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Ballast Water Treatment Performance Evaluation under Real Changing Conditions

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Abstract: We conducted a shipboard ballast water test using seawater of extreme turbidity collected from Shanghai Port (China) (>300 mg total suspended solids (TSS)/L), and normal seawater collected in other ports (<100 mg TSS/L). All three types of International Maritime Organization (IMO)-approved ballast water management system (BWMS) tested failed to properly operate because of filter clogging or insufficient generation of oxidants under near-fresh water conditions with extremely high concentration of suspended solid during ballasting. It was also found that the number of microorganisms increased with longer ballast water retention time, with higher numbers in the treated discharge water. The results suggest that when operating a BWMS involving a filter unit in areas with water having high concentrations of suspended solids, the filter unit should be used during ballast water discharge, rather than during ballasting. This method has the advantage of removing ≥50 µm organisms at discharge that could not be removed by a filter during ballasting. For ballast water retained for long storage times, the results suggest the use of BWMSs involving UV units or electrolysis during deballasting. In addition, BWMSs involving electrolysis units provide the opportunity to maintain residual total residual oxidant (TRO) levels, using a partial ballast tank. Although the BWMSs tested are a small subset of the large number of IMO-approved BWMSs, the results demonstrate that there is a significant gap between the technology currently available and capacity to meet IMO and US Coast Guard standards.

Keywords: ballast water; ballast water management system; shipboard test; turbidity; invasive species

1. Introduction

Invasive aquatic species can disrupt native ecosystems of affected regions. Biofouling and ballast water are major mechanisms in the movement of exotic species among ocean ecosystems. Global ballast water discharged from vessels engaged in international trade has been estimated to exceed 3.1 billion tons per year, involving in excess of 7000 organisms being transferred among regions, potentially adversely affecting the environment, human health, and the economy in receiving environments [1–5]. The International Maritime Organization (IMO) established the International Convention for the Control and Management of Ship's Ballast Water and Sediments (BWMC) in 2004, which aimed to minimize the movement of harmful organisms and pathogens via ballast water [6]. The BWMC came into force on 8 September 2017, and under Regulation B-3 (based on ship renewal surveys associated with the International Oil Pollution Prevention Certificate [7]) it requires that most ships moving among international ports from that time to 8 September 2024 have installed a type-approved ballast water management system (BWMS).

For a BWMS to receive approval, land-based and shipboard ballast water tests must be conducted. The land-based test requires five successive tests involving freshwater, brackish water, and seawater under conditions in accordance with BWMS Code [8]. However, aquatic environmental conditions in certain regions may be worse than the test water conditions specified in the BWMS Code. An experience-building phase (EBP) from 2018 to 2022 was approved by the Marine Environment Protection Committee (MEPC) to monitor implementation of the BWM Convention, with the aims of identifying those aspects of the convention's implementation that are working well, and to shed light on issues that require further attention [8,9]. To this end, the EBP is structured in three stages: a data gathering stage, a data analysis stage, and a review stage. Another important goal of the EBP is to develop standardized sampling and analysis procedures.

Technologies used in BWMSs included electrolysis, ultraviolet irradiation, ozonation, filtration, and thermal treatment. A total of 45 BWMSs had received final approval from the IMO through November 2019. Among the approved BWMSs, the main treatment methods include electrolysis (22 BWMSs), chemical injection systems (13 BWMSs), UV systems (6 BWMSs), and ozone systems (4 BWMSs) [10]. The BWMS implemented depends on the characteristics of the equipment and the installation conditions including vessel dimensions and ballast water flow rates of the ship. The main BWMSs installed on ships are UV and electrolysis devices. Of the 45 BWMS developed, 32 (71%) involve a filter unit in the pretreatment stage, designed to physically remove organisms ≥50 µm in size.

There are two BWMS approval test methods: the BWMS Code and the U.S Coast Guard Environmental Technology Verification (USCG ETV) protocol methods [11,12]. Although these involve slightly different test water conditions, the criteria for discharge of treated water are the same (Table 1). The most significant difference between the test water conditions for the land-based test and the water from a specific port environment is the total suspended solids (TSS) (Table 1). The test conditions for TSS in the USCG ETV protocol is 24 mg L^{-1} in all test waters, while for the BWMS Code is TSS >50 mg L^{-1} for fresh and brackish water, and 1 mg L^{-1} for seawater. However, some ports worldwide have intense maritime traffic, and their waters may contain extremely high particle loads. For water having a high TSS concentration, filter clogging occurs even before backwashing, so it may be difficult to stably operate the BWMS [13]. In addition, inorganic particles (e.g., sand) can impact UV transmittance (UV-T), cause light diffusion, and have an abrasive effect on equipment component surfaces (e.g., lamps), and the presence of organic particles can result in a reduction of the potential for oxidation of active substances, cause agglomeration, and may also result in shadowing (thereby diminishing UV-T) [14].

Table 1. Minimum criteria for land-based (LB) and shipboard (SB) testing.

Variable	Uptake Water			Discharge Water	
	LB		SB	Control Water [(2)]	Treated Water [(3)]
Salinity (psu)	M [(1)]: 28–34	B [(1)]: 10–20, F [(1)]: <1	Measured	-	-
Particulate organic carbon (mg/L)	1	5	Measured	-	-
Dissolved organic carbon (mg/L)	1	5	Measured	-	-
Total suspended solid (mg/L)	1	50	Measured	-	-
Escherichia coli (CFU 100 mL^{-1})	Measured		-	-	<250
Intestinal enterococci (CFU 100 mL^{-1})	Measured		-	-	<100
Vibrio cholera (O1 and O139) (CFU 100 mL^{-1})	Measured		-	-	<1
Heterotrophic bacteria	10^3 bacteria mL^{-1}		-	-	Measured
Organisms ≥10 µm and < 50 µm (organisms mL^{-1})	$>10^3$		>100	>10 (SB) >100 (LB)	<10
Organism of ≥50 µm (organisms m^{-3})	$>10^5$		>100	>10 (SB) >100 (LB)	<10

[(1)] M: Marine water, B: Brackish water, F: Fresh water. [(2)] BWMS Code did not require testing of control discharge water during shipboard testing. [(3)] The criteria of treated discharge water (D-2 criteria) are the same for both land-based and shipboard tests.

The purpose of this study was to evaluate the performance of BWMSs in relation to the D-2 standard. The study was based on three international vessels equipped with the three types of BWMS widely used in vessels. In addition, we assessed problems that can occur during BWMS operation in certain environments, including high concentrations of TSS, and proposed some operational approaches that may eliminate or reduce the risk of introduction of invasive species. The study was intended to aid proper implementation of the BWMC, and thus protects environments from invasions by exotic aquatic species introduced through ballast water, which is the purpose of the Convention.

2. Materials and Methods

2.1. Routes and Dates of the Shipboard Test

The routes of the ships used in the shipboard test were via major ports in China, Hong Kong, and Southeast Asia, including Pusan Port (Figure 1). In this study, shipboard tests were performed on three commonly used types of BWMS. Type A is a filter + UV system, type B is an electrolysis system, and type C is a filter + electrolysis system. Shipboard tests were conducted from 1 to 11 October 2013 for the type A BWMS, from 30 November to 17 December 2013 for the type B BWMS, and from 5 to 12 June 2014 for the type C BWMS (Table 2). BWMS operation was performed by the navigation officer, maintenance of the equipment was performed by the manufacturers' specifications, and all tests were performed by the test personnel.

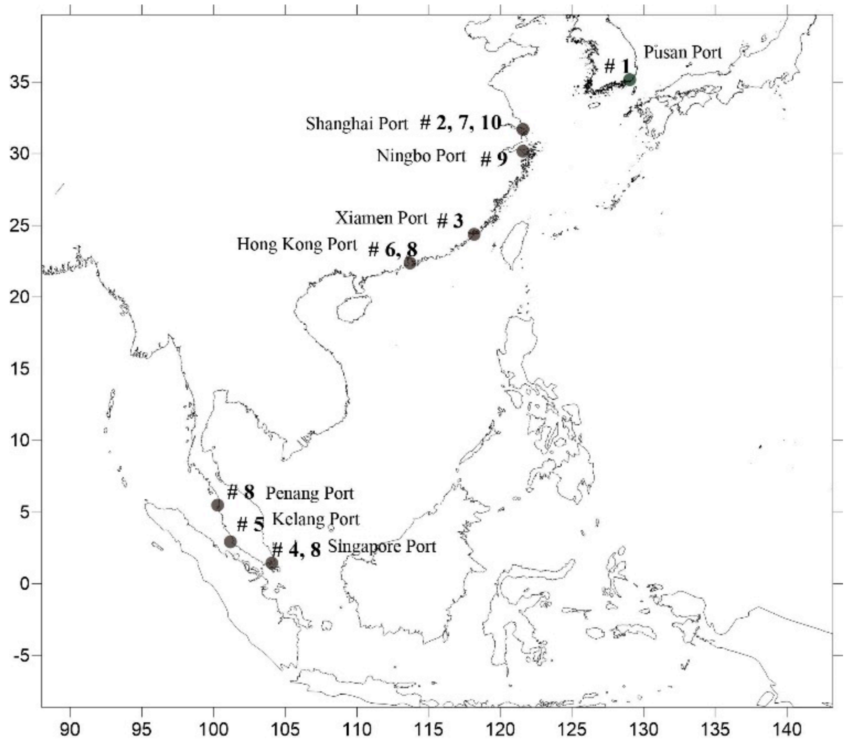

Figure 1. Ports where ballasting was conducted during shipboard tests of vessels having on board type A, B, or C BWMSs (type A: filter + UV; type B: electrolysis; type C: filter + electrolysis).

Table 2. Summary of ballasting and deballasting operations for three types of BWMS installed on vessels.

Type of BWMS	Trial No.	Date (YYMMDD)	Location	Mode	Type of Water	Water Volume Tested (m^3)	Operational Time Start Time End		Notes
							Start	End	
Filter + UV	1	131002	Port of Pusan	B [1]	Uptake	900	01:37	01:59	Deballasting not allowed in Port of Shanghai
					Treatment	866	02:02	02:44	
			Pusan–Shanghai	DB [1]	Control		22:17	22:50	
					Treatment		20:14	22:10	
	2	131004	Port of Shanghai	B	Uptake	1068	04:39	05:24	No ballast treatment due to high turbidity (NTU > 1000)
					Treatment	-	-	-	
	3	131005	Port of Shaman	B	Uptake	999	19:25	19:52	Filter Panel fault, no ballasting
					Treatment		-	-	
Electrolysis	4	131130	Port of Singapore	B	Uptake	556	15:50	16:50	
					Treatment	546	20:20	22:15	
		131203	Port of Penang	DB	Control		10:25	11:30	0.010 g neutralizer m^{-3}
					Treatment		08:39	10:05	
	5	131201	Port of Klang (Maleisya)	B	Uptake	639	17:55	19:20	
					Treatment	649	19:35	20:50	
		131207	Singapore–Hong Kong	DB	Control		10:10	11:50	0.013 g neutralizer m^{-3}
					Treatment		08:30	10:00	
	6	131211	Port of Hong Kong	B	Uptake	571	03:20	04:40	
					Treatment	589	04:41	05:41	
		131213	Hong Kong–Shanghai	DB	Control		15:00	16:35	0.0097 g neutralizer m^{-3}
					Treatment		13:00	14:30	
	7	131215	Port of Shanghai	B	Uptake	810	00:20	01:56	BWMS shut down because target total resident oxidant (TRO) was not formed (TRO 1.96 ± 0.13 mg L^{-1})
					Treatment	-	-	-	

Table 2. *Cont.*

Type of BWMS	Trial No.	Date (YYMMDD)	Location	Mode	Type of Water	Water Volume Tested (m^3)	Operational Time Start Time End		Notes
							Start	End	
Electrolysis	8	131203	Port of Penang	B	Uptake	100	12:58	13:10	
					Treatment	134	13:11	13:26	
		131206	Port of Singapore	B	Uptake	301	23:25	23:42	
					Treatment	149	23:25	23:42	
		131211	Port of Hong Kong	B	Uptake	261	02:48	03:18	
					Treatment	198	02:22	02:47	
		131212	Hong Kong–Shanghai	DB	Control	539	14:27	15:41	0.019 g neutralizer m^{-3}
					Treatment	502	12:57	14:05	
Filter + Electrolysis	9	140608	Port of Ningbo	B	Uptake	449	10:38	11:35	
					Treatment	429	11:42	12:36	
		140611	Shanghai–Pusan	DB	Control	408	14:49	15:49	
					Treatment	410	13:41	14:40	
	10	140610	Port of Shanghai	B	Uptake	329	15:50	16:32	Equipment failure
		140612	Port of Pusan	DB	Control	317	09:06	09:42	

[1] B: ballasting, DB: deballasting.

2.2. Shiboard BWMSs

A total of 83 BWMSs had been final type approved according to the IMO guideline G8 [15], of which 45 BWMSs that make use of Active Substances had received final approval from the IMO up to November 2019 (Figure 2a) [10]. Of the 45 BWMSs, 22 BWMSs used electrolysis equipment as the main treatment equipment, and these products are divided into three types. The first model (8 BWMSs) is to install the electrolysis device in the main pipe so that the ballast water passes directly through it (B type in this study), of which 4 BWMSs have a filter unit. The second model (13 BWMSs) is to form a high total residual oxidant (TRO) concentration using an electrolysis device and to then add this (to match the set TRO concentration) to the ballast water (C type in this study), all of which have a filter unit. The third model (1 BWMS) is a device that generates high TRO using an electrolysis device, stores it in the tank, and injects it directly into the ballast tank when necessary. There are 13 BWMSs using chemical substances, and there are two types: injection of chemicals into pipes (12 BWMSs) and injection of them into the ballast tank (1 BWMS). Of the 4 BWMSs using ozone, two have a filter and two have no filter, and all six BWMSs using UV have a filter (A type in this study). Among the developed BWMS, there are 11 BWMS products that combine two or more main treatment devices (e.g., electrolysis device + UV; electrolysis device + ozone, etc.). The total residual oxidant (TRO) concentration range for BWMSs using electrolytic devices, and chemical injection devices that make use of active substances, varied from 1 to 20 mg L^{-1} (Figure 2b), and the mesh size of most filter devices used in BWMS was 40–50 µm (Figure 2c). The mesh size of the filter in types A and C was 50 µm, and the maximum TRO concentrations in types B and C were 10 mg L^{-1} and 3 mg L^{-1}, respectively.

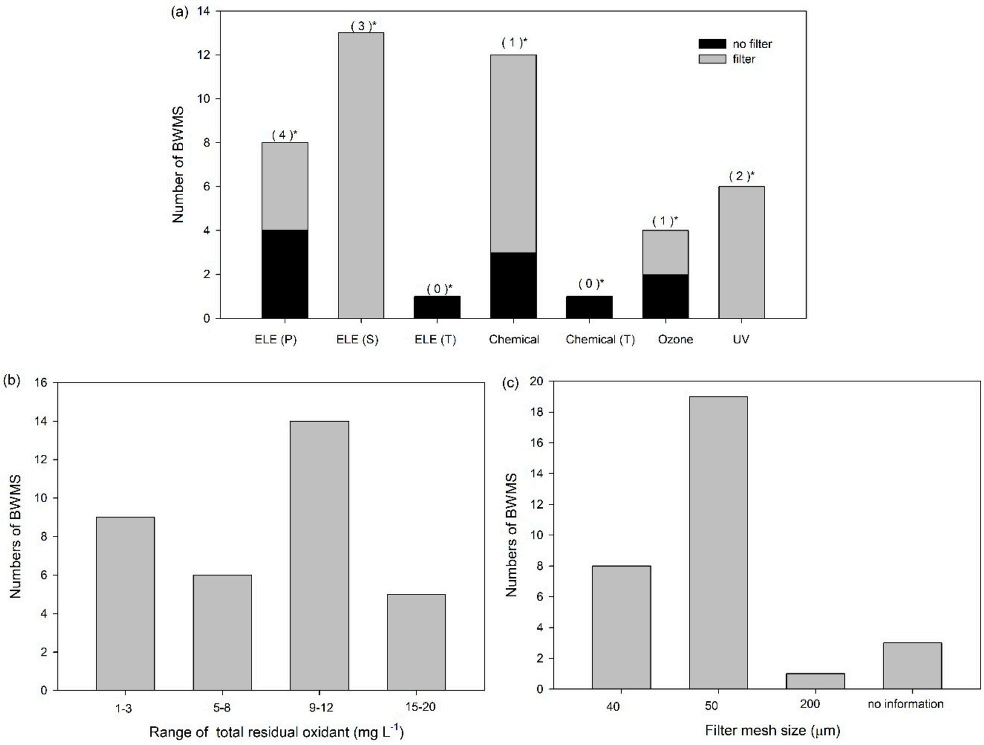

Figure 2. (**a**) Classification by major equipment of BWMSs that make use of an active substance (AS) that received final approval from the International Maritime Organization (BWMSs using a UV device do not produce AS but are included in this list). (**b**) Target total residual oxidant (TRO) concentrations using active substances and (**c**) filter mesh size using the filter as a pretreatment among these BWMSs. ELE (P), injection of TRO directly into the pipe; ELE (S), injecting TRO as a side stream method; ELE (T), injection of TRO directly into the ballast tank; Chemical, active substance into the pipe, Chemical (T): active substance into ballast tank; (.)* combine two or more main treatment devices (e.g., electrolysis device + UV; electrolysis device + ozone, etc.).

2.3. Ballast Water Sampling and Analysis

Sampling and analysis methods for shipboard tests were made in accordance with IMO guidelines G8 and G2 [16,17]. Although IMO guideline G8 was revised to BWMS Code in 2018, the sampling and analysis methods performed in this study were not significantly different. Sampling of uptake water and untreated discharge water during the ballasting test were performed at the start (20%), middle (50%), and end (80%), with respect to the time taken to fill the ballast water tank. In the deballasting test, the treated discharged water was collected nine times at 10% intervals (10%–90%) with respect to the time taken to empty the ballast water tank. The sampling amount, analysis amount, and analysis method of the shipboard test are summarized in Table 3.

Table 3. Sampling, analysis volumes, and analysis methods.

Variable	Sample Volume	Analysis Volume	Analytical Method	Remark
POC, DOC, TSS	≥4 L (3)	100~500 mL	APHA (6) 5310B(DOC) JGOFS-Protocols (7) (POC) APHA 2540D (TSS)	All samples analyzed in triplicate; treated discharge water was sampled 9 times from 10% to 90% of the total amount discharged.
Phyto-PAM		5 mL		
Escherichia coli	≥1 L (3)	10–20 mL	AOAC (8) (998.08)	
Intestinal enterococci		20–40 mL	EPA (9) 1600	
Vibrio cholera (O1 and O129)		10–20 mL	APHA 9260H	
Heterotrophic bacteria		0.1–0.2 mL	APHA 9215A	
Organisms ≥10 µm and < 50 µm (1)	>10 L (3)	0.5–1 mL	APHA 10200F Garvey et al. (2007)	
Organisms ≥ 50 µm (2)	≥1 m^3 (≥9 m^3) (4)	30 mL (1/5, all) (5)	APHA 9260H Gollasch & David (2010)	

(1) Uptake water samples were analyzed by concentrating 1 L to 300–500 mL using a mesh (<5 µm), and control and treated discharge water samples were analyzed by concentrating 10 L to 300–500 mL using a mesh (<5 µm). (2) All samples were analyzed by concentrating 1 m^3 to 300–500 mL using a mesh (<35 µm). (3) Discrete grab sampling (begin, middle, end). (4) Continuous sampling of treated discharge water. (5) The treated discharged water in trials 1–3 was analyzed using about 1/5 of the concentrated sample, while in the other trials the entire concentrated sample was analyzed. (6) American Public Health Association (APHA), 2012. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington, DC. (7) Joint global ocean flux study (JGOFS) protocols, 1994. Protocols for the core measurements, Intergovernmental Oceanographic Commission (IOC) manuals and Guides No. 29, UNESCO (8) Association of Analytical Communities (AOAS). *E. coli* Petrifilm™-AOAC 998.08. (9) U.S. Environmental Protection Agency (USEPA). 2002. Method 1600, 1603. Publication EPA-821-R-02-022. USEPA Office of Water, Office of Science and Technology, USEPA, Washington, D.C.

Water temperature, salinity, and dissolved oxygen concentration were measured in situ using a water quality measurement apparatus (YSI6600; Yellow Springs Inc., USA). Chemical analysis carried out included particulate organic carbon (POC), dissolved organic carbon (DOC), and total suspended solids (TSS). Samples for analysis of the DOC were gravity filtered directly from a glass syringe. Water was filtered before acidification to $1 \leq pH \leq 2$ with H_3PO_4 or H_2SO_4. Immediately after acidification, the sample was frozen to a temperature of less than −20 °C and analyzed within 28 d of sampling. Analysis of the DOC was carried out using a TOC analyzer (TOC-V_{CPH}, Shimadzu Co.). Adequate volumes of sample for POC were filtered onto precombusted 25 mm Whatman GF/F filters. The filters were removed, placed in capsular tissue, wrapped in aluminum foil, and stored frozen in a deep freezer (−20 °C) until analyzed. Analyses of the POC were carried out using a FlashEA™ 1112 elemental analyzer (ThemoQuest, Inc.). Adequate volumes of sample for TSS was filtered onto precombusted 47 mm Whatman GF/F filters, which were weighed in the laboratory. The filters were removed, placed in a Petri dish, wrapped in aluminum foil, and stored frozen in a deep freezer (−20 °C) until analyzed.

A biological efficacy test was performed to detect organisms having sizes of ≥50 µm, ≥10 µm to <50 µm, and <10 µm. All analysis methods were performed using the methods described in IMO guidelines G2 (Table 3). For organisms ≥50 µm, the concentrated subsample was mixed thoroughly and placed in a Bogorov counting chamber under a stereo microscope at 40×. They were designated as "live" if they were actively moving or exhibited an escape behavior when probed with a fine needle. Live/dead determination of ≥10–50 μm organisms was analyzed using the autofluorescence method and fluorescein diacetate (FDA) staining method. In the autofluorescence method, the sample was loaded into a Sedgewick Rafter Counting Chamber, and analyzed under epifluorescence microscopy (Axiostar plus; Carl Zeiss, Germany) using a blue excitation filter (excitation: 450–490 nm, emission: ≥520 nm). In the FDA method, the FDA (10209CE, Sigma-Aldrich) working solution (250 μM) was prepared by diluting the stock solution (10 mM) 40 times with regent grade dimethylsulfoxide (DMSO). Each sample was stained by 25 μL of FDA working solution to 1 mL sample in microtubes for 15 min. Under the epifluorescence microscopy (Axiostar plus; Carl Zeiss, Germany), live cells appear bright green. For measuring the size of organisms, we determines the smallest visible axis of the organism and measures the maximum visible width of the smallest visible axis.

To analyze heterotrophic bacteria, a 0.1 mL of sample was spread on the salinity-adjusted marine agar plates. The plates were incubated for 48 h at 20–25 °C (marine agar). To analyze intestinal enterococci, a 20–40 mL of sample was filtered onto the 0.2 μm membrane filter and then filters were placed on the intestinal enterococci agar plate. The pretreated agar plates were incubated for 24 h at 41 °C. To analyze *E. coli*, a 10–20 mL sample was filtered onto the 0.2 μm membrane filter and then filters were placed on the membrane, 3 M Petrifilm *E. coli* Count Plates. The 3 M Petrifilm EC Plate were incubated for 24 h at 35 °C. To analyze *Vibrio cholera*, a 10–20 mL of sample was filtered onto the 0.2 μm membrane filter and then filters were placed on the TCBS (bisulfate citrate bile sucrose) agar. Pretreated TCBS agar plates were incubated for 24 h at 35 °C. After dropping one or two drops of catalase (oxidase) into the yellow colored CFU, if it turned purple within 10–20 s, then it was designated as positive, and if not or partly purple, it was designated as negative.

Biological analysis of ≥50 μm organisms and ≥10 μm to <50 μm was completed within 6 h after sampling, and pretreatment of <10 μm organisms and chemical analysis (DOC, POC, TSS) also pretreated within 6 h. Pathogenic microorganism culture and analysis was done on board. Species analysis of ≥50 μm organisms and ≥10 μm to <50 μm was completed in a laboratory after fixation using formalin and lugol, respectively. Additionally, chlorophyll-*a* and active chlorophyll-*a* were analyzed using a pulse-amplitude modulated fluorometer (Phyto-PAM, Walz GmbH, PHYTO-C). This device measures only the chlorophyll of living phytoplankton by measuring the active fluorescence value. We used Pearson's correlation analysis for assessing statistical significance, using SPSS 18.

3. Results

3.1. Effect of Storage in the Ballast Tank on Ballast Water Properties

The POC and DOC concentrations measured in the uptake water for ballasting in the port of this study were slightly higher than or within the range of values for test waters used for assessing BWMS for approval. However, the concentrations of TSS were higher than that for water testing in the land-based test, particularly for the port of Shanghai, China (Tables 1 and 4). In the second, seventh, and tenth trials at Shanghai Port, the TSS concentrations were 690 ± 134, 309 ± 58.5, and 351 ± 21 mg L^{-1}, respectively. The values for the physicochemical factors in the discharged water were not significantly different from those in the uptake water, but the TSS concentration during deballasting tended to be lower than during ballasting. In particular, when the ballast water, which was pumped on board from Shanghai Port with no BWMS, was discharged at Pusan Port in the 10th test cycle, the TSS concentration decreased from an average of 351 mg L^{-1} during ballasting to 42.0 mg L^{-1} during deballasting. During deballasting, the TSS concentrations in samples taken at the beginning of deballasting (20% of the time), in the middle of the process (50% of the time), and at the end (80% of the time) during the 10th trial showed sequentially lower concentrations (68, 32, and 27 mg L^{-1} TSS, respectively), indicating that the TSS concentration was lower in the upper layer of the ballast water. In this study, there was a statistically significant correlation between nephelometric turbidity units (NTU) and TSS (Figure 3).

Table 4. Environmental condition observed during the testing for three types of BWMS installed on vessels.

Type of BWMS	Trial No.	Sample		Temp. (°C)	Salinity (psu)	DO (mg L^{-1})	pH	NTU	TSS (mg L^{-1})	POC (mg L^{-1})	DOC (mg L^{-1})	Holding Time
Filter + UV	1	B	UW (1)	24.7 ± 0.02	32.1 ± 0.26	7.32 ± 0.13	8.02 ± 0.04	7.50 ± 0.51	28.9 ± 12.4	0.68 ± 0.02	1.16 ± 0.01	21 h
		DB	CW (1)	24.8 ± 0.01	30.9 ± 0.02	6.30 ± 0.06	8.08 ± 0.01	9.79 ± 1.51	43.8 ± 18.7	0.60 ± 0.05	1.14 ± 0.25	
			TW (1)	25.3 ± 0.28	30.5 ± 0.19	6.30 ± 0.11	8.08 ± 0.02	8.22 ± 1.12	57.8 ± 3.30	0.53 ± 0.05	0.90 ± 0.03	
	2	B	UW *	25.1 ± 1.37	19.0 ± 0.06	7.39 ± 0.06	8.12 ± 0.02	996 ± 7.07	690 ± 134	10.41	0.92 ± 0.02	0 h
	3	B	UW *	30.0 ± 0.20	26.0 ± 0.30	6.60 ± 0.07	8.17 ± 0.02	99.3 ± 27.11	93.3 ± 3.21	3.02 ± 0.21	0.81 ± 0.02	0 h
Electrolysis	4	B	UW	30.7 ± 0.68	32.3 ± 0.12	6.62 ± 0.34	8.06 ± 0.01	4.05 ± 0.50	22.0 ± 5.9	0.53 ± 0.06	1.30 ± 0.20	4 days
		DB	CW	30.4 ± 0.42	32.08 ± 0.12	6.30 ± 0.11	8.03 ± 0.01	3.08 ± 0.57	19.0 ± 3.29	0.37 ± 0.02	1.31 ± 0.09	
			TW	29.6 ± 0.06	31.5 ± 0.28	6.66 ± 0.09	7.96 ± 0.01	3.77 ± 0.48	18.7 ± 4.1	0.34 ± 0.02	1.78 ± 0.13	
	5	B	UW	30.5 ± 0.63	27.5 ± 0.44	5.95 ± 0.06	7.85 ± 0.01	31.9 ± 7.61	51.5 ± 15.1	0.7 ± 0.14	2.21 ± 0.56	6 days
		DB	CW	29.4 ± 0.49	28.0 ± 0.08	5.78 ± 0.56	7.67 ± 0.02	11.8 ± 13.6	34.3 ± 11.9	0.68 ± 0.35	1.85 ± 0.1	
			TW	28.4 ± 0.11	27.7 ± 0.41	5.86 ± 0.14	7.54 ± 0.02	5.92 ± 5.95	15.7 ± 7.20	0.53 ± 0.16	1.66 ± 0.04	
	6	B	UW	21.5 ± 0.31	33.7 ± 0.77	6.84 ± 0.11	8.00 ± 0.01	9.33 ± 4.07	22.8 ± 7.00	0.55 ± 0.08	1.14 ± 0.06	2 days
		DB	CW	20.3 ± 0.41	33.9 ± 0.09	6.99 ± 0.09	8.01 ± 0.01	3.94 ± 2.39	17.1 ± 3.90	0.43 ± 0.10	1.29 ± 0.20	
			TW	20.1 ± 0.11	32.3 ± 0.17	7.21 ± 0.05	7.96 ± 0.02	4.16 ± 1.99	20.3 ± 5.90	0.39 ± 0.08	1.38 ± 0.05	
	7	B	UW **	13.5 ± 0.91	1.53 ± 0.46	9.63 ± 0.27	7.88 ± 0.03	309 ± 58.5	310 ± 63	0.64 ± 0.08	2.33 ± 0.17	0 h
	8	B	UW	29.7	32.3	6.59	8.04	8.04 ± 0.09	23.5 ± 9.48	0.89 ± 0.01	1.11 ± 0.01	9 days
			UW	29.7	31.1	6.31	8.03	6.13 ± 0.36	22.4 ± 2.83	0.59 ± 0.14	1.21 ± 0.01	
			UW	21.4	32.8	6.95	7.99	14.7 ± 1.25	29.4 ± 0.85	0.55 ± 0.08	1.22 ± 0.01	
		DB	CW	21.6 ± 0.53	32.7 ± 0.06	7.17 ± 0.06	8.06 ± 0.02	3.77 ± 0.77	16.9 ± 7.20	0.43 ± 0.04	1.12 ± 0.13	
			TW	21.2 ± 0.07	31.9 ± 0.27	7.34 ± 0.09	7.96 ± 0.01	6.87 ± 3.15	23.2 ± 7.90	0.47 ± 0.08	1.20 ± 0.03	
Filter + Electrolysis	9	B	UW	21.09 ± 0.34	28.20 ± 0.14	7.54 ± 0.05	7.92 ± 0.01	76.4 ± 21.08	82.0 ± 41.5	-	-	3 days
		DB	CW	21.3 ± 0.01	28.7 ± 0.03	7.44 ± 0.02	7.87 ± 0.02	28.8 ± 11.5	88.0 ± 35.1	-	-	
			TW	21.3 ± 0.03	28.6 ± 0.06	7.44 ± 0.06	7.84 ± 0.02	61.6 ± 34.1	101 ± 55.9	-	-	
	10	B	UW ***	22.7 ± 0.18	20.4 ± 0.17	7.68 ± 0.02	7.85 ± 0.02	400 ± 28.3	351 ± 21.0	-	-	2 days
		DB	CW	21.0 ± 0.03	21.6 ± 0.01	7.93 ± 0.08	7.84 ± 0.02	14.28 ± 2.23	42.0 ± 20.3	-	-	

* BWMS shut down due to filter clogging caused by high suspended solid, ** BWMS shut down because a target TRO concentration was not formed due to high suspended solid and low salinity, *** an error occurred in the equipment maintenance process. (1) UW: uptake water, CW: untreated discharge water, TW: treated discharge water.

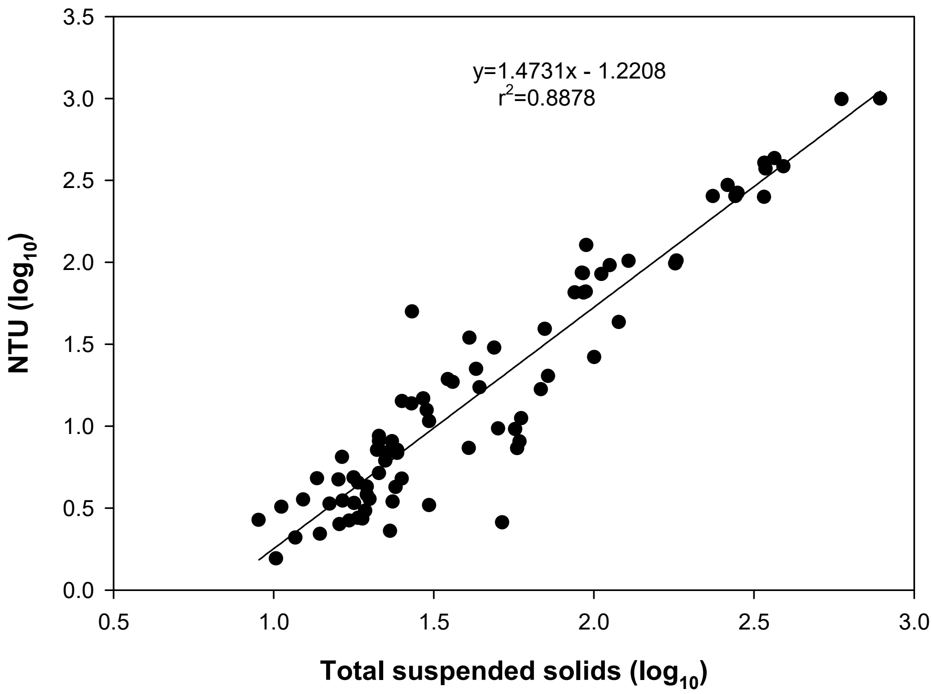

Figure 3. Correlation between total suspended solids (TSS) and nephelometric turbidity units (NTU) measured in shipboard tests.

3.2. Vessel Installed with a Type A BWMS (Filter and UV Unit)

On-board testing of a type A system was conducted on a vessel transiting the ports of Pusan, Shanghai, and Xiamen (Table 3). The environmental conditions of uptake water in the three ports were water temperature, 25–30 °C; salinity, 19–32; pH, 8.02−8.17; NTU, 7.5−996; TSS, 28.9−690 mg L^{-1}; POC, 0.68−10.4 mg L^{-1}; and DOC, 0.81−1.16 mg L^{-1} (Table 4). Ballast water taken up at Pusan Port was discharged while sailing from Pusan to Shanghai. Consequently, the storage time for the ballast water on the vessel was the shortest (21 h) among the shipboard tests conducted in this study. No significant difference was found in the physicochemical parameters in uptake and discharge water (Table 3). In the Pusan Port uptake water there were 4600 ± 2600 organisms m^{-3} for those ≥ 50 µm and 5.49 ± 0.95 organisms mL^{-1} for those in the size range ≥10 to <50 µm, which exceeded only the criteria of organisms ≥50 µm for shipboard testing (Table 5). For organisms <10 µm, the levels of *E. coli* and *Enterococcus* were 354 ± 68.4 and 45.1 ± 32.8 CFU 100 mL^{-1}, respectively. In the treated discharged water, organisms ≥ 50 µm were not detected, while there were 0.85 ± 0.42 organisms mL^{-1} in the size range ≥10 to <50 µm. For organisms <10 µm, *E. coli* was not detected, and there were 7.41 ± 5.41 CFU 100 mL^{-1} for *Enterococcus*. These values met the criteria for discharge of treated water in the shipboard test (Table 5). Although heterotrophic bacteria are not included in the D2 criteria, the levels were high in all test waters. Organisms in Pusan Port water were highly diverse, including four phyla and 14 species for those ≥50 µm, and four phyla and 20 species for those in the size range ≥10 to <50 µm (Tables 6 and 7).

Table 5. Biological parameters in ballasting and deballasting waters for three types of BWMS installed on vessels.

Type of BWMS	Trial No		Sample	≥ 50 µm	10–50 µm		Chl-a	Active Chl-a	Heterotrophic Bacteria	*E. coli*	Intestinal Enterococci	*Vibrio cholera*
					Autofluorescence	FDA						
				(Organisms m^{-3})	(Organisms mL^{-1})		(µg/L)	(µg/L)	(CFU/100 mL)			
Filter + UV	#1	B	UW$^{(1)\dagger}$	4600 ± 2600	13.6 ± 2.03	5.49 ± 0.95	-	-	TNTC $^{(2)}$	354 ± 68.4	45.1 ± 32.8	0
		DB	CW$^{(1)}$	6800 ± 1900	4.99 ± 1.46	4.11 ± 1.36	-	-	TNTC	14.4 ± 15.1	>2419	0
			TW$^{(1)\dagger\dagger\dagger}$	0.0	0.85 ± 0.42	0.32 ± 0.17	-	-	TNTC	0	7.41 ± 5.41	0
	#2	B	UW †	61400	71.3 ± 38.8	28.0 ± 15.5	-	-	-	-	-	-
	#3	B	UW †	6400	36.0 ± 16.7	10.6 ± 5.4	-	-	-	-	-	-
Electrolysis	#4	B	UW ††	407 ± 27	123 ± 17	51.2 ± 6.74	0.05 ± 0.02	0.08 ± 0.02	4000 ± 4000	4.44 ± 7.26	53.3 ± 30	0
		DB	CW	993 ± 375	6.51 ± 2.3	5.21 ± 1.82	0	0	3100 ± 2000	2.22 ± 4.41	8.89 ± 12.7	0
			TW †††	0	0	0	0	0	132 ± 158	0.74 ± 2.67	2.59 ± 6.56	0
	#5	B	UW ††	5100 ± 2100	436 ± 184	201 ± 90.3	0.14 ± 0.03	0.11 ± 0.05	4100 ± 2900	279 ± 50.9	876 ± 202	0
		DB	CW	563 ± 78	91 ± 129	89.8 ± 128	0.07 ± 0.05	0.03 ± 0.02	1000 ± 585	1.11 ± 3.33	28.9 ± 28.0	0
			TW †††	0	0	0	0.015	0	27900 ± 14362	1.11 ± 3.20	12.2 ± 23.1	0
	#6	B	UW ††	2400 ± 976	194 ± 87.7	98.5 ± 52.8	0.07 ± 0.01	0.09 ± 0.01	889 ± 540	394 ± 107	256 ± 71	0
		DB	CW	952 ± 105	29.7 ± 25	31.0 ± 26.7	0.04 ± 0.02	0.03 ± 0.02	353 ± 329	14.4 ± 12.4	0	0
			TW †††	0.3 ± 0.4	0.01 ± 0.01	0.07 ± 0.01	0.01 ± 0.07	0	22.2 ± 23.5	0	0	0
	#7	B	UW †	307 ± 111	63.2 ± 4.7	29.8 ± 2.62	3.23 ± 0.40	0.34 ± 0.01	613 ± 291	2350 ± 418	1400 ± 206	0
	#8	B	UW †	18400	71	34	0.33	0.47	1500 ± 324	96.7 ± 46.2	430 ± 261	0
		B	UW †	3100	73	43	0.07	0.07	327 ± 159	20	80 ± 10	0
		B	UW ††	2400	100	103	0.08	0.08	1400 ± 579	66.7 ± 11.5	337 ± 55.1	0
		DB	CW	535 ± 536	1.06 ± 0.5	9.93 ± 5.03	0.01 ± 0.00	0.02 ± 0.01	1200 ± 794	26.7 ± 22.4	21.1 ± 7.82	0
			TW †††	0	0.07 ± 0.2	0.14 ± 0.41	0	0	8.44 ± 63.0	0	0.37 ± 1.92	0
Filter + Electrolysis	#9	DB	UW †	693 ± 41.8	9.73 ± 3.49	7.42 ± 5.11	0	0.25 ± 0.07	186 ± 204	4.44 ± 7.26	18.9 ± 17.6	0
			CW	491 ± 7.02	11.7 ± 2.72	3.10 ± 1.40	0	0.04 ± 0.01	393 ± 174	1.11 ± 3.33	6.67 ± 7.07	0
			TW †††	0	0.01 ± 0.03	0.06 ± 0.10	0	0	34.1 ± 40.0	0	0	0
	#10	B	UW †	876 ± 151	8.05 ± 2.12	14.8 ± 5.75	6.09 ± 0.33	0.45 ± 0.03	1400 ± 1700	2.22 ± 6.67	50.0 ± 39.7	0
		DB	CW	346 ± 47.6	1.24 ± 0.39	6.91 ± 2.69	0	0	506 ± 212	5.22 ± 5.33	0.89 ± 1.36	0

UW†: the number of organisms ≥10 to <50 µm in size does not meet the criteria of test water, UW††: the number of organisms ≥10 to <50 µm in size does meet the criteria of test water, TW†††: the number of organisms in discharge water does meet the D-2 criteria. [(1)] UW: uptake water, CW: untreated discharge water, TW: treated discharge water. [(2)] TNTC: too numerous to count.

Table 6. Number of phylum and species of ≥10 and <50 sized organisms in shipboard tests.

	Trial Number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
PHYLUM										
Bacillariophyta	13	4	4	38	16	34	8	37	15	9
Dinophyta	1	-	-	-	-	10	-	-	1	-
Heterokontophyta	5	1	1	1	3	4		3	4	4
Protozoa	1	1	-	-	-	-	-	-	1	1
Phylum/species	4/20	3/6	2/5	2/39	2/19	3/39	1/8	2/40	4/21	3/14

Table 7. Number of phylum and species of ≥50 sized organisms in shipboard tests.

	Trial Number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Phylum										
Arthroda	10	5	6	18	10	10	5	12	11	11
Annelida	1	-	-	1	1	-	-	-	-	1
Chaetognatha	1	-	-	1	1	-	-	1	1	-
Mollusca	2	1	1	-	-	-	-	-	-	-
Phylum/species	4/14	2/6	2/7	3/20	3/12	1/10	1/5	2/13	2/12	2/12

In terms of the biological conditions of the uptake water and control discharge water, the number of organisms ≥50 µm in size ranged from 307 to 61,400 organisms m^{-3}, and those in the size range ≥10 to <50 µm varied from 1 to 436 organisms mL^{-1}. In six shipboard tests in which the biological efficacy test was performed, organisms >50 in size satisfied the criteria of test water in all test cycles, but organisms ≥10 to <50 µm in size satisfied the criteria of test water of four test cycles. The number of organisms between ≥50 µm, and ≥10 to <50 µm in size in the treated discharge water was less than 1 organism m^{-3} and 1 organism mL^{-1}, respectively. Among the organisms <10 µm in size in the control discharged water, the number of microorganisms in the control water was lower than that of the uptake water, but the microorganisms in the control water were higher than those in the uptake water in the first test cycle. The organisms <10 µm in size in treated discharge water were significantly lower than that of uptake water and control discharge water, but heterotrophic bacteria increased 6.6 times in the fifth test cycle. *Vibrio cholera* was not detected in any of the test waters during the shipboard tests. The commissioning test, which evaluates the performance of BWMS after installing the BWMS on the ship, determines whether the discharged treated water satisfies D-2 without the criteria of uptake water. Six shipboard tests in which the biological efficacy test was performed satisfied the criteria of commissioning test, and of four test cycles were satisfied with the criteria of shipboard test for type-approval test of BWMS.

For the filter backwashing conditions for A type and C type BWMSs, the filter differential pressure (DP) was set to 0.6 bar. In three attempts at ballasting in Shanghai Port, the DP of the type A system exceeded 0.7 bar as soon as ballasting was initiated, and the BWMS was shut down after 3 min. This occurred because the TSS concentration was so high that suspended particles clogged the filter, and backflushing was activated. However, the BWMS was stopped because it was unable to meet the DP operating conditions within 3 min. During transit from Shanghai Port to Xiamen Port, the filter unit was continuously backflushed to unclog the filter. However, in Xiamen Port the TSS levels also caused clogging of the BWMS. The filter was removed from the equipment and underwent maintenance, and in Yantian Port the BWMS was again operating normally. Therefore, only the uptake water conditions for Shanghai and Xiamen ports were analyzed. In uptake water at Shanghai and Xiamen ports, the organism levels (Table 5) were 61,400 and 6400 organisms m^{-3} for those ≥50 µm and 28.0 ± 15.5, respectively, and 10.6 ± 5.4 organisms mL^{-1} for those in the size range ≥10 to <50 μm (organisms <10 μm were not analyzed).

3.3. Vessel Installed with a Type B BWMS (Electrolysis Unit)

On board testing of a type B system was conducted on a vessel in ports of Singapore, Kelang, and Penang (Malaysia), and Hong Kong and Shanghai (China) (Table 3). As this vessel had four ballast water tanks that could be used for shipboard tests, two ballast tanks were used for complete ballasting and deballasting shipboard tests in Singapore, Kelang, Hong Kong, and Shanghai. However, the BWMS did not operate at Shanghai Port because of the low TRO concentration generated (average 1.96 ± 0.13 mg L^{-1}), which was well below the shutdown level specified in the operating manual (TRO <4 mg L^{-1} for 10 min). The other two ballast tanks were used for testing ballast water from Penang (30%), Singapore (30%), and Hong Kong (40%), and a deballasting test was carried out on the way from Hong Kong to Shanghai (Table 3).

The ranges for environmental parameters of uptake water in the Singapore, Kelang, Penang, and Hong Kong ports were 21.5–30.7 °C for the water temperature, 27.5–33.7 for the salinity, 7.85–8.17 for pH, 4.05–31.9 for NTU, 22.0–51.5 mg L^{-1} for TSS, 0.53–0.70 mg L^{-1} for POC, and 0.81–1.16 mg L^{-1} for DOC (Table 4). For Shanghai Port the water temperature was 13.5 °C, and the salinity was 1.53, both of which were lower than the other ports. The amount of neutralizing agent (45–55 wt.% of sodium thiosulfate, $Na_2S_2O_3$) injected during full ballasting and deballasting was 0.01, 0.013, and 0.0097 g neutralizer m^{-3} in the fourth, fifth, and sixth trials, respectively. However, when deballasting mixed water (eighth trial), approximately 0.019 g neutralizer m^{-3} of neutralizing agent was injected, which was twice as much as the average amount injected in other test cycles (Table 3). In terms of the biological conditions of the uptake water, the number of organisms ≥50 μm ranged from 407 to 7988 organisms m^{-3}, and those in the size range ≥10 to <50 μm varied from 96 to 123 organisms mL^{-1}; these values met the test water standard. The treated discharge water also met the D-2 criteria. Although the number of organisms in the size range ≥10 to <50 μm was low in the uptake water at Shanghai Port, the measured chlorophyll-*a* and active chlorophyll-*a* values in the water were higher than those measured in other shipboard tests.

The active chlorophyll-*a* concentration and microscopic counts of living organism (FDA fluorescence) were only significantly correlated for active chlorophyll-*a* concentrations less than 0.2 μg L^{-1} (Figure 4). The value of Phyto-PAM exceeding 0.2 was measured when the TSS concentration was high (Figure 4). Among the organisms <10 μm in size in the uptake water, *E. coli* numbers ranged from 4.44 to 394 CFU 100 mL^{-1}, while *Enterococcus* ranged from 53.3 to 1400 CFU 100 mL^{-1}; for treated discharge water the ranges were 0–1.11 and 0–12.2 CFU 100 mL^{-1}, respectively. The heterotrophic bacterial counts ranged from 327 to 4100 CFU 100 mL^{-1} in the uptake water, and 8.44–132 CFU 100 mL^{-1} for treated discharge water, except for Kallang Port. *Vibrio cholerae* were not detected in any test water during the shipboard tests (Table 5).

During the ballasting test at Shanghai Port, the BWMS shut down because the TRO concentration did not exceed 4 mg L^{-1} during 10 min of BWMS operation; this is the shutdown value for BWMS operation. In two attempts at BWMS operation, the average TRO concentrations were 2.02 ± 0.1 and 1.91 ± 0.08 mg L^{-1}. In water from Singapore Port, organisms ≥50 μm in size (encompassing three phyla and 20 species,) and those in the size range ≥10 to <50 μm (three phyla and 39 species) were highly diverse (Tables 6 and 7).

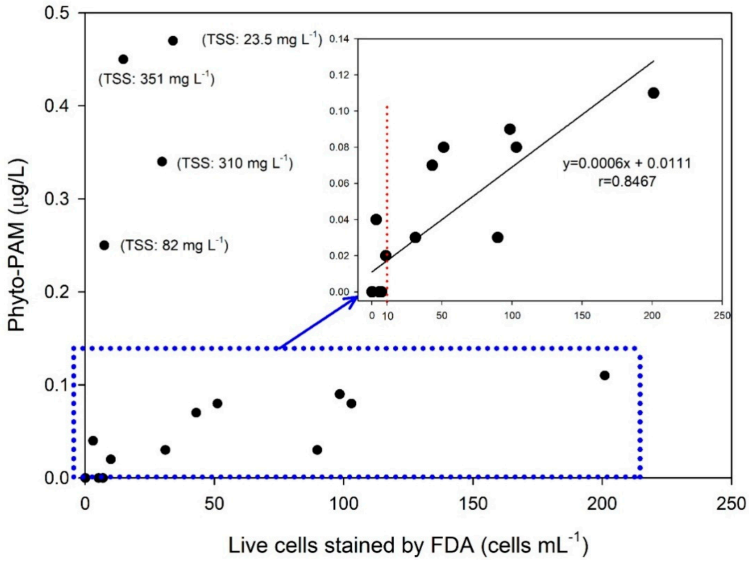

Figure 4. Correlation between live cells stained by FDA and Phyto-PAM values in the shipboard tests.

3.4. Vessel Installed with a Type C BWMS (Filter and Electrolysis Unit)

The vessel with the type C system traveled from Pusan Port to Ningbo and Shanghai ports, and then returned to Pusan Port (Table 3). The ballast water taken up at Ningbo Port was discharged while sailing from Shanghai to Pusan because of the short time between Ningbo and Shanghai ports (Table 3). After ballasting in Ningbo Port, an error occurred in the equipment maintenance process, so in Shanghai port the ballasting and deballasting tests were only performed on uptake water using the ship's ballast pump. Among the physical conditions of the uptake water in the two ports, the water temperature and pH were not significantly different, but the salinity of Shanghai Port water was lower than that for Ningbo Port, and the NTU and TSS values for Shanghai Port water were approximately five-fold higher than for Ningbo Port (Table 4).

In the uptake water of Ningbo Port, the number of organisms ≥50 μm met the test water standard, whereas the number of organisms in the range ≥10 to <50 μm did not meet the standard. Organisms in each size category were rarely detected in the treated discharge water, thus satisfying the D-2 criteria. Among the organisms <10 μm in size, *E. coli* and intestinal enterococci were at low concentrations in the uptake water and control discharged water and were not detected in the treated discharged water. The number of heterotrophic bacteria in the uptake water was lower than in the control discharged water, but higher than in the treated discharged water (Table 5).

During ballasting at Shanghai Port, the number of organisms ≥50 μm in size in the control discharge water was naturally reduced relative to the uptake water by approximately three-fold, and organisms in the size range ≥10 to <50 μm were reduced by approximately two-fold. The chlorophyll-*a* and active chlorophyll-*a* values were high in the uptake water, but neither was detected in the control discharged water. Among the organisms <10 μm in size in the control discharged water, the number of heterotrophic bacteria was approximately three-fold lower than in the uptake water, the number of *E. coli* was approximately two-fold higher, and almost no intestinal enterococci were detected in the treated discharge water (Table 5). In Ningbo Port water, organisms ≥50 μm were diverse (two phyla and 12 species), and those in the size range ≥10 to <50 μm were highly diverse (three phyla and 14 species) (Tables 6 and 7).

4. Discussion

The POC and DOC concentrations measured at the ports during this study were within the range of, or a little higher, than values for test waters for approval of BWMSs. However, the TSS concentration was higher than that for test waters in the land-based test, and this was particularly apparent in ports located near Shanghai (Tables 1 and 4). Depending on the particle size distribution, density, and sediment quality, suspended solids can cause problems including filter clogging, interference with UV transmittance, and increased oxidation potential [13,14].

The filter units installed in BWMSs are primarily to remove organisms ≥50 µm in size, and not to remove suspended solids, so the filter sizes are usually 40–50 µm (Figure 2). To enable normal BWMS operation, the equipment is designed for backflushing when the DP of the filter inlet and outlet increases. In a submission by China for the 70th MEPC, the concentration of suspended solids in Yangsan Port (Shanghai) was reported to be 230–1560 mg L^{-1} throughout the year [13]. In this study, the concentration of TSS in the uptake water of the port near Shanghai was 260–785 mg L^{-1}. At this level of TSS, filter equipment will largely be unable to operate near the Yangtze River. In cases where vessels cannot properly treat ballast water in ports having high suspended solids, those vessels could be permitted to take on ballast water without treatment, but exchange that ballast water on the high seas with BWMS-treated seawater. However, because of safety issues for vessels and crews associated with such ballast water exchange, no decision was made at the 70th MEPC [18].

Milliman et al. [19] and Shen [20] suggested that approximately 40% of the suspended solids entering the estuary of the Yangtze River are deposited in the estuary. Wang et al. [21] studied the major components of TSS in the estuary of the Yangtze River using a laser particle size analyzer. They found that suspended solids in the estuary comprised 16% clay, 42% silt, and 42% sand. It was also reported that the suspended particles in the estuary of the Yangtze River were larger than those in the estuary of the Huanghe River. This suggests that the suspended solids in Shanghai Port should more readily settle over time. This was confirmed in the pretreatment process for the TSS test in Shanghai Port, specifically that the TSS concentration in the 10th test decreased significantly during deballasting in Pusan Port. For this reason, filter clogging will not occur during deballasting. Therefore, for high turbidity areas such as Shanghai Port, ballasting could involve bypass of the filter with only UV operating, and then during deballasting the water can be treated by both filtration and UV treatment, as the BWMS should operate normally without filter clogging. This method may not remove 100% of organisms ≥50 µm in size, in accordance with the D-2 standard, but should remove most. However, it is very unusual for filtration to be used at deballasting, perhaps because the crew and manufacturer consider maintenance of the filter too difficult. Ship owners would probably be unhappy as this approach may result in additional sediment accumulation at the bottom the ballast tank. For this reason, most of the captains manage ballast tanks efficiency, and try not to do ballasting in Shanghai, China. However, if ballasting is only needed for an emergency situation in a port having high suspended solid concentrations, then this approach using only a filter unit in deballasting should be effective in preventing invasions by exotic aquatic species. The TRO generated in BWMSs having electrolytic equipment is designed to maintain a level sufficient to kill organisms during storage in ballast tanks, but UV equipment in BWMSs have no sterilizing effect during storage. To compensate for this, those BWMSs using UV equipment also perform UV treatment during deballasting. Among those BWMSs using filter devices, only one BWMS has been approved for application to both ballasting and deballasting. In addition, if a new filtration system is developed that can filter even in areas with high suspended solids, it may be an alternative to perform disinfection during ballasting.

To apply filtration during deballasting it is necessary to know the concentration of TSS in the port water entering the vessel. In this study, the Pearson's correlation coefficient (r^2) for NTU and TSS was 0.8878, indicating that the concentration of TSS can be indirectly measured using a turbidity meter (Figure 3). In ports suspected of having a high TSS concentration, the crew could firstly measure the turbidity using sea-to-sea mode. If the measured turbidity value exceeds standard criteria, the BWMS could be programmed to operate as described above. In addition, in high turbidity conditions the UV transparency is lowered because of shadowing effects resulting from abrasive polishing of the surface of the UV lamp, and the accumulation of TSS components during ballasting, thereby reducing the UV intensity and reducing the BWMS efficiency [14].

Electrolysis systems involving no filter may be preferred as they are easier to maintain and operate. However, electrolysis devices without filters (type B) can also have problems treating water from ports having high concentrations of suspended solids [14]. Interference with sensor measurement can occur because of the introduction of suspended matter to the TRO sensor measurement area, which can cause failure of the BWMS operation through the TRO measurements. As a specific TRO is formed in the type B system from current and voltage, it is possible to predict the current and voltage values required to generate target TROs. The target TRO is set in the BWMS by adjusting the current voltage to achieve the target value. If operation of the BWMS is controlled by current and voltage when ballasting in ports having water containing high TSS concentrations, it may be possible to prevent shutdowns that may occur because of malfunction of the sensor caused by the suspended solids. To manage ballast water more stably when using this method, it is necessary to use a portable TRO meter to record whether the concentration formed is in the operating range, and to measure residual TRO during the period of ballast water storage.

In type B systems it is difficult to generate high TRO concentrations when the salinity is low, and an increase in the oxidation potential is necessary where the concentration of organic substances in suspended matter is high [14]. In this study the type B system did not achieve the target TRO in the low salinity conditions of Shanghai Port (the average TRO was <2.0 mg L^{-1} over approximately 10 min), so the BWMS was stopped. The portable TRO meter value was similar to the TRO measurement in the BWMS, so it was not a malfunction of the TRO sensor caused by suspended solids. This type of BWMS is equipped with a salinity meter, and when low salinity is detected in a port, the flow rate is automatically adjusted to achieve the allowable TRO concentration. As the type C system forms a target TRO using a salt water tank, there is no problem in operating this type of BWMS in a fresh water area, other than the disadvantage of having to fit an extra tank or ballast tank designated to store seawater on the vessel. In addition, all type C systems have a filter unit, making it difficult to operate these BWMSs when high TSS concentrations are involved.

For approval, land-based tests of BWMSs have to be conducted to determine holding times. According to the BWMS Code, in a land-based test the BWMS must operate successful in at least five consecutive test cycles at each salinity. For two test cycles, according to IMO guideline G9 [22] the holding time should be five or more days, to assess the risk of disinfection byproducts generated in BWMSs that make use of active substances, and should be performed using the holding time specified by the manufacturer. Vessels are constantly entering and leaving ports that are sometimes in close proximity, so uptake and discharge of ballast water may occur within one day. In other cases, ballasted waters may be stored for at least 20 days before discharge, depending on the shipping route [23,24]. When the holding time is long, microbial pathogens <10 μm in size may increase in number because of the decomposition of organic matter, and as a result the water at discharge may not meet the D-2 standard. In this study, the microbial concentration in treated discharge water was higher than that in uptake water in the fifth test, which had the longest storage time (six days). As systems having the UV devices repeat UV sterilization at discharge, the problem of microbial growth during long-term storage may be less than that for systems using electrolysis devices. To solve this problem, BWMSs having electrolysis devices could be used to treat ballast water during discharge, with subsequent neutralization or UV treatment. In this case, since it is neutralized and discharged immediately after using the electrolysis device, the time may be too short to treat pathogenic microorganisms. As a result of the biological efficacy testing immediately after treatment in the land-based test for a type-approval test of BWMS, only pathogenic microorganisms were detected in 7 out of 30 test cycles, and most of the detected pathogenic microorganisms were less than 1 CFU 100 mL^{-1}. However, it takes about an hour to sample by neutralizing after continuous sampling, so the contact time of active substance (TRO) is longer than the method proposed in this paper. This proposed method should be conducted on land-based or on a shipboard test to evaluate whether it is effective in killing the microorganisms and is not hazardous to the environment. In the land-based test, a test should also be carried out as to how much TRO concentration is appropriate.

Another method to remove pathogenic organisms associated with long-term storage is to maintain the residual TRO concentration in the tank by applying partial ballasting to the ballast tank. In BWMSs fitted with electrolysis devices, TRO is formed during ballasting, but residual amounts remain during storage in the ballast tank, and this residual contributes to the killing of organisms. In the eighth trial of sequential ballasting, it was found that the residual TRO concentration in the ballast water tank was maintained, inferred because the amount of neutralizing agent that had to be injected increased by a factor of two over other periods during deballasting (Table 3). However, future research into the formation of disinfection byproducts (DBPs) will be necessary, because in maintaining the residual TRO concentration and using electrolysis devices during deballasting it may be possible to form more disinfection byproducts than occurs using the approved operational method [25]. An approach to compensating for the shortcomings of filter clogging in the presence of high suspended solid concentrations, the problem of TRO formation in fresh water areas and the rapid reduction of residual TRO by organic substances, is to treat ballast water using an in-tank method using TROs. However, using this approach it is difficult for the active substance to diffuse throughout the ballast water if the ballast tank in the hull contains complex bulkheads. Thus, in building new vessels it is important to design ballast tanks that take account of the diffusion of active materials.

The IMO allows for use of an indicative analysis method that counts living organisms in the size range ≥10 to <50 μm in a device developed using the Pulse-Amplitude-Modulation (PAM) principle in a commissioning test that verifies performance after installation of a BWMS on a vessel [26,27]. The indicative analysis uses an instrument-based method for counting living organisms instead of methods involving direct counts using a fluorescent microscope or growth medium. The Phyto-PAM can analyze the chlorophyll of living organisms in the size range ≥10 to <50 μm within 10 min in treated discharge water, but not the number of these organisms. When the TSS concentration was high, an outlier of the Phyto-PAM value was often measured, indicating the possibility that the measured value might be disturbed by turbidity (Figure 4). In addition, the D-2 criterion for treated discharge water is <10 organisms mL^{-1}, which increase the level of inaccuracy because this value is close to the detection limit (Figure 4). Results reported by Gollasch and David [26] and the document submitted by Singapore to the 75th MEPC suggest that indicative analysis can underestimate the true levels of these organisms [27]. The Maritime and Port Authority of Singapore surveyed ballast water in 11 vessels operating BWMSs that entered the main port of Singapore between April and November 2019, and three of these did not meet the D-2 standard for treated discharge water [26]. However, for shipboard tests in our study, conducted using six normal BWMSs and involving both ballasting and deballasting, the reliability of the approved BWMSs was confirmed because in all tests they satisfied the D-2 standards for the discharge of treated water.

5. Conclusions

The approved BWMSs tested in this study performed well in the treatment of typical seawater influents, but failed when high concentrations of suspended solids under near-fresh water conditions were involved. We suggest the following to address this in the emergency situation, while satisfying the D-2 requirements for discharging ballast water.

1. For water having high suspended solid concentrations, it is recommended that BWMSs using filter devices undertake the filtering during deballasting rather than ballasting. For BWMSs using electrolysis, it is recommended that parameters including current and voltage be controlled, rather than controlling the TRO sensors.
2. For long-term storage of treated ballast water, especially those containing high concentrations of suspended particles, retreatment of ballast water prior to discharge may be necessary.
3. When partial ballasting is performed, additional ballasting and treatment may sustain residual TRO level in the tanks that may assist in reducing harmful bacterial level.

In addition, regular training of the crew of vessels in BWMS operation and maintenance plays an important role in the smooth implementation of the system. To use the proposed method, the set value for NTU for use of a filter device in ballasting, and the set value for determining the main device for use in deballasting should be verified through land-based and/or shipboard tests. In particular, the method for maintaining a residual TRO and for using electrolysis device in deballasting should be studied with respect to environmental risks because of possible effects on the concentration or characteristics of disinfection byproducts and the substance for neutralization in ballast water.

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