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Review article

Ecological impacts of ballast water loading and discharge: insight into the toxicity and accumulation of disinfection by-products

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A R T I C L E I N F O

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A B S T R A C T

Since the implementation of the International Maritime Organization 2004 regulation, most ships have been equipped with on-dock ballast water treatment. While this method is effective in solving the invasive alien species problem, concerns are raised due to the potential release of disinfection by-products (DBPs) as the result of the chemical treatment. This review paper aims to summarize the history of ballast water management (BWM) and the currently used on-dock technology. Chlorination, oxidation, and ozonation are highlighted as the most currently applied methods to treat ballast water on-dock. This paper then focuses on the potential release of toxic DBPs as the result of the selected corresponding treatment methods. Tri-halo methane, haloacetic acid, and several acetic acid-related compounds are emphasized as toxic DBPs with concentrations reaching more than 10 μg/L. The potential toxicities of DBPs, including acute toxicity, carcinogenicity, genotoxicity, and mutagenicity, to aquatic organisms, are then discussed in detail. Future research directions related to the advanced treatment of DBPs before final discharge and analysis of DBPs in coastal sediments, which are barely studied at present, are suggested to enhance the current knowledge on the fate and the ecological impact of BWM.

1. Introduction

Ballast water is a mandatory part of ships to provide stability and maneuverability during journey (Apetroaei et al., 2018). Ballast water is commonly stored in a ballast tank when the cargo hold is empty or not fully filled or additional stability is needed to sail a rough sea (ClearSeas, 2017). In addition to the aforementioned functions, ballast water can also be used to set the buoyancy of the ship, in which additional weight causes lower sinking of the ship structure below the surface water level (USDA, 2021).

Ballast water can be fresh or seawater, depending on the uptake source (Carney et al., 2017). Most of the ballast water is seawater obtained from the origin port of the ship (Lv et al., 2022). When the ship reaches its destination to load cargo up, the ballast water is then discharged (Carney et al., 2017). The discharge of ballast water is one issue that raises several concerns related to environmental impacts (Apetroaei et al., 2018; Hess-Erga et al., 2019; Zhu et al., 2020). Depending on the size of the cargo ship, the amount of transported ballast water in a cargo ship ranges from 1,500 m^3 to >5,000 m^3 (Bielski et al., 2018).

Introduction of foreign species carried in the ballast water into the receiving port area is the main issue in this particular topic (Apetroaei et al., 2018). Saburova et al. (2022) reported the blooming of *Heterocapsa circularisquama* as alien species in the Northwest Indian Ocean introduced by the discharge of ballast water from Western Pacific cargos. The massive growth of this alien species had caused high mortality rate of bivalves in the area. Similarly, Queiroz et al. (2021) mentioned the first

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record of invasive phytoplankton species of *Chaetoceros danicus, Planctonema lauterbornii,* and *Coscinodiscus* cf. *wailesii* in Maranhão coast in Brazil as the result of shipping activities in the nearby port. Introduction of nonindigenous fouling communities in Western Mediterranean ports was also reported by Tempesti et al. (2022), who stated that tourist ships carried more alien species compared with commercial cargo ships.

Aside from the introduction of nonindigenous species, the transport of contaminants, such as heavy metals, toxins, or pharmaceutical components, is also being concerned, given that ballast tanks somehow not only contain water but also sediments (Lv et al., 2022; Rata et al., 2018; Valković and Obhođaš, 2020). These concerns had been discussed in detail during the Ballast Water Management Convention held by the International Maritime Organization (IMO) in 2004, which set a major leap to the ballast water utilization in cargo ships. One of the major outcomes from IMO was a regulation that on-dock treatment should be conducted for ballast water before releasing it to the receiving port, which came into enforcement IMO, 2017 (Valković and Obhođaš, 2020). The treatment is mostly set to reduce/kill the organisms carried together during the ballast water loading (Petersen et al., 2019).

Some articles have already studied and reviewed the implementation of IMO 2004 regulation to the current ballast water treatment in cargo ships (Chen et al., 2021; Jang et al., 2020; Outinen et al., 2021). The most used technologies for on-dock ballast water treatment include chlorination, electrochemical, oxidation, and ozonation (Summerson et al., 2019). While the treatment result is mostly promising, the current attention has shifted into the accumulation of chemicals used during the on-dock ballast water treatment and potential disinfection by-product (DBPs), which can be more toxic than the disinfection itself, contributing to be more potential danger due to the ballast water discharge area in the receiving port (Gonsior et al., 2015; Shah et al., 2015; Boonnorat et al., 2019). This particular topic is rarely studied, while the currently available discussion remains scarce.

This paper aims to review briefly the ballast water treatment in cargo ship transportation, as well as its known environmental pollution. This review paper then thoroughly discusses the used method for on-dock treatment of ballast water in accordance with the implementation of IMO regulation. This paper highlights the novelty of potential toxicity of DBPs to aquatic organisms and the potential accumulation of toxic DBPs in the discharging area in the receiving port. The presented review article is expected to create awareness of the potential toxicity of DBPs from on-dock ballast water treatment. This paper is also expected to be used as a reference for the establishment of future regulations related to on-dock ballast water treatment.

2. Ballast water

Ballast water is a large amount of water loaded into a ship to assist the ship in adjusting the trim, fixing the list, controlling draught, and maintaining stability or hull stresses on the ship within permissible limits (Bailey, 2015). Tons of water are applied as ballast on the ship to fill the ballast tanks in the lower hull (Pepliński, 2019; Chen et al., 2021). The water in the ballast tank can control stability when loading and unloading cargo due to uneven weight of the ship and, especially, when the ship is maneuvering at sea during the voyage (Lakshmi et al., 2021). Ballast water is widely used in bulk cargo carriers, large tankers, and cruise ships (Carney et al., 2017). Large ships have their big ballast tanks to carry a great amount of water (Bielski et al., 2018).

A ship is filled with ballast water at the source port during the loading and unloading process (Yang et al., 2017). The ballast tank is filled fully with water without any cargo load during voyage when it leaves the source port. The ship starts loading cargo along with the process of discharging ballast water (David et al., 2018). The ballast water is discharged outside the ship when it arrives at the destination port, where cargo is loaded on board. The ballast tank becomes empty with a full cargo load during onward voyage (Bai and Jin, 2016).

The ship sails anywhere with ballast water of approximately 30%–50% of the total load, or the equivalent of one hundred gallons to more than 2.5 million gallons (Sheppard, 2018), depending on the ship size. As a guide to ship sanitation, the World Health Organization stated that all ships in the world can carry approximately 10 billion metric tons (or approximately 11 billion U.S. tons) of ballast water for transport worldwide (WHO, 2011). Ballast water as much as 10%–50% of the ship's tonnage filling the ballast tanks is drained while in the coastal area, along with changes in the ship's load to return the center of gravity and ship stability (Bai and Jin, 2016). This process resulted in the displacement of approximately 10–12 billion tons of saltwater to other coastal areas (Simard et al., 2011; Bai and Jin, 2016; Outinen et al., 2021).

3. Ballast water loading

The loading of ballast water requires pumps to fill the tank up (Witanto, 2019). The source of ballast water can be from freshwater, commonly transported to the dock using trucks, or seawater taken directly in the port area (Bailey, 2015). Most of the application uses the seawater to reduce the operational cost. During the loading, the filling system is somehow not only pumping the seawater but also organisms and sludge carried together with the water (Lakshmi et al., 2021).Fish, algae, plankton, and bacteria were reported as the organisms mostly carried during the loading of ballast water (Hess-Erga et al., 2019; Maraqa et al., 2021). Sludge was also reported to be carried during ballast water loading by Valković and Obhođaš (2020). In other study, Hewitt et al. (2009) indicated that sediment, which contained crustacean, protozoa, bacteria, and diatoms, was also absorbed during ballast water loading. In summary, the loading of ballast water carried foreign macroorganisms, microorganisms, and chemicals, which could harm the receiving port when discharged.

4. On-dock ballast water treatment

The process of transferring liquid or sediment (ballasting/de-ballasting) will have negative impacts on the ecosystem where the ballast process occurs (Berger, 2017). To minimize these negative impacts, IMO suggested standard ballast processes to reduce the potential problems. According to IMO, there are two standards to reduce the impact of ballast water: D-1 and D-2 (Vorkapić et al., 2016; Herdzik, 2018). D-1 is the ballast method by exchanging ballast water in the middle of sea (more than 200 nautical miles from the coast). D-2 is the use of an on-dock ballast water treatment system.

In 2004, IMO adopted the ballast water management (BWM) D-1 convention standard. They regulated water discharge ballast and risk reduction methods for alien species. In 2017, IMO issued the ballast water hygiene standard D-2 as standard for ballast water treatment. The D-1 standard can be applied via two ways: by using a sequential method and a flow through method (Vorkapić et al., 2016; Herdzik, 2018). The sequential method requires the discharge of ballast water to the suction pump. The flow through method requires overfilling the tank by pumping to achieve 95% water change with 3 times the tank volume (IMO, 2017). IMO also regulates the importance of reducing biological invasion of the ballast water discharged following the D-2 regulation, as summarized in Table 1. Most of the currently used ballast water treatments utilize the chemical method, considering that it has been proven to have great treatment efficiency and fast process (Lakshmi et al., 2021).

5. Ballast water discharge

5.1. Ecological impact of ballast water discharge

Thousands of marine species that are carried away during the processes of applying and removing ballast water, resulting in an exchange of organisms in the area, can disrupt the balance of marine ecosystems in

Table 1. On-dock ballast water treatment.

Treatment method	Operating principle	Disadvantages	References
Mechanical methods			
Filtration	Porous barriers	- Inefficient energy - Large size of the system - Sediment discharge - Extremely small particles may escape from the system.	Parsons (2003)
Cyclonic separation	A powerful centrifugal force separates heavier particles.	- Inefficient energy - Large size of the system - Sediment discharge - Extremely small particles may escape from the system.	Tsolaki and Diamadopoulos (2010); Jing et al. (2012)
Physical disinfection			
Cavitation and ultrasound	High amplitude sound energy and frequency destroy cell membranes.	- Considerably risky for human health and safety - Damage the hull	Tsolaki and Diamadopoulos (2010); Jing et al. (2012)
Heat treatment	An elevated temperature kills organisms.	- Low energy efficiency	Tsolaki and Diamadopoulos (2010)
Deoxygenation	Organisms suffocate due to oxygen deficiency.	- Removing anaerobic microorganisms is not effective in short-range navigation (<4 days).	Tsolaki and Diamadopoulos (2010)
UV radiation	Ultraviolet radiation kills microorganisms.	- Not effective in removing suspensions and large organisms - Inefficient energy - Large size of the system - Inability to discharge ballast water by gravity	Albert et al. (2010); Stehouwer et al. (2015)
Chemical treatments			
Chlorination, chlorine dioxide, electrolysis	Chlorine kills organisms.	- Not effective in low-salinity areas - Produces unwanted chlorinated hydrocarbons and trihalomethane - Increases corrosion - Secondary neutralization of residual hypochlorite during ballast discharges is unavoidable. - Maintenance and replacement of electrodes are difficult.	Kuzirian et al. (2001); Perrins et al. (2006); Wu et al. (2011)
Ozonation	Bromine kills organisms.	- Inefficient energy - Difficulty in detecting ozone leak - Corrosion of the ballast system - Requires neutralization during de-ballasting process	Kuzirian et al. (2001); Perrins et al. (2006); Wu et al. (2011)
Periclean	Oxidation kills organisms.	- Considered expensive - Difficult to obtain - Problem with storage space	Kuzirian et al. (2001); Perrins et al. (2006); Wu et al. (2011)
SeaKleen	Chemical kills organisms.	- Inevitable secondary neutralization - Difficult to obtain	Kuzirian et al. (2001); Perrins et al. (2006); Wu et al. (2011)

certain areas (Demann and Wegner, 2019; Hess-Erga et al., 2019; Jang et al., 2020). The mixing of native organisms that have long inhabited an area with alien organisms can also cause competition (Saburova et al., 2022). Invasion of marine species carried by ballast water is a serious threat to the marine environment (Kumar, 2021; Kurniawan et al., 2020). The entry of new species into a new environment even affects the economy and human health in a certain area (Burtle, 2014). The ecological impacts that arise include the emergence of competition between native and alien species in foraging for food, resulting in the possibility of native species being preyed upon by newcomers (Queiroz et al., 2021). This condition can change the original habitat and cause a reduction in native biodiversity due to native species being replaced by alien species (Imron et al., 2019; Saburova et al., 2022). In fact, there were signs of a new species invasion being recognized around 1903 with the discovery of the Asian phytoplankton algae (*Biddulphia sinensis*) by scientists in the North Sea (IMO, 2001). IMO (2017) also reported that approximately 10 billion tons of ballast water transferred all over the world are carrying various types of organisms, such as bacteria, viruses, larvae, marine animals, and plants, which are freely transferred by releasing ballast water to new areas. In the 1980s, Canada and Australia conveyed about the invasion of new species to the Marine Environment Protection Committee (MEPC), which is part of the IMO.

The economic impacts that arise due to environmental pollution from ballast include the decrease in fishery production, which can be caused by the transfer of new species that attack native species, and the possibility of harmful algae being carried away during the ballast water disposal process (Jing et al., 2012; Werschkun et al., 2014). Human health is also threatened, with evidence of a cholera epidemic due to ballast discharge that occurred in Mobile Bay, Alabama on the United States coast of the Gulf of Mexico in 1992 (Cohen et al., 2012). In addition, several researchers found cases of transporting *Vibrio cholerae*, which is a disease-causing pathogen in humans carried by the exchange of ballast water entering the Chesapeake Bay (Cohen et al., 2012; Hallegraeff and Bolch, 1991; Purwanti et al., 2020). Therefore, a ballast water treatment system is required to minimize the risk of organism exchange (Carney et al., 2017; Imron et al., 2021).

5.2. History prior to IMO conference 2004

Before the issue of ballast water exchange became the attention of the international maritime world, ballast water carried by ships was discarded and simply pumped into the tanks on board, without any special treatment (Cohen et al., 2012). After several regions realized the potential dangers posed by the exchange of ballast water, regulations emerged from the local areas regarding the rules for the disposal and entry of ballast water on ships (IMO, 2017). The United States then initiated the Nonindigenous Aquatic Nuisance Prevention and Control Act (NANPCA) of 1990 Task Force for Aquatic Nuisance Species to conduct studies and report to

Table 2. Regulation on maximum released organisms during ballast water discharge.

Organism group	Maximum number of viable organisms
Dimension $\geq$50 μm	Less than 10 per m^3 of discharged water
10μm $\geq$ Dimension $\leq$50 μm	Less than 10 per mL of discharged water
Vibrio cholerae (O1 and O139)	Less than 1 colony-forming unit (CFU) per 100 mL of water samples or less than 1 CFU per g (wet weight) of zooplankton samples
Escherichia coli	Less than 250 CFU per 100 mL of discharged water
Intestinal Enterococci	Less than 100 CFU per 100 mL of discharged water

congress to identify areas where ballast water exchange can be conducted without causing environmental damage and to determine the need for surveillance of ships entering the U.S. waters (Verna and Harris, 2016). In 1992, the Great Lakes BWM program became a mandatory (Sturtevant et al., 2019). The Coast Guard issued regulations (33 Code of Federal Regulations Section 151, Subsection C) to prevent the introduction and spread of aquatic nuisance species into the Great Lakes via ship ballast water and enacted regulations regarding civil and criminal penalties for violating these regulations (Coast Guard, 2020). In 1996, amendments to NANPCA by the National Invasive Species Act was made, declaring that all ships entering the U.S. waters (after operating outside of the US Exclusive Economic Zone) are directed to conduct a ballast water exchange (i.e., at sea) or an alternative preapproved action by the Coast Guard (Coast Guard, 2020; Sturtevant et al., 2019).

5.3. Impact of IMO conference 2004 on ballast water discharge

On 13 February 2004, the International Convention for the Control and Management of Ballast Water and Ship Sediment took place in London (Učur, 2011). From the conference, IMO adopted more than 15 sets of guidelines and documents from MEPC (Jing et al., 2012). These guidelines forced the cargo ship industry to utilize on-dock ballast water treatment, focusing on the reduction of viable organisms to the maximum value, as shown in Table 2 (Petersen et al., 2019).

6. Potential release and accumulation of DBPs in the receiving port

6.1. On-dock ballast water treatment technology and potential release of by-products

Many onboard treatment technologies are applied for BWM (Werschkun et al., 2014; Apetroaei et al., 2018). As previously mentioned, the most used technologies include chlorination, electrochemical, oxidation, and ozonation treatments (Summerson et al., 2019). The aforementioned treatment methods achieved high removal efficiency, as detailed by many researchers. Chlorination achieved 75%–99% efficiency in removing various organisms in ballast water (Ichikawa et al., 1992; Bolch and Hallegraeff, 1993; Gray et al., 2006), electrochemical treatments had plankton removal efficiency $>$99% (Dang et al., 2003; Jang et al., 2020), oxidation with various oxidants removed 97%–99% of various organisms (Wright et al., 2007; de Lafontaine et al., 2008), and ozonation may remove up to 99% of various organisms in ballast water (Oemcke and Van Leeuwen, 2005; Perrins et al., 2006). Despite their great and reliable efficiencies, a concern was raised due to the environmental effect caused by the application of disinfection, known as DBPs (Delacroix et al., 2013; Shah et al., 2015; Ziegler et al., 2019). These chemicals are the results of the used reagent with natural characteristics of water (Ziegler et al., 2019) or originated from the reactions between total residual oxidants (TRO) and the dead organisms in storage during voyage (Jang and Cha, 2020). Considerable research highlighting the DBPs from various on-dock ballast water treatments is summarized in Table 3.

On the basis of Table 3, DBPs potentially released after ballast water treatment are mostly bromate-, HAA-, and THM-related compounds. Bromate is released from the reaction of bromide in sea/brackish water with ozone under free chlorine existence (Gounden and Jonnalagadda, 2019). HAA and THM are the by-products of chlorination as hypochlorous acid interact with natural organic matter in the sea/brackish water (de Vera et al., 2016; Huang and Shah, 2018). These chemicals are listed as toxic compounds, which may affect the ecosystems in the receiving

Table 3. On-dock ballast water treatment technologies and their associated by-products.

Treatment method	Main reagent	Disinfection by-products*	Finding(s)	Source
Chlorination	Chlorine	THM HAA	• Brominated THM was formed by the increase in bromide concentration in water. • DCAA, TCAA, DBAA, and TBAA were found as DPBs from the use of chlorine.	Shah et al. (2015)
Chlorination	Hypochlorous acid Hydroxyl radicals	Dibromochloromethane Chlorate MBAA TBAA	• Lignin was subjected as the precursor to THM formation.	Delacroix et al. (2013)
Electrochemical	Chlorine	HAA	• DBAA, MCAA, and DBAN were found as DBPs. • DBPs resulted from the reactions of decomposed dead organisms with TRO during the storage time.	Jang and Cha (2020)
Electrochemical	Chlorine	THM	• 2,2,4-Tribromo-5-hydroxy-4-cyclopentene-1,3-dione was formed as the result of dissolved organic matter reactions with Br.	Gonsior et al. (2015)
Oxidation	Peracetic acid	HAA	• MBAA, DBAA, and TBAA were found as DBPs by using peracetic acid.	Shah et al. (2015)
Ozonation	Ozone	Bromate HOBr HAA	• Bromate formation was affected by the salinity of water. • HOBr was formed under low bromide concentration in water. • DBAA and TBAA were detected at $>$10 μg/L, which showed potential harm to aquatic organisms.	Shah et al. (2015)
Ozonation	Ozone	THM	• Brominated THM was formed during ozonation. • Different natural organic matter concentrations significantly affected the THM formation. • Oxidant residue, storage time, and iodide concentration significantly affected the iodinated-THM formation.	Zhu et al. (2020)

*THM: Tri-halo methane, HAA: Haloacetic acid, MBAA: Monobromoacetic acid, DCAA: Dichloroacetic acid, TCAA: Trichloroacetic acid, MCAA: Monochloroacetic acid, DBAA: Dibromoacetic acid, TBAA: Tribromoacetic acid, DBAN: Dibromoacetonitrile.

port during the discharge of ballast water (Oginawati et al., 2021a, 2021b; US-EPA, 1998).

6.2. Potential toxicity of DBPs

Currently, there is no specific regulation worldwide for monitoring the release of DBPs from on-dock ballast water treatment (Hess-Erga et al., 2019). The current approach only sets the maximum allowable release of TRO with a maximum value of 0.2 mg/L of Cl_2 for chlorination systems, 0.45 mg/L of Br_2 for ozonation systems, and 0.5 mg/L of H_2O_2 + 0.3 mg/L of PAA for oxidation by using peracetic acid systems (Summerson et al., 2019). Regulation related to DBPs released from ballast water treatment is currently limited due to the diversity of by-products and the limited study conducted on this particular topic. Several potential toxicities of the aforementioned compounds are tabulated in Table 4.

6.3. Potential accumulation of DBPs

Understanding the fate, water may become the most abundant existence of those compounds, while sediment has also potential for solid accumulation through the changes in some environmental factors. As the receiving body in ports, coastal areas receive abundant amount of treated ballast water, which has high potential of DBP exposure. Aside from the water, Alkhatib and Peters (2008) also mentioned the potential accumulation of THM in sediment. Previously, Martin et al. (1993) stated that natural organic matter in sediment became a major precursor for THM formation when reacted with free halogens (such as chlorine). This explanation may also apply to coastal sediment due to the interaction of DBPs (mostly free chlorine or bromide) with natural organic matter in coastal sediment (Gounden and Jonnalagadda, 2019; Huang and Shah, 2018). However, research on this particular matter is currently limited.

Table 4. Potential toxicity of disinfection by-products to aquatic ecosystem.

Method	Reagents/by-products*	Affected medium/organisms	Potential toxicity	Source
Chlorination	• THM • HAA • Chlorite • Bromide	Aquatic organisms	• Carcinogenicity • Adverse reproductive and development problems	US-EPA (1998)
Chlorination	• Tribromomethane • HAA • TBAA • DBAA • Chlorodibromoacetic acid • Bromoacetonitrile • Dichlorobromomethane • Chloral hydrate	*Isochrysis galbana* *Phaeodactylum tricornutum*	• Discharged ballast water was concluded as acutely toxic to algae with 50% reduction in growth.	Ziegler et al. (2018)
Chlorination	• MBAA • TBAA • Dibromochloromethane • Chlorate • Tribromomethane	*Skeletonema costatum*	• Risk assessment showed five DBPs gave risk value >0.5 (having potential risk for the marine environment).	Delacroix et al. (2013)
Chlorination	• THM • HAA • Bromate	Aquatic organisms	• Carcinogenicity • Genotoxicity	Werschkun et al. (2012)
Chlorination	• Chlorate • Chlorite • Haloorganics • Chloroorganics • Trichloromethane • Tichloroacetonitrile • Bromoorganics • Tribromomethane • TBAA • Bromate • Perchlorate • Chloropicrin	Aquatic organisms	• Acutely toxic to *Daphnia magna*	Summerson et al. (2019)
Chlorination Ozonation	• Haloamides • Haloacetonitriles • Iodo-THM	Mammals	• Adverse health effects	Krasner et al. (2006)
Electrochemical	• Brominated organic compounds	Aquatic organisms	• Tribromoethene showed the highest ecological impact to marine ecosystem.	Gonsior et al. (2015)
Oxidation	• Mexel 432 ®	*Cyprinus carpio* L.	• The compounds derived from Mexel 432 ® were toxic to newly hatched and developed larvae. • Toxicity was not reduced even after 15 days of exposure.	Arehmouch et al. (1999)
Oxidation	• Brominated organic compound	Aquatic organisms	• Mutagenicity	Ziegler et al. (2019)
Oxidation	• TCAA	Aquatic organisms	• Toxic to larvae of several species	Summerson et al. (2019)
Oxidation	• MCAA • DBAN	Aquatic organisms	• Risk assessment showed that both compounds have high risk to marine ecosystem.	Jang and Cha (2020)
Oxidation	• Iodoacetic acid	Mammals	• Cell cytotoxicity • Genotoxicity	Krasner et al. (2006)
Ozonation	• DBAN	Aquatic organisms	• Acutely toxic to *Pimephales promelas*	Summerson et al. (2019)

*THM: Tri-halo methane, HAA: Haloacetic acid, MBAA: Monobromoacetic acid, DCAA: Dichloroacetic acid, TCAA: Trichloroacetic acid, MCAA: Monochloroacetic acid, DBAA: Dibromoacetic acid, TBAA: Tribromoacetic acid, DBAN: Dibromoacetonitrile.

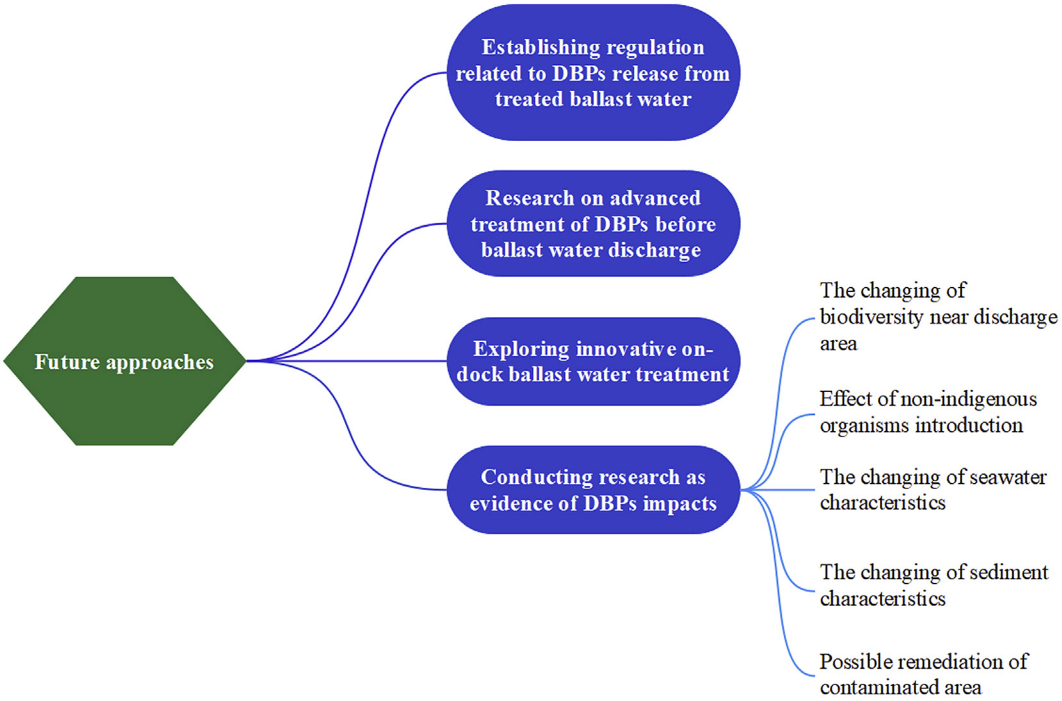

Figure 1. Future approaches for DBPs release from ballast water treatment.

7. Future approaches

With reference to the prior discussed items, challenges await to be detailed, as summarized in Figure 1.

To reduce the potential toxicity of DBPs in port areas, IMO already set a regulation to conduct a ballast water exchange as far as minimum of 50 nautical miles from the nearest land (Section 6) (Učur, 2011). However, this approach will not reduce the amount of DBPs released to the marine environment. This regulation only prevents further contamination of the nearest human ecosystem, not the marine ecosystem (Kurniawan et al., 2021a). On the basis of this fact, specific regulation related to DBPs released from ballast water should be established. The DBPs are well understood to be related to the utilized treatment method and the characteristics of the water (Gonsior et al., 2015; Shah et al., 2015; Ziegler et al., 2019); thus, a regular cargo ship with scheduled route can address this issue. The regulation can be set to be specific on the utilized treatment method and the storage time, as the most affecting factors for the release of DBPs. Through establishing this kind of regulation, the potential toxicity of DBPs from ballast water can be reduced from the source.

In accordance with the establishment of the regulation related to DPBs, advanced on-dock treatment for DBP removal should also be managed. Several technologies, such as adsorption, are known to have good efficiency in removing DBPs from water (Jiang et al., 2017; Zainudin et al., 2018; Verdugo et al., 2020). In addition, a biological approach using microbes, as a green technology and being inexpensive to operate and maintain compared with other physicochemical techniques (Imron et al., 2020; Kurniawan et al., 2021c), can be explored to biodegrade DBPs effectively, although this method may impose long retention time (Ighalo et al., 2022; Igwegbe et al., 2022). Through implementing these technologies as advanced treatment for ballast water before discharge, the potential impact of DBPs can be greatly reduced, and marine environmental pollution can be prevented. Research on innovative methods to treat ballast water on-dock is also suggested to enrich the exploration. Lakshmi et al. (2021) mentioned the laser beam option to decrease the viable organisms in ballast water tanks, which has great potential to reduce the formation of DBPs. Carbon nanotubes and ceramic filters can also be used to inactivate organisms in ballast water. The utilization of nonoxidizing biocides, such as naphtoquinone, glutaraldehyde, and lysoglycerophosphocholine, may also become an alternative option to avoid DBP formation during on-dock ballast water treatment (Sayinli et al., 2021).

Before regulations and advanced treatment for DBP-related compounds can be established, research on the ecological aspect of ballast water release in receiving ports is necessary to provide clear evidence of the discussed topic (Werschkun et al., 2012; Apetroaei et al., 2018; Hess-Erga et al., 2019). Research is suggested to focus on the changing biodiversity around port areas, the effect of the existence of nonindigenous organisms introduced through ballast water release, changes in the water and sediment characteristics in port areas, and possible remediation of contaminated areas. These topics are considered greatly interesting to be conducted and may highly contribute to the knowledge on ballast water pollution in ports and prompt possible remediation of contaminated areas (Kurniawan et al., 2021b; Purwanti et al., 2019).

8. Conclusions

BWM via on-dock treatment seemed to be effective in controlling the invasive alien species problem during the de-ballasting process. However, several concerns related to the release of DBPs are currently emerging. Given that chemical treatment is currently the most used on-dock technology, the release of tri-halo methane, haloacetic acid, monobromoacetic acid, dichloroacetic acid, trichloroacetic acid, monochloroacetic acid, dibromoacetic acid, tribromoacetic acid, and dibromoacetonitrile is revealed by several researchers. Potential toxicities, including carcinogenicity, genotoxicity, cell cytotoxicity, and acute toxicity, to aquatic organisms are highlighted. Possible adverse health effects to mammals are also mentioned as the result of food web transfer. Research related to the accumulation of DBPs in receiving port areas is currently limited. Future research directions are suggested to focus on the magnification of DBP concentration in water and the potential accumulation in sediment near receiving port areas that later can result in detrimental effects on the ecosystem.

Declarations

Author contribution statement

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