VIF) are shown in Table 11.

Based on Table 11, it can be explained that the relationship between variables in the structural model of the sewage treatment model with environmentally friendly technology on commercial ships to reduce pollution is free of multicollinearity because the inner VIF value is less than 5. The implementation of Annex IV MARPOL 1973/1978 on safety and health of the crew has an internal VIF value of 1,655, the implementation of Annex IV of MARPOL 1973/1978 on the treatment of sewage with environmentally friendly technology on commercial ships to reduce pollution obtained a value of 1,979, the safety and health of the crew work on the treatment of sewage with environmentally friendly technology on commercial ships to reduce pollution obtained a value of 2,383, the application of occupational health safety procedures (X3) to the implementation of Annex IV MARPOL 1973/1978 obtained an inner VIF value of 1,303, the application of occupational health safety procedures to the processing of sewage with environmentally friendly technology on commercial ships to reduce pollution obtained an inner VIF value of 1,479, Sewage treatment technology to the Implementation of Annex IV MARPOL 1973/1978 obtained an inner VIF value of 1,401 and sewage processing technology (X3) to Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution obtained an inner VIF value of 1,639.

Table 11. Inner VIF values

Construct	Crew Occupational Safety and Health	Sewage Treatment with Environmentally Friendly Technology on Commercial Ships to Reduce Pollution
Implementation of Annex IV of MARPOL 1973/1978	1.655	1.979
Crew occupational safety and health		2.384
Implementation of occupational health safety procedures	1.303	1.479
Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution		
Sewage treatment technology	1.401	1.639

Source: Primary data, 2025

The next inner test of the model is hypothesis testing to determine the direct influence of exogenous variables Implementation of annex IV MARPOL 1973/1978, sewage processing technology, application of occupational health safety procedures to the variables of industrial safety and occupational health of Crew and the influence of exogenous variables of the implementation of annex IV MARPOL 1973/1978, sewage processing technology, application of occupational health safety procedures to the variables of industrial sewage processing with technology environmentally friendly on commercial ships to reduce pollution. The results of the direct influence hypothesis test are shown in Table 12.

Based on Table 12, it can be explained that all exogenous variables have a positive and significant influence on endogenous variables because the P value has a value of less than 0.05. The direct influence of exogenous variables on indogenic variables consists of positive and significant direct influences the implementation of Annex IV MARPOL 1973/1978 on the safety and health of the crew is shown by the original sample value of 0.369 and the P value of 0.000, the direct positive and significant influence between the implementation of Annex IV MARPOL 1973/1978 on sewage treatment with environmentally friendly technology on commercial ships to reduce pollution is shown by the original sample value of 0.273 and the P value of 0.000, Positive and significant direct influence safety and health of crew to sewage treatment with environmentally friendly technology on commercial ships to reduce pollution of 0.250 and P value 0.003, the direct effect of the application of occupational health safety procedures on crew safety and health is 0.271 and P value 0.000, the direct effect of the application of occupational health safety procedures on sewage processing with environmentally friendly technology on commercial ships to reduce pollution is 0.213 and P value 0.001, the direct effect of sewage processing technology on crew safety and health is 0.316 and P value 0.000 and the effect of direct sewage treatment technology to sewage processing with environmentally friendly technology on commercial ships to reduce pollution by 0.226 and P value 0.002.

Furthermore, the internal model test was to analyze the indirect influence of the implementation variables of Annex IV MARPOL 1973/1978 on sewage processing with environmentally friendly technology on commercial ships to reduce pollution through variables between safety and crew health, the indirect influence of the variables of the application of occupational health safety procedures on the processing of sewage with environmentally friendly technology on commercial ships to reduce pollution through the variables between safety and health of crew and the indirect influence of sewage treatment technology variables on sewage processing with environmentally friendly technology on commercial ships to reduce pollution through the variables between crew safety and health shown in Table 13.

Table 12. Path coefficient

Path Coefficient	Original Sample (O)	Mean	Standard Deviation (STDEV)	T Statistics	P Values
Implementation of Annex IV of MARPOL 1973/1978 → Crew Safety and Health	0.369	0.369	0.080	4.000	0.000
Implementation of Annex IV MARPOL 1973/1978 → Sewage Treatment with Environmentally Friendly Technology on Commercial Ships to Reduce Pollution	0.273	0.273	0.077	3.525	0.000
Safety and Health of Crew → Sewage Treatment with Environmentally Friendly Technology on Commercial Ships to Reduce Pollution	0.250	0.251	0.084	2.956	0.003
Implementation of Occupational Health Safety Procedures → Safety and Health of Crew	0.271	0.276	0.070	3.867	0.000
Implementation of Occupational Health Safety Procedures → Sewage Treatment with Environmentally Friendly Technology on Commercial Ships to Reduce Pollution	0.213	0.212	0.064	3.315	0.001
Sewage Treatment Technology → Safety and Health Crew	0.316	0.314	0.066	4.810	0.000
Sewage Treatment Technology → Sewage Treatment with Environmentally Friendly Technology on Commercial Ships to Reduce Pollution	0.226	0.228	0.073	3.135	0.002

Source: Primary data, 2025

Table 13. Specific indirect effects

Path	Original Sample (O)	Mean	Standard Deviation (STDEV)	P Values
Implementation of Annex IV of MARPOL 1973/1978 → Crew Safety and Health → Sewage treatment with environmentally friendly technology on commercial vessels to reduce pollution	0.092	0.093	0.038	0.016
Implementation of Occupational Health Safety training → Crew Safety and Health → Sewage treatment with environmentally friendly technology on commercial vessels to reduce pollution	0.068	0.069	0.02	0.016
Sewage Treatment Technology → Crew Safety and Health → Sewage treatment with environmentally friendly technology on commercial vessels to reduce pollution	0.079	0.080	0.035	0.023

Source: Primary data, 2025

Based on Table 13, it can be explained that there is an indirect effect of the implementation variables of Annex IV MARPOL 1973/1978 on sewage processing with environmentally friendly technology on commercial ships to reduce pollution through the variables between safety and crew health positively and significantly by 0.092 units with a P value of 0.016. Exist The indirect effect of the variables of the application of occupational health safety procedures on sewage processing with environmentally friendly technology on commercial ships to reduce pollution through the variables between safety and crew health positively and significantly 0.068 units with P values of 0.016 and the indirect influence of sewage treatment technology variables on sewage processing with environmentally friendly technology on commercial ships to reduce pollution through variables between safety and crew health positively and significantly of 0.079 units with P values of 0.023. Sewage Processing Analysis Model with environmentally friendly technology on commercial ships to reduce pollution can be shown in Figure 1.

Based on Figure 1, the analysis model of sewage treatment with environmentally friendly technology on commercial ships to reduce pollution, it can be explained that the safety and health of crew work together are influenced by the implementation of Annex IV of MARPOL 1973/1978, the application of occupational health safety procedures, and sewage processing technology and Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution is jointly affected by the implementation of Annex IV of MARPOL 1973/1978, The application of occupational health safety procedures, and sewage processing, safety and crew health technology.

In the SmartPLS-SEM analysis, the value of R Square functions to assess the ability of exogenous variables to explain endogenous variables; the higher the value of R Square, the better the model in explaining the relationship between constructs. The value of R Square of the sewage treatment analysis model with environmentally friendly technology on commercial ships to reduce pollution is shown in Table 14.

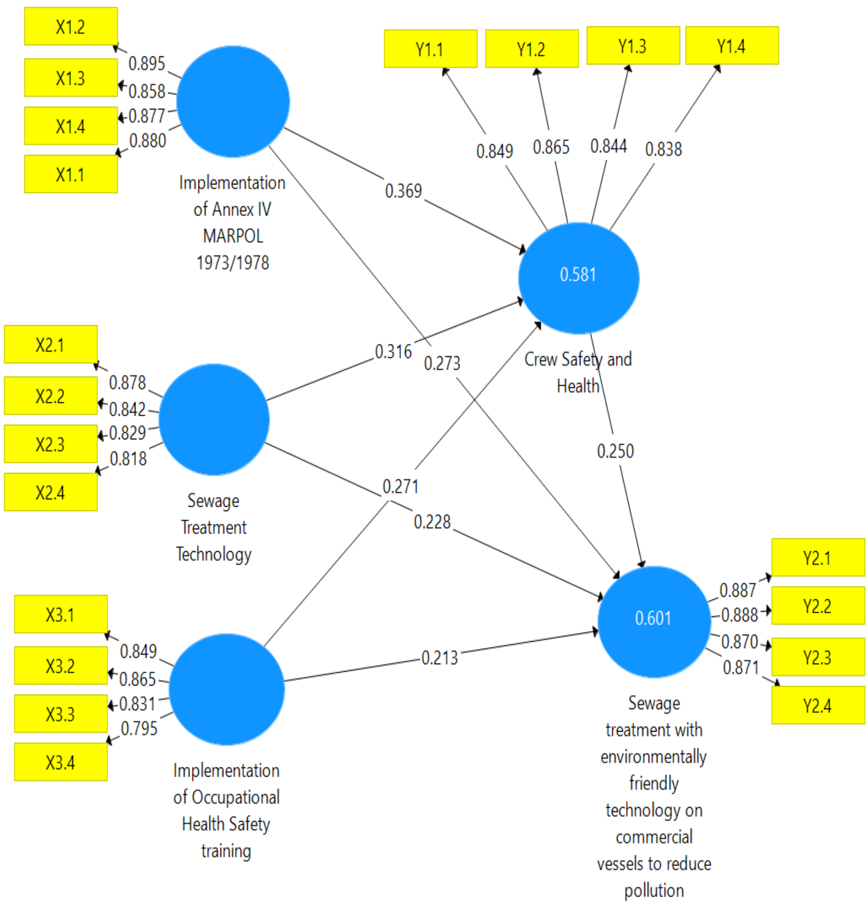

Figure 1. Sewage treatment analysis model with eco-friendly technology on commercial ships to reduce pollution
Source: Primary data, 2025

Table 14. R Square value

Construct	R Square
Crew safety and health	0.581
Sewage treatment with environmentally friendly technology on commercial ships to reduce pollution	0.601

Source: Primary data, 2025

Based on Table 14, it can be explained that the independent variables of the implementation of Annex IV MARPOL 1973/1978, the implementation of occupational health safety procedures, and sewage treatment technology have a moderate effect on the safety and health variables of the crew of 0.581 because the R Square value is 0.50 - 0.75 and the implementation variable of Annex IV MARPOL 1973/1978, The application of occupational health safety procedures, and sewage, safety and crew health processing technology has a moderate effect on sewage processing with environmentally friendly technology on commercial ships to reduce pollution by 0.601 because the R Square value is 0.50–0.75.

4. DISCUSSIONS

Based on the results of this study with SmartPLS-SEM analysis, it was found that the implementation of annex IV MARPOL 1973/1978 had a direct effect on the treatment of sewage with environmentally friendly technology on commercial ships to reduce pollution coefficient by 0.273, with a P Values of 0.000 this is consistent with previous research which stated that compliance with international regulations is the main foundation in protecting the marine environment [9, 11]. The results of this study also add empirical evidence that regulatory compliance has an impact on crew health safety and health directly safety and health with a coefficient of 0.369, with a P Value of 0.000, and regulatory compliance also has an indirect impact through an increase in the safety and health of crew members by 0.092 with a P Value of 0.016. This shows that regulations not only function as a legal instrument, but also as a learning mechanism that increases crew awareness of health and safety risks in waste treatment.

The positive influence of sewage treatment technology on environmentally friendly treatment to reduce pollution by 0.226 with P Values confirms the importance of adopting technology according to the size of the vessel, operating area, and international standards. In line with previous literature [11, 15], the use of modern technologies such as biological treatment and UV disinfection is effective in reducing the levels of pathogens and pollutants. This finding indicates that vessels employing UV disinfection, MBR systems, or biological treatment technologies, all of which comply with MEPC.227(64) effluent requirements, achieve higher environmental performance. These technologies reduce pathogens, solids, and chemical residues, resulting in safer and more sustainable waste discharge practices. The novelty of this study is the discovery of the effect of technology not only on the quality of waste treatment, but also on crew safety of 0.316 with P values of 0.001 and the indirect influence of sewage treatment technology on sewage treatment environmentally friendly technology on commercial vessel to reduce pollution through the variable between crew safety and health of 0.079 with P values of 0.023. In other words, the proper application of technology reduces exposure to hazardous chemicals and the risk of work accidents, resulting in a dual effect on environmental and occupational health aspects.

The application of occupational health safety procedures has been proven to have a significant effect on crew safety, with a coefficient of 0.271 with a P value of 0.000, as well as the application of occupational health safety procedures to sewage processing with environmentally friendly technology to reduce pollution by 0.213, with a P value of 0.001. These findings reinforce previous research that stated that safety culture contributes to crew behavior in managing waste [15, 16]. The results of this study show that without the support of the implementation of strict occupational health safety procedures, even advanced technology will not be optimal in preventing marine pollution. This means that regulations and technology must be integrated with human-based risk management.

This study proves the mediating effect of safety and crew health on the relationship between regulations, wage processing technology, and the application of occupational health safety procedures with waste treatment with environmentally friendly technology on commercial ships to reduce pollution. A significant indirect effect value (P values < 0.05) indicates that improved crew welfare and health strengthen the effectiveness of the application of environmentally friendly technology. This shows that a holistic approach, which focuses not only on regulation or technology, but also on crew working conditions, is key to the successful implementation of sustainable waste treatment systems on commercial ships.

This research has theoretical implications, namely, from the academic side, this research expands the theory of environmental compliance and maritime safety by adding an integrative perspective between international regulations (Annex IV MARPOL), human factors (the implementation of occupational health safety procedures and crew health safety), and technology. The structural model obtained (R Square = 0.601 for the main endogenous variable) shows that the combination of regulatory, technological, and occupational safety factors can explain more than 60,1 % of the variability of sewage treatment with environmentally friendly technologies to reduce pollution. This reinforces the literature that multidimensional approaches are more effective than single approaches.

For the shipping industry that affirms that the MARPOL Regulation must be enforced consistently, with stricter port supervision, investment in environmentally friendly technologies such as biological treatment systems, membranes, and UV disinfection must be prioritized not only on cruise ships, but also on commercial ships, crew occupational health safety training needs to be expanded so that crew understand the risks of waste treatment and be able to operate the technology safely. Governments and shipping companies need to build a maritime safety culture that is integrated with environmental protection policies.

The novelty of this research lies in the development of an integrative analysis model that connects Annex IV MARPOL, the application of occupational health safety procedures, and processing technology with the health safety of crew members as mediators. Most of the previous research focused on garbage management or the application of technology on cruise ships, while this study expanded the scope to commercial ships by involving human factors as the key to the success of environmentally friendly sewage processing.

5. CONCLUSIONS

This study proves that sewage treatment with environmentally friendly technology on commercial ships to reduce pollution is significantly influenced by three main factors, namely the implementation of Annex IV MARPOL 1973/1978. The application of occupational safety and health procedures and the processing technology used.

The findings of the study show that compliance with Annex IV of MARPOL contributes significantly to the safety and health of crew and to the treatment of sewage with environmentally friendly technology on commercial ships to reduce pollution. International regulations have proven to function as a legal instrument as well as an educational mechanism. Sewage processing technology has a positive effect on the quality of sewage processing on commercial ships to reduce pollution while reducing risks that threaten the safety of crew health. The sewage treatment technology referred to in this study includes UV-based disinfection, biological processing systems, and membrane bioreactors that meet the international performance standards defined in

MEPC.227(64). This dual effect shows that sewage treatment technology supports the sustainability of marine ecosystems as well as the safety of work on ships. The implementation of crew health safety procedures plays an important role in reducing the risk of accidents and diseases due to wastewater processing. Without a strong safety culture, technology, and regulations are not optimal in preventing marine pollution. Crew safety and health are proven to be mediating variables that strengthen the relationship between regulations, occupational health safety procedures, and technology for sewage processing with environmentally friendly technology on commercial ships to reduce pollution.

The structural model with SmartPLS-SEM analysis obtained is an analysis model of sewage treatment with environmentally friendly technology on commercial ships to reduce pollution, which shows the relationship between the implementation of the model also identifies a positive and significant indirect effect (0.092) of Annex IV implementation on environmentally friendly sewage treatment through crew safety and health.

This study has several limitations that should be considered when interpreting the findings. First, the research employs a cross-sectional design, which captures conditions at a single point in time and does not allow causal relationships to be established conclusively. Longitudinal or time-series data would provide a stronger basis for evaluating the dynamic effects of regulations and technology adoption. Second, the data were collected using self-reported questionnaires, which may introduce response bias, including social desirability bias and recall bias, especially in items related to safety practices and compliance behavior. Third, the sample was limited to commercial vessels operating within Indonesian waters, which may introduce national-context bias. Operational characteristics, enforcement intensity, and technological adoption may differ in other countries, limiting the generalizability of the results. Future studies should consider multi-country comparative data or a broader sampling framework to enhance external validity.

Based on the results of the study, it is recommended to the shipping industry not only on cruise ships but also on all commercial vessels, integrating the implementation of Annex IV of MARPOL into safety management, including internal supervision and regulatory compliance audits, providing ongoing training to crew members on occupational health safety and the operation of sewage treatment technology so that occupational risks can be minimized. It is also recommended to the government, in this case the Port and Municipal Authority, to increase supervision at ports related to compliance with Annex IV MARPOL and ensure the availability of adequate sewage reception facilities.

The limitation of this research is that the sample used is Indonesian-flagged merchant ships, which are required to comply with the 1973/1978 MARPOL regulations, but the results of this research can be generalized to merchant ships owned by other countries whose countries refer to the 1973/1978 MARPOL regulations. As a recommendation, if there is data availability, it is hoped that future research can be carried out on foreign-flagged ships from various countries to combine subjective perceptions of the implementation of MARPOL regulatory compliance. Next research can also be developed with a sample of domestic ships, which are referred to in national regulations that do not require referring to MARPOL to provide recommendations for preventing marine pollution from various types of ships.

For the next study, it is recommended to carry out an expansion of the study by adding external variables such as company support, technology investment cost factors, and the role of port authorities. For further research, it is also recommended to make comparisons between domestic and international ships to identify the implementation of regulations, and it is recommended to develop a model based on life cycle assessment to measure the long-term impact of the application of environmentally friendly technology in sewage treatment on ships.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The dataset includes anonymized responses and does not contain any personal or confidential information.

ACKNOWLEDGMENT

This work was supported by the Directorate of Research and Community Service, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Main Contract No. 128/C3/DT.05.00/PL/2025; Derivative Contract No. 039/LL7/DT.05.00/PL/2025; Derivative Contract No. B/017/DT.05.00/PL/UHT.C7/V.2025). The authors also express sincere thanks to Hang Tuah University for institutional support that facilitated the implementation of this research. In addition, the authors extend their appreciation to the participating maritime institutions and ship crews for their valuable support and cooperation during the research process.

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