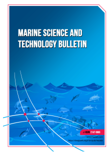
Mar. Sci. Tech. Bull. (2022) 11(4): 397-415
e–ISSN: 2147–9666
info@masteb.com

dergipark.org.tr/en/pub/masteb
www.masteb.com
DOI: 10.33714/masteb.1162688



Marine Science and Technology Bulletin

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REVIEW ARTICLE

Ballast water problem: Current status and expected challenges

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ARTICLE INFO

Article History:
Received: 16.08.2022
Received in revised form: 15.09.2022
Accepted: 07.10.2022
Available online: 22.12.2022

Keywords:
Ballast water management
Ballast water treatment
Invasive species

ABSTRACT

Transporting non-native species in ballast tanks has been a major challenge over the years. The number of surviving species in the host environment is quite small compared to those of all introduced. However, even a single species can cause great harm to the environment, economy, and public health. Ballast water treatment issues are difficult and complex as the performance of the treatment is highly affected by the variable characteristics of the seawater. In addition, targeted organisms are in a wide spectrum. The International Convention on the Control and Management of Ship Ballast Water and Sediments requires ships to manage ballast water with a Type Approved System in compliance with the Ballast water discharge standard defined in the Convention. The Ballast Water Management Systems Approval (G8) Guide was revised in 2016 and accepted as the BWMS Code (Ballast Water Management Systems Approval Code) as the mandatory regime in 2018. According to the implementation schedule of this mandatory approval regime, the ballast water management system installed on or after 28 October 2020 must be type-approved according to the IMO's revised G8 requirements. Several systems use different methods with their limitations. However, the ballast water problem does not seem to end only with the installation of the systems on ships. Although substantial international progress has been made in ballast water management (both technically and regulatory), there are still several issues regarding effectiveness, compliance monitoring, and the environment.

Please cite this paper as follows:

Bilgin Güney, C. (2022). Ballast water problem: Current status and expected challenges. *Marine Science and Technology Bulletin*, *11*(4), 397-415. https://doi.org/10.33714/masteb.1162688

ABBREVIATIONS

BW	Ballast Water
BWMS Code	Ballast Water Management Systems Approval Code
BWM Convention	International Convention for the Control and Management of Ship's Ballast Water and Sediments
BWTS	Ballast water treatment system (the same as BWMS)
BWMS	Ballast water management system (the same as BWTS)
D-1	Regulation D-1, Ballast Water Exchange Standard
D-2	Regulation D-2, Ballast Water Performance Standard
G8	Guidelines for Approval of Ballast Water Management Systems
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
USCG	US Coast Guard

Introduction

Ballast is a term that describes any solid or liquid placed on a ship to provide safe navigational conditions by increasing draft, changing trim, regulating stability, or keeping stress loads within acceptable limits. With the use of steel-hulled ships, water began to be used as ballast. However, as a result, ships not only transfer commercial products and people but transfer

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around 12 billion tons of ballast water among biogeographic regions annually (Bax et al., 2003).

Mostly, the ballasting procedure occurs at the ports when the ships discharge their load. As they discharge their load, ships need to compensate for this lost weight. In addition to this, ships also need to compensate for weight loss caused by fuel consumption, freshwater consumption, etc. along the voyage. To compensate for the weight loss, water from the surrounding is pumped into the ballast tank. During the ballasting process, anything small enough to pass through the ballasting system, including the organisms, is also taken into tanks. These organisms are then translocated with the ballast water and discharged to regions where they did not exist before. Due to human activities, many nonindigenous species enter new environments all over the world, but invasive species are among the most important human-induced threats to the oceans (Gollasch, 2006), and ballast waters have the most important share among all vectors. (Lavoie et al., 1999; Olenin et al., 2000; Steve Raaymakers, 2002; Occhipinti-Ambrogi & Savini, 2003).

The transportation of non-indigenous species in ballast tanks has attracted the scientific world's attention since the 1970s (Medcof, 1975; Carlton, 1979). The detection of the Black Sea-origin zebra mussel in the Great Lakes region of America (Hebert et al., 1989)., the poisonous seaweed species originating from Japan in Australia (Hallegraeff & Bolch, 1991), and the carnivorous honeycomb jellyfish from the eastern coast of America in the Black Sea (Berdnikov et al., 1999) raised also the attention of the governments and the public.

Ballast water management is a multifaceted issue where international rules, ship-related technical solutions, and environmental factors coexist. Due to the dimensions of the problem global action was required to solve it. The International Maritime Organization (IMO) (the United Nations' specialized agency responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships) adopted the International Convention for the Control and Management of Ship's Ballast Water and Sediments in 2004 and the Convention is in force since September 8, 2017. The convention is also known as Ballast Water Management Convention (BWM Convention for short). Currently, there are 91 contracting parties (representing 92.23% of world merchant tonnage) to the BWM Convention (the actual numbers can be followed from IMO's official website). All vessels registered under the BWM Convention Contracting Parties that receive and use ballast water during international voyages are obliged to comply with the Convention rules.

On the other hand, instead of being a party to the convention, the United States of America has developed its own Legislation (i.e., Final Rule). The 'Final Rule' is enforced by the US Coast Guard (USCG) and the Environmental Protection Agency. 'Final Rule' became effective in June 2012 and applies to all vessels discharging in U.S. waters that take on ballast water outside the U.S. and Canadian Exclusive Economic Zone.

The Consequences of Transport of Ballast Water Organisms

There are numerous examples of introductions of nonindigenous species to new regions with ballast waters all over the world. The European Environment Agency reports that 346 ballast-related non-indigenous species were introduced into European seas between 1949 and 2021 (European Environment Agency, 2021). The number of species transported to the Baltic Sea with ballast waters was reported to be 105 as of 2005 (Leppäkoski & Gollasch, 2006), in the Laurentian Great Lakes (located on the Canada-US border) 43 non-native animals and protists were established between 1959 and 2003 and the introduction of 67% of these species was again related to ballast water (Grigorovich et al., 2003).

The number of surviving species in the host environment is quite small compared to the total number of introduced species. However, even a single species can cause serious damage to the receiving ecosystem. The settlement of organisms in a new environment depends on certain factors. The most important of these include the absence or scarcity of natural enemies, the organism's ability to spread widely, and the existence of suitable and empty ecological niches (Cirik & Akçalı, 2002). The survival of these species in the new environment is largely determined by differences in physical and chemical properties between donor and recipient sites; the greater these differences, the less likely the survival of living organisms, but never zero (National Research Council, 1996). Their invasion success, on the other hand, depends on the inoculation density of the organisms and their ability to survive and reproduce (Hess-Erga et al., 2019). If all conditions are favorable in the new area, survived species may become invasive, and significant changes occur in the ecology: these species struggle with local species for habitat and food; they use local species as a food source; they can live as parasites on native species; they may cause hybridization of local species; they change the habitat; they may change environmental conditions such as water clarity and hydraulic regime, chemical regime; they change the food web in the ecosystem and displace native species, causing a reduction in natural biodiversity (Nichols, 2001; Raaymakers, 2002). There are numerous examples of the introduction of invasive species by ballast water, some of which have devastating effects.

The introduction of zebra mussels (*Dreissena polymorpha*) into North America is one of the most severe examples due to its rate of spread and continuing ecological and economic consequences. They were first identified in North America in 1988 (Hebert et al., 1989). The studies on the physiological ecology of North American zebra mussels suggest that they probably originated from the northern shore of the Black Sea and reached to Great Lakes region by ballast water (McMahon, 1996). Just a few years after they were detected, they had spread to many of the inland waterways. (Roberts, 1990) and by 2022, zebra mussels are reported to be found in 31 states in the USA (Benson et al., 2022). Their biological features (such as high fertility, pelagic larval stage, and bysso-pelagic drifting ability of juveniles) and human activities such as commercial shipping, fishing, and boating were the main reasons for their rapid spread (Griffiths et al., 1991). Their ability to attach to hard surfaces with byssal threads with around 1-2 Newtons and to form extremely large colonies (up to 700,000 individuals/m^2) makes zebra mussels a major threat (Dölle & Kurzmann, 2020).

They colonize water supply pipes of many structures such as public water supply plants, industrial facilities, hydroelectric and nuclear power plants, etc. (Roberts, 1990). Monitoring and control of zebra mussels cost an average of US$30 million per year in the Great Lakes area of the United States during the mid-1990s (Burtle, 2014) and the economic losses of US and Canadian water users in the Great Lakes region between 2000 and 2010 are estimated to be 5 billion dollars (Glomski, 2015).

Figure 1. Water intake pipe clogged with adult zebra mussels (de Kozlowski et al., 2002)

Mnemiopsis leidyi, with its devastating impact on the fisheries in the Black Sea and Azov Seas, is another notorious example of the invasive species introduced with ballast water. *M. leidyi* is a north American comb jelly, introduced to the Black Sea in the early 1980s by ballast water from ships, probably coming from the northwest Atlantic coastal region; and in 20 years spread into the Sea of Azov, Sea of Marmara, the Aegean Sea, and lately the Caspian Sea (Shiganova et al., 2001). Through the years, the density of this species in the Black Sea increased up to 1 kg of biomass per m^2 (Raaymakers, 2002). The success of *M. leidyi* was related to the lack of its predators, the ability for competing with pre-existing gelatinous consumers of zooplankton (such as *Aurelia aurita*), and the predation on eggs and larvae of zooplankton-eating fish (Shiganova et al., 2001). The sharp decline in pelagic fish stocks (especially anchovy stocks) in the Black Sea during this period is largely explained by the mass occurrence of the *M. leidyi* (Kideys, 1994), and as a result, the arrival of this species in this region has had a major impact on the fisheries in the Black Sea and Azov Seas; and The Black Sea coast of Türkiye has been the region most affected by this species (Knowler, 2005).

Over the decades, ballast waters and sediments are also associated with the transfer of phytoplankton that will cause harmful algae blooms (HABs) (Olenin et al., 2000; Butrón et al., 2011; Hallegraeff, 2015a; H. Wu et al., 2017; Lin et al., 2021). In his extensive article, Hallegraeff (2015a) states that in the studies on ships' ballast waters for many years, almost all known harmful algae bloom species have been documented in the viable form (Hallegraeff, 2015a). Harmful microalgae species, which have different structures and degrees of toxicity, directly affect fish and shellfish and cause many diseases such as skin allergies, respiratory disorders, and digestive system disorders in people who consume them. Tourism can be damaged due to aesthetic losses such as foaming on the sea due to discoloration caused by some algae explosions and bad odors (van den Berghl, 2002).

In addition to invasive species, it has been determined that many pathogens, including enterobacteria, *Vibrio* spp., and *Escherichia coli*, which threaten human health, can be transported to different regions in ballast tanks (McCarthy & Khambaty, 1994; Ruiz et al., 2000; Takahashi et al., 2008; Altug et al., 2012; Wu et al., 2017; Lv et al., 2018b).

Shipboard Management of Ballast Water According to The IMO BWM Convention

In the BWM Convention, ballast water management is defined as *'any mechanical, physical, chemical, and biological processes, either singularly or in combination, to remove, render harmless, or avoid the uptake or discharge of Harmful Aquatic Organisms and Pathogens within Ballast Water and Sediments'* (IMO, 2004). Ballast water management on the ship includes all the applications made on the ship for the above-mentioned purpose. 'Control and Management Requirements for Ships' are specified in Part B of the Annex to the Convention. The requirements can be summarized in three items:

1. All ships should have a *Ballast Water Management Plan* approved by the Administration
2. All ships should have a *Ballast Water Record Book*
3. Fulfill ballast water management requirements for ships

The 'ballast water management requirements for ships' stated in the last item are carried out by performing *ballast water exchange* on ships or using a *ballast water treatment system.* The Convention requires ships to manage their ballast water, with a method in compliance with *The Standards for Ballast Water Management* which are defined in the D section of the Annex of the Convention:

Regulation D-1, Ballast Water Exchange Standard is an interim measure that requires ships to exchange their coastal ballast water with open seawater with an efficiency of at least 95 percent volumetric exchange. The ballast water exchange should be conducted 200 nautical miles from the nearest land and in waters with a depth of at least 200 m (MEPC, 2017b).

The main idea behind this method is that large numbers of coastal organisms taken up with ballast water have a low chance of survival when discharged into the open sea, and a small number of offshore organisms taken up during the exchange cannot survive after being released into coastal areas due to the physical and chemical differences between the donor and recipient regions. There are three acceptable ballast water exchange methods such as sequential method, flow-through method, and dilution method.

The sequential method is applied by emptying the existing coastal water in the ballast tanks in the open sea and filling the tanks with open seawater again (MEPC, 2017b). With this method, at least 95% of the ballast water by volume must be exchanged.

The flow-through method is carried out by overflowing the ballast water taken into the ballast tanks from the overflow outlets on the deck or by using different devices (MEPC, 2017b). To achieve the desired 95% exchange standard, it is necessary to pump water up to three times the volume of the tanks and allow it to overflow from the tanks.

In the dilution method, replacing the existing ballast water in the ballast tanks is accomplished by discharging the same amount of water from the bottom at the same rate as the water is taken from the top (MEPC, 2017b). To achieve a 95% volume change with this method, three times the volume of the tanks should be filled from the top and discharged from the bottom of the tank.

Regulation D-2, Ballast Water Performance Standard (IMO, 2004) is the ultimate standard to achieve. This standard defines the maximum permissible concentration of viable organisms and specified indicator microbes harmful to human health in the discharge (Table 1). To achieve this standard ships should be installed with ballast water treatment systems (BWTSs) which are Type Approved according to *Regulation D-3 Approval requirements for Ballast Water Management systems.* (IMO, 2004):

Table 1. Organism limits per volume of ballast water (Campara et al., 2019)

Organism Size Indicator Microbes	IMO D-2 Regulation BW Performance Standard	USCG Regulation BW Discharge Standard
Size ≥50 μm in min dimension	<10 viable organisms/m^3 of BW	<10 living organisms/m^3 of BW
10 ≤ Size < 50 μm in min dimension	<10 viable organisms/mL of BW	<10 living organisms/mL of BW
Toxicogenic *Vibrio cholera* (O1 and O139)	<1 cfu /100 mL, or <1 cfu/g (wet weight) zooplankton samples	<1 cfu/100 mL
Escherichia coli	<250 cfu/100 mL	<250 cfu/100 mL
Intestinal enterococci	<100 cfu/100 mL	<100 cfu/100 mL

Note: μm: micrometer / cfu: colony forming unit / mL: mililiter / m^3: cubic meter

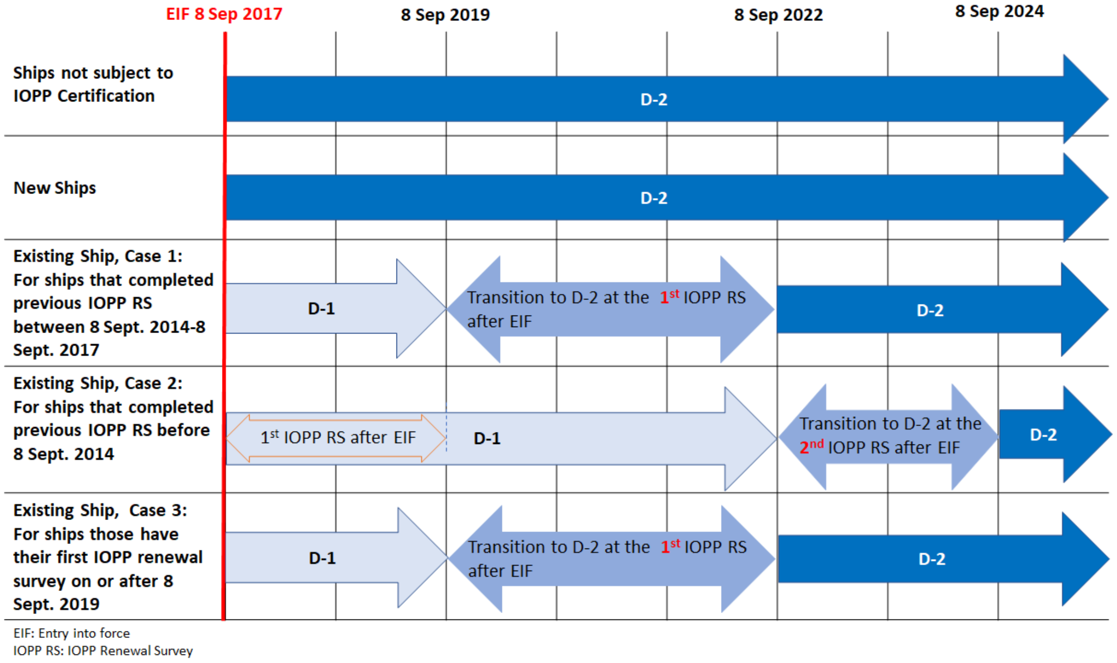

Figure 2. Schedule for compliance with the BWM Convention

As the BWM Convention is in force, the ships registered by the contracting Parties are required to be installed with a ballast water treatment system within a schedule related to their IOPP renewal survey[1] (MEPC, 2017a) and by 8 September 2024, those ships all shall be installed with BWTSs (Figure 2). In Figure 2, '*New Ships*' refer to ships whose keel is laid on or after 8 September 2017, and '*Existing Ships*' refer to ships whose keel is laid before 8 September 2017.

The numerical values of IMO D-2 standards are similar to those identified by the USCG (Table 1). However, there are some differences in the methodologies that they accept for detecting organisms within the size class '10 ≤ size < 50 µm in minimum dimension' and also in their approval processes.

For the uniform application of the BWM Convention, 14 sets of Guidelines were developed by the IMO Member States from July 2005 to October 2008. Some of these Guidelines have been revised since their initial adoption. However, *Guidelines for Approval of Ballast Water Management Systems(G8)* adopted by the Marine Environment Protection Committee (MEPC) is of quite different importance among all guidelines as it is the main component for the implementation of the BWM Convention. These guidelines were also called G8 for short. All ships need to be installed with a system that has a Type Approval Certificate granted following G8. If a ballast water treatment system makes use of an active substance, a second approval process is included in the above-mentioned approval process. The active substance is defined as '*a substance or organism, including a virus or a fungus, that has a general or specific action on or against Harmful Aquatic Organisms and Pathogens* in the BWM Convention (IMO, 2004). With this additional process system's suitability for safety, human health, and the environment is evaluated. This additional process should be following the *Procedure for approval of ballast water management systems that make use of active substances (G9)*, which is called G9 for short.

The Revision of Guidelines for Approval of Ballast Water Management Systems(G8)

Even though the first G8 has provided an important and detailed description of the tests that must be completed and the procedures that must be followed to grant IMO Type Approval to a ballast water management system (BWMS), some gray areas have been identified over the years. Recognizing the differences in the approval processes of the systems based on the applications of the administrations, the IMO Marine Environment Protection Committee determined that there are some uncertainties in the G8 guideline regarding the approval processes and these uncertainties may affect the system reliability. In addition, shipowners have experienced that despite investing millions of US dollars to purchase and install a BWTS approved according to this manual, it does not always perform as expected when installed and operated on board their

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[1] The IOPP renewal survey refers to the renewal survey associated with the IOPP Certificate (International Oil Pollution Prevention Certificate) required under MARPOL73/78 Annex I

ships. In summary, the revision of the G8 guidelines became inevitable and was in part promoted by shipowner organizations such as the International Chamber of Shipping (ICS).

As a result, the Marine Environment Protection Committee of IMO adopted the *2016 Guidelines for Approval of Ballast Water Management Systems (G8)* (MEPC, 2016). This revised G8 was made mandatory for the approval of ballast water management systems at the Committee's 72nd Session in April 2018 and was adopted as the *BWMS Code (Code for Approval of Ballast Water Management Systems)* as a mandatory regime (MEPC, 2018). This was an evolutionary change for the Type Approval process of the systems because the old G8 was only a guideline, not a regulatory requirement. Also, the 2016 Guidelines include more prescriptive explanations and stricter requirements for the required type approval tests compared to the old G8.

One of the most significant revisions regards testing facilities. In the old G8, there were no requirements regarding the independence of the laboratory of the manufacturer (MEPC, 2008). However, the 2016 Guidelines and the BWMS Code stipulate that test facilities must be independent; this means that laboratories cannot be affiliated in any way with the manufacturer, vendor, or supplier of any ballast water management system.

Another important issue that was not specified in the old G8 was the temperature. The revised G8 and BWMS Code requires BWMS performance should be checked through a ballast water temperature range of 0°C to 40°C (2°C to 40°C for freshwater) and a mid-range temperature of 10°C to 20°C should be the subject of an assessment verified by the Administration.

The 2016 Guidelines and the BWM Code are more stringent on the requirements for land-based and shipboard testing. For example, land-based tests consist of at least five consecutive successful test cycles in each salinity, and for ship testing, the BWMS should be set up to allow the ship to be used in all ballast operations during the 6-month test period and at least three consecutive valid tests.

Another important revision is about the requirement of the System Design Limitations. According to the 2016 Guidelines and also the BWMS Code manufacturer should identify the System Design Limitations, this limitation should be validated during testing, and indicated on the Type Approval Certificate. System Design Limitations should be established for all known parameters to which the design of the BWMS is sensitive and that are important to the operation of the BWMS. There was no requirement in the old G8 regarding the System Design Limitations

Ballast Water Treatment Systems

Ballast water treatment is more difficult and complex compared to wastewater or drinking water treatment. The physical and chemical properties of ballast waters differ significantly depending on the region where the ballast operation is carried out. Each of these properties can cause different effects on the method to be used. In addition, the targeted organisms vary depending on the region where the ballast operation is carried out, and they range from benthic organisms living at the bottom to pelagic organisms in the water phase, from crustaceans to jellyfish, from viruses to fish. Moreover, the technical and operational conditions of ships are also among the limiting factors in the development of ballast water systems.

There is no single method that sufficiently eliminates all ballast organisms. Hence, combined systems in which more than one method is used together for ballast water treatment have been developed and presented to the market.

Many of the systems have two stages. In the first stage (pre-treatment), Particles and large organisms in the ballast water are removed from the ballast water by mechanical methods, making the ballast water ready for the next treatment stage. In the treatment stage, several methods can be used. By employing more than one method in the systems, it is aimed to expand the range of targeted organisms while increasing the flexibility of the BWTS with combined systems consisting of several steps.

Treatment Technologies Used in The System

Mechanical treatment methods

Screen filters, membrane filters, and disc filters are widely used in ballast water treatment. Filtering mesh size is very important in terms of efficacy (Bailey et al., 2022). Although there are systems with different filtration capacities in the market, the major concern is clogging problems (Matheickal et al., 2003). However, in many filter systems, this problem is overcome by backwashing, and the cleaning of the filters can be ensured by short-term automatic backwashing by making use of sensors that determine the pressure difference (McCluskey et al., 2005; Dobroski et al., 2007).

Hydrocyclones are another option for pre-treatment. In hydrocyclones, the fluid enters the system tangentially and the cylindrical chamber ensures that the flow is spiral; the rotational flow is realized in this way and the centrifugal force on the fluid ensures that the high-density solid particles are pushed toward the separator wall and thrown out (McCluskey & Holdø, 2009). Its effect on organisms is not as efficient as filters (Parsons & Harkins, 2002; Waite et al., 2003) and may vary depending on the density and shape of the particles and organisms contained in the ballast water (Zhou et al., 2005).

Physical treatment methods

Every organism has an optimal temperature range in which it can live. Exceeding this range can lead to the death of many organisms. The applicability of heat treatment depends on the supply of energy that can raise the temperature of the ballast water to the required temperature during the voyage and keep it at this temperature for the time required for treatment. As the temperature increases, the time required for treatment decreases (Oemcke & Van Leeuwen, 2005; Quilez-Badia et al., 2008). On the other hand, Quilez-Badia et al. (2008) suggest that the required treatment can be achieved by prolonging the exposure time at lower temperatures. Several studies have been conducted to provide the energy from the main engine, auxiliary machinery, and other heat sources on the ship and alternative systems that can be applied for different ship types have been proposed (Rigby et al., 1999; Mountfort et al., 2003; Quilez-Badia et al., 2008; Balaji et al., 2014).

Ultraviolet (UV) radiation provides treatment by disrupting the chemical bonds in DNA (deoxyribonucleic acid) and RNA (ribonucleic acid) molecules and cell proteins of organisms (Hijnen et al., 2006; Hess-Erga et al., 2008) This method is highly effective on microorganisms however its efficiency is directly related to the clarity of the water(Hijnen et al., 2006; Azar Daryany et al., 2008; Hess-Erga et al., 2008), therefore, it is suggested to combine UV with an efficient pre-treatment in the systems. UV is utilized in most of the BWTS in combination with a filter. The ballast water management systems are generally tested for the IMO Type approval in warmer seasons when plankton concentrations are high; however, Casas-Monroy et al. (2018) demonstrated that when combined with a filter, UV-C irradiation is also effective across a range of low temperatures (18°C, 12°C, and 2°C) on organisms from two size classes (≥ 10 to < 50 μm and ≥50 μm) (Casas-Monroy et al., 2018). On the other hand, higher life forms and crustacean organisms are highly resistant to UV-based treatment and therefore UV-based treatment systems do not have sufficient effect on such organisms. To overcome the current limitations, the UV method can be used in conjunction with advanced oxidation techniques based on oxidizing radicals formed by photolysis in a significant proportion of BWTSs (Wu et al., 2011a; Wu et al., 2011b; Zhang et al., 2014). Also, the DNA damage of organisms can be repaired through different mechanisms, and among these mechanisms photo repair is the most important, therefore lower UV doses may be sufficient if the water is treated at the intake and left in dark ballast tanks; higher UV doses may be more efficient in the absence of post-dark treatment (Olsen et al., 2016; Romero-Martínez et al., 2021).

The purpose of ultrasound (US) technology is to create acoustic cavitation with high-frequency vibrations created in the liquid and to benefit from the disinfectant effect of the physical and chemical processes that occur during this period. When the microscopic gas bubbles formed during cavitation burst, very high local heat is released, and it also causes the formation of disinfectants such as hydroxyl radicals and hydrogen peroxide (Sassi et al., 2002; Viitasalo et al., 2005). The effect of this technology depends on the size of the organism, results can be obtained with lower energy in a shorter time in large organisms compared to small organisms (Gavand et al., 2007; Holm et al., 2008). The cavitation produced, depends on the frequency, power density, duration of action, and the properties of the water. On the other hand, high-intensity ultrasound energy is required to provide the desired standard in microbiological disinfection in large-scale waters (Joyce et al., 2003). This system is more suitable for low ballast capacity and low flow rates due to the higher cost per ballast water (Mesbahi, 2004). However, hydrodynamic cavitation, which is not currently involved in ballast water treatment, has significant potential in ballast water treatment due to lower energy consumption and operating costs (Cvetković et al., 2015).

Chemical injection

The use of chemical methods in ballast water treatment has become an important field of study as a result of the inclusion of microbial organisms in the scope of IMO's ballast water discharge standards, and the investigation of the effects of various chemical substances, including commercial products, on some target species has accelerated.

Chemicals to be used in ballast water treatment can generally be examined under two major groups oxidizing biocides and non-oxidizing biocides. Oxidizing-type biocides, which work by destroying the cell membrane and other organic structures, are also used in wastewater treatment (Dobroski et al., 2007; Kazumi, 2007). Chlorine, chlorine dioxide, bromine, hydrogen peroxide, peracetic acid, and ozone are among the leading biocides. Peraclean® Ocean, a commercially available liquid form product for ballast water treatment, is a rapid oxidizer. Its active ingredients are peracetic acid (PAA) and hydrogen peroxide (H_2O_2) (Yves de Lafontaine et al., 2008; R Fuchs & de Wilde, 2003; Rainer Fuchs et al., 2001) and it is effective on bacteria spores, yeasts, molds, protozoa, algae, and viruses between pH 5 and 9 (Montemezzani et al., 2015). Peraclean® Ocean was able to rapidly eliminate organisms in the water column of the ballast tank under different environmental conditions during a test with real ballast conditions on board; however, treated water needs to be managed appropriately to minimize potential environmental impacts due to toxicity levels (De Lafontaine et al., 2009). In addition, corrosion is an important point to be considered in the use of biocide in ballast water disinfection as it increases with the increase of the oxidizing potential due to biocides (Kornmueller, 2007).

Non-oxidizing biocides are being developed as an alternative to oxidizing biocides due to the corrosion problem. This group of biocides provides inactivation of organisms by destroying the reproductive and nervous systems of organisms or by interfering with their metabolic functions (Kazumi, 2007). In a laboratory study of 18 low molecular weight quinones (common building blocks of many biological molecules, e.g., vitamin K1), four of them (juglone, plumbagin, menadione, and naphthazarin) were found to be effective on most planktonic organisms even concentrations below 1.0 mg/l (Wright et al., 2007). The commercial product marketed under the brand name SeaKleen® (with menadione as the active ingredient) was tested in various studies. It is effective on cladocerans and rotifers, rather than green microalgae (Montemezzani et al., 2015). SeaKleen® was also found to be effective on resting eggs of different taxa (Raikow et al., 2006) however insufficient as a biocide on bacteria (Gregg & Hallegraeff, 2007). In addition, the slow degradation of SeaKleen® after the time required for disinfection was underlined (Raikow et al., 2006; Gregg & Hallegraeff, 2007).

Electrochemical systems

The chemical injection may not be appropriate for all ships due to several reasons such as the limited available space for storage, supply problems in the ports, and safety risks to the crew. On the other hand, *in situ* production of various disinfectants such as chlorine (Cl_2) gas and hypochlorous acid (HOCl) by applying electrochemical processes constitutes an important alternative for ballast water treatment. Two distinct methods employ electrochemical (el-chem) technology.

In the first method, the electrochemical reactor functions based on the electrolysis of NaCl present in seawater to produce chlorine species such as hypochlorite and hypochlorous acid or sodium hypochlorite. (Matousek et al., 2006; Bilgin Güney & Yonsel, 2013). In this system a portion of the main ballast stream (so-called side-flow) is passed through the electrolysis cells to produce disinfectant that is rich in chlorine species, then this produced disinfectant is injected into the ballast stream (Cha et al., 2015; Petersen et al., 2019; Joo et al., 2022). The second method is direct electrolysis, where the whole ballast water (so-called full-flow) passes through the electrochemical reactor (Tsolaki et al., 2010; Nanayakkara et al., 2011; Lacasa et al., 2013; Moreno-Andrés et al., 2018). During this process, a low concentration of disinfectant is also produced. The disinfection is mainly based on the lethal effect of the electrical field, in addition to this produced disinfectant is also utilized. Although no active substance is added to the seawater in both methods, active substances are released during electrolysis.

The efficiency of electrochemical systems is affected by the salinity and temperature of seawater, as well as the pollutants and their concentrations (Bilgin Güney & Yonsel, 2013; Yonsel et al., 2014). Therefore, the electrochemical systems to be used in ballast water treatment should be optimized according to the properties of seawater that are subject to treatment. It should also be taken into account that electrolysis products can accelerate corrosion in ballast tanks (Kim & Jang, 2009).

Ballast Water Treatment Systems Approved Compliance with the 2016 Guidelines (G8) or the BWMS Code

According to the implementation schedule of the mandatory approval regime, BWTS installed on or after 28 October 2020 must be type-approved according to the IMO revised G8 requirements. However, if BWTS was installed before 28 October 2020, the existing type approval remains valid.

The BWTSs which received IMO Type approval by the 2016 Guidelines (G8) or the BWMS Code (resolution MEPC.279(70) or MEPC.300(72)) are given with their treatment components in Table 2. The names of the approved system are gathered from IMO's official website (IMO, 2021), and the information on the treatment technologies of the individual systems is found through an internet search.

According to IMO's website, there are 47 IMO Type Approvals granted by the 2016 Guidelines (G8) and the BWMS Code. When that list was studied, it is noted that PureBallast and Echlor Systems have been Type Approved two times, once by 2016 Guidelines (G8) and once under the BWMS Code. So, these brands have been listed in Table 2 only once each. Among the brands in Table 2, 'Envirocleanse inTank™' systems (8th and 11th rows) have changed the name to 'inTank BWTS™' and have once granted IMO Type Approval under the new name. And lastly, Trojan Marinex BWT listed in the 39th row has exited the market due to business reasons as a result of regulatory delays and challenging market dynamics. However, there are ships already equipped with the Trojan Marinex Ballast Water Treatment (BWT) system.

Table 2. BWTSs approved by the 2016 Guidelines (G8) or the BWMS Code

	Name of the ballast water management system	**Pre-treatment**	**Treatment**
1	Ecochlor® Ballast Water Management System	Filter	Chemical injection (ClO_2)
2	GloEn-Patrol 2.0	Filter	UV
3	BalClor® Ballast Water Management System	Filter	El-chem (side stream)
4	BSKY™ Ballast Water Management System	Hydrocyclone and US	UV
5	CompactClean ballast water management system	Filter	UV
6	OceanGuard® Ballast Water Management System	Filter	AEOP and US
7	HiBallast™ Ballast Water Management System	Filter	El-chem (side stream)
8	Envirocleanse inTank™ Electro chlorination Ballast Water Treatment System	Not employed	El-chem (side stream)
9	Evolution Mini, Evolution BWMS	Filter	UV
10	ERMA FIRST BWTS, model FIT 75-3000	Filter	El-chem (full stream)
11	Envirocleanse inTank™ Bulk Chemical Ballast Water Treatment System	Not employed	Chemical injection (NaOCl)
12	BLUE OCEAN SHIELD BWMS	Filter	UV
13	Bawat BWMS Mk2	Not employed	Heat (pasteurization)
14	PureBallast 3.2 and PureBallast 3.2 Compact Flex ballast water management system	Filter	UV
15	Oceansaver Ballast Water Treatment System MKIIB	Filter	Electrodialysis (side stream)
16	Hyde GUARDIAN -US BWTS	Filter	UV
17	ECS HYCHLOR™ BWMS	Filter	El-chem (side stream)
18	Miura BWMS	Filter	UV
19	LeesGreen® Ballast Water Management System (LeesGreen® BWMS)	Filter	UV
20	Wärtsilä Aquarius UV BWMS	Filter	UV
21	MICROFADE II BWMS	Filter	Chemical injection (TRO)
22	Seascape BWMS	Filter	UV (US for lamp cleaning)
23	NiBallast™ ballast water management system (NiBallast™ BWMS)	Filter	Microfiltration 10 µm, Nitrogen generator
24	Wärtsilä Aquarius EC BWMS	Filter	El-chem (side stream)
25	Cyeco Ballast Water Management System	Filter	UV
26	KBAL BWMS	Pressure vacuum reactor	UV
27	oneTank	Not employed	Chemical injection (TRO)
28	Semb-Eco BWMS	Filter	UV
29	Electro-Cleen™ System (ECS)	Not employed	El-chem (full stream)
30	Purimar™	Filter	El-chem (side stream)
31	EcoGuardian™ BWMS	Filter	El-chem (side stream)
32	TLC-BWM	Filter	UV
33	SKF BlueSonic BWMS	Filter	UV (US for lamp cleaning)
34	Optimarin Ballast System (OBS) and Optimarin Ballast System Ex (OBSEx)	Filter	UV
35	ATPS-BLUEsys BWMS	Not employed	El-chem (full stream)
36	inTank BWTS	Not employed	El-chem/chemical (NaClO)
37	BALPURE® Ballast Water Management System	Filter	El-chem (side stream)
38	Trojan Marinex BWT™	Filter	UV
39	NGT BWMS	Filter	UV
40	JFE BallastAce®	Filter	Chemical injection (NaClO)
41	PACT marine Ballast Water Management System (Pact marine BWMS)	Filter	UV
42	KURITA BWMS	Not employed	Chemical (NaClO)
43	BIO-SEA® BWTS	Filter	UV
44	SeaCURE® BWMS and SeaCURE Models SC-F-500 to SC-F-6000	Filter	El-chem (side stream)
45	Atlantium Purestream™ 100/200/300/500/900/1200/1500	Filter	UV

Examining Table 2, out of 45 brands 37 have a pre-treatment stage. The most employed pre-treatment technique (35 systems) is filtering. Most of these systems can filter organisms >40 µm. Pressure vacuum reactor and hydro-cyclone (coupled with the ultrasound) were used in only one system each. Systems without a pre-treatment stage are mostly chemical or electrochemical systems. Only one uses pasteurization with heat treatment.

Considering the treatment stage, it is seen that 24 brands rely on physical methods, that is, they do not use active substances. UV technology is the most used technology not only among the physical systems but also among all the systems in the list and it is used in 22 systems. One system uses microfiltration (organisms >10 µm) coupled with Nitrogen as inert gas and one system uses heat treatment for pasteurization.

21 systems make use of active substances either through direct injection or onboard generation. The most widely used among these systems is electrochemical technology with 13 systems. 9 of the electrochemical systems use the electro-chlorination method (i.e., side flow process) to produce disinfectant by processing a small amount of ballast water, which is then injected into the entire ballast water. Among these, the inTank system is based on chemical injection and recirculation of the ballast water. However, the chemical can either be generated from seawater onboard or optionally liquid bulk is dosed. The last 3 of the electrochemical systems treat all ballast water directly through the electrochemical process (i.e., full flow process). Totally 6 systems use direct chemical injection (other than the inTank system), one uses electrodialysis and one uses Advanced Electrocatalysis Oxidation Process coupled with ultrasound.

It should be noted that the type approval processes of systems using active substances also require a second approval process that will be conducted following the G9 guideline. Thus, the Type Approval of these systems takes longer than those that do not use active substances, and this process is costlier for system manufacturers.

While selecting a system, along with the environmental acceptability, ships' specifications, operational characteristics, system limitations, safety, installation, and operational cost also must be evaluated (Satir, 2014; Ren, 2018).

Expected Challenges

One of the main issues raised is about *Regulation D-2, Ballast Water Performance Standard,* as there is no general limitation for most bacteria and the majority of other microorganisms with dimensions less than 10 µm in the D-2 Standard. Both IMO Convention and US Coast guard regulations have limitations based on some indicator organisms regarding the human health for this size class. However, these indicator microorganisms are rarely detected in even untreated ballast water samples (Doblin & Dobbs, 2006; Lv et al., 2018a; Petersen et al., 2019) while there is a high abundance of diverse microbial communities hosted by ballast tanks including pathogens and viruses (Altug et al., 2012; Lv et al., 2017; Hwang et al., 2018). Hence, standards based on indicator organisms may not be sufficient when evaluated in terms of human health, the aquaculture industry, and food security, (Cohen & Dobbs, 2015; Drillet, 2016).

The second issue is about the methodology that will be used for assessing compliance with Regulation D-2. The fact that limiting standards address viable/live in ballast water makes it very difficult to study organisms smaller than 10 µm and currently available methods for examining microorganisms do not fully meet all the main criteria for BWM in terms of accuracy, feasibility, and reliability (Bailey et al., 2022; Hess-Erga et al., 2019). The methodology issue also applies to the size class of organisms ≥10 to <50 µm, although not as much for organisms smaller than 10 µm (Casas-Monroy et al., 2022). Casas-Monroy et al. (2022) tested indicative analysis devices against microscopy for size class of organisms ≥10 to <50 µm. However, the results of indicative devices had a weak correlation with microscopy based on numeric estimates, and uncertainty for abundances below and close to the D-2 standard was higher.

In addition to methodological problems, recolonization is another challenge to consider. The disinfection may increase the biological availability of organic matter and even after successful disinfection, recolonization may occur (Hess-Erga et al., 2019). Type-approval test results, where the concentration of microorganisms in treated discharges exceeds those in untreated by up to three orders of magnitude, suggest that onboard treatment systems could turn ballast tanks into 'bacterial incubators' (Cohen & Dobbs, 2015). Also, as the majority of the approved BWMSs are based on disinfection with UV, the repair mechanism against UV-induced damage (Tosa & Hirata, 1999; Jungfer et al., 2007; Guo et al., 2009) needs to be considered.

The available information on the effects, advantages, and disadvantages of BWTS systems is mostly obtained from laboratory-scale studies. Due to the complex nature of ballast water treatment, the methods need to be extensively tested under realistic conditions (Hess-Erga et al., 2019). The study for evaluation of ballast water management systems on operational ships gives us important insight into the future of the ballast water problem (Bailey et al., 2022). In that study, Bailey et. al. (2022) evaluated ballast water samples from 29 different ships calling on the Canadian Ports. The results showed that 48% of these samples exceed the standards for organisms ≥ 50 µm in minimum dimension. Bailey et. al. (2022) discusses multiple reasons extensively. Among these, Bailey et. al. (2022) suggests the incorrect installation of the systems and the inadequacies to be experienced during the operation and maintenance of the installed systems could also lead to exceeding the ballast water discharge limit, as operational issues were reported in 10% the tests where the discharge limits were exceeded. Briski et. al. (2015) carried out experiments on 3 individual ships having different types of treatment systems. They tested the efficacy of the management strategies as 'ballast water treatment alone' and 'ballast water treatment plus ballast water exchange'. They observed combining with ballast water exchange had a significant additional effect on reducing the plankton (Briski et al., 2015).

Also, the ballast sediment can pose implications due to its biotic and abiotic properties. The majority of the approved ballast water treatment systems have primary treatment. They are expected to reduce the amount of sediment to be accumulated to a degree, but they may sufficiently eliminate the accumulation. Because the ballast tank sediment particles are mostly in clay (2 µm or less) and silt (2–63 µm) form (Maglić et al., 2016) which are smaller than the treatment limits of the major pre-treatment systems having 40-50 µm mesh size. In addition, some of the approved systems do not include a pre-treatment stage). Bailey et al. (2022) detected fine sediment in one-third of the samples collected from 29 BWMS-built ships (some without a pre-treatment stage); this suggests that even if vessels are set up with BWMSs, sediment can accumulate at the bottom of the tank. The bottom sediment can host a variety of organisms and some of these organisms are extremely resistant with the capability of germination when conditions are favorable (Johengen et al., 2005; Hallegraeff, 2015b; Bilgin Güney et al., 2016; Lv et al., 2018b; Shang et al., 2019; Dong et al., 2021; Tang et al., 2022). Accumulated sediment should be handled cautiously (Maglić et al., 2019). There are a few studies on reducing sediment accumulation and/or facilitating sediment removal (Yuan et al., 2017; Bilgin Güney et al., 2020; Pereira et al., 2021; Bilgin Güney, 2022); these suggested systems were effective to some extent in laboratory scale.

A significant number of ballast water treatment systems use active substances for disinfection. Disinfection by-products (DBPs) that will be released after disinfection vary not only depending on the chemical used but also on other available substances, factors such as pH, and temperature (Werschkun et al., 2014; Moreno-Andrés & Peperzak, 2019; Zhu et al., 2020). Despite the neutralization phase of systems, disinfectant by-products remain an important issue to be controlled and monitored, especially in receiving environments (Jang & Cha, 2020; Kurniawan et al., 2022) and spreading areas. (Maas et al., 2019) as some of them may reach levels that can pose risk to aquatic organisms (David et al., 2018)

Discussion and Conclusion

Ballast water management has become a major environmental challenge for the IMO and the global shipping industry. The BWM Convention was developed as the result of decades of rigorous work and additional 12 years were needed to meet its entry into force requirements. However, efforts continue to eliminate uncertainties and ensure more efficient implementation. Among these efforts, the revision of Guidelines for Approval of Ballast Water Management Systems(G8) in 2016 and adopting it as a BWM Code was an evolutionary action. With the revisions, the two most important international regimes for ballast water management, the IMO BWM Convention and the U.S Coastguard Final Rule, have been more harmonized, which will relieve system manufacturers and shipowners.

From June 2008, when the first Type Approval was given, until 2018, a total of 78 Type Approvals were given. Some of them are already tested against BWM Code and some of them are on the queue. Yet, there are tens of thousands of ships that are already installed systems granted approvals in compliance with the old G8. As the shipowners fulfill their responsibilities on time, their approvals are valid. That means they are not required to take new action for compliance again. The consequences of the problem areas identified in the old G8 will only become clear with time.

Moreover, there is no available system that sufficiently eradicates the whole ballast organisms. The repair mechanism and regrowth of the organisms are still an issue for future translocation. It is seen that even if the ships are installed with ballast water management systems the discharge standards can be exceeded. Although ballast water exchange is a temporary requirement of the BWM Convention, it can be considered an integral component of a ballast water management strategy to support ballast water treatment systems, as it reduces the number of organisms to be disinfected in ballast tanks.

In addition to system-related reasons, inadequacies to be experienced onboard the ship during the operation maintenance of the system could also result in limit exceeding. This shows that comprehensive training of the crew is of great importance. Trainings should be well planned taking into account the educational and professional history of the crew responsible for operating and maintaining the system on board. Training documents and manuals should be clear and concise.

On the other hand, there are still considerations on the compliance testing methodologies both for organisms less than 10 µm and organisms in the size class of ≥10 to <50 µm and smaller. Available methods for testing organisms smaller than 50 µm for compliance assessment do not fully meet all the key criteria for BWM in terms of accuracy, feasibility, and reliability.

In addition, one of the main issues raised is that there are no general regulations for organisms less than 10 µm. Only three indicator organisms regarding human health, are subject to control, many others are ignored. Public health risks from the introduction of human pathogens other than these three organisms via ballast water may persist so more comprehensive limitations can be needed regarding human health.

Technologies based on chemical treatment are used in a significant part of ballast water treatment systems. Before the ballast water is discharged, disinfection chemicals and by-products are reduced to an acceptable level by the neutralization stage of the treatment system. However, even if they are present in low concentrations in ballast water, there will be a high total inflow of disinfection by-products as there will be continuous and high volumes of ballast water discharge, especially to large international ports. Therefore, disinfection byproduct concentration in seawater and sediment should be monitored in these ports and the spreading areas of the discharged waters.

Accumulated sediment is another concern as it can host a variety of organisms in different life forms. Although the pre-treatment stage of some ballast water treatment systems reduces sediment amount, they cannot completely prevent sediment intake. It is important to minimize the sediment intake with practical applications and precautions that can be taken on the ship.

In conclusion, although great progress has been made toward solving the ballast water problem, there are still many issues that need to be considered by the different stakeholders of ballast water management and due to the nature of the problem, the considerations are not limited to those reviewed in this study. Applications and technologies that will be alternatives to ballast water treatment systems such as the use of potable ballast water, permanent ballast, and port-based treatment options should be investigated. In addition, ship design alternatives should be developed instead of traditional methods to build the ships of the future. For this purpose, the concepts proposed to completely eliminate or reduce the need for ballast water (i.e., *ballastfree* ship, *zero-ballast* ship, *minimal ballast* ship) can be revisited, or new concepts can be developed by changing the existing perspective on conventional shipbuilding approaches.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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