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Health Risks of Heavy Metals Exposure from Ballast Water

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Abstract*. Ballast water plays a crucial role in maintaining ship stability during shipping, but it also carries environmental and human health risks due to the heavy metals it carries. This study aims to examine the health risks posed by exposure to heavy metals in ballast water and to assess the effectiveness of management practices implemented in the maritime industry. Using a literature review method, this study examines various scientific sources related to the content of heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) in ballast water, as well as their impacts on human health and marine ecosystems. The results indicate that heavy metals in ballast water can cause long-term toxic effects such as neurological disorders, kidney damage, and respiratory and reproductive disorders. The greatest risk is experienced by maritime workers who are directly exposed through inhalation or skin contact during the ballast water sampling and processing process. To minimize these risks, strict work safety protocols, improved ballast water treatment technology, and regular monitoring of heavy metal levels are required. Thus, this study emphasizes the importance of strengthening ballast water management policies and practices that are oriented towards human health and environmental sustainability.*

Keywords: *Ballast Water; Environmental Sustainability; Health Risks; Heavy Metals; Maritime Workers.*

1. INTRODUCTION

Ballast water is a vital component in ship operations, maintaining balance and stability during shipping. In the process, ships fill ballast tanks with seawater from their port of origin and discharge it at their port of destination. While seemingly simple, this practice has complex environmental and health implications. Ballast water carries not only marine organisms that can become invasive species, but also sediment particles, microplastics, and hazardous heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn), which are toxic and non-biodegradable. The accumulation of these heavy metals in the marine food chain has the potential to threaten human health and disrupt the balance of aquatic ecosystems (Banerji et al., 2012).

More than 80% of the world's traded goods are transported by sea, and between 1970 and 2008, the volume of maritime cargo tripled (Asariotis et al., 2010). An estimated 3–10 billion tons of ballast water are transported annually worldwide (Globallast, 2000). Thus, ballast water serves as a major vector for the movement of marine life and pollutants from one ecosystem to another. According to the International Union for Conservation of Nature (IUCN, 2008), invasive species are the greatest threat to biodiversity, and ballast water discharge is a major cause of their spread. In addition to ecological impacts, heavy metal and other chemical pollution from ballast water has significant economic and health consequences, such as water degradation, disruption to aquaculture activities, and increased risk of disease due to exposure to toxic substances.

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The International Maritime Organization (IMO), through the 2004 International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention), has set standards to prevent transboundary pollution from ballast water discharges (International Maritime Organization, 2004). This convention sets maximum limits on the number of living organisms and hazardous chemicals that may be released into the marine environment. However, its implementation still faces various obstacles, including limited ballast water treatment technology, lack of toxicity monitoring, and low awareness of the potential health risks (Tsolaki & Diamadopoulos, 2010).

One of the main problems that arise in ballast water management is the presence of Ballast Water Management Systems (BWMS) that use oxidative active materials to kill microorganisms in ballast water tanks. This disinfection process produces various chemical by-products known as disinfection by-products (DBPs), such as trihalomethanes, haloacetic acids, bromates, and aldehydes, which are known to be carcinogenic and mutagenic (Richardson et al., 2007). Long-term exposure to DBPs can cause health problems such as bladder cancer, reproductive system disorders, and toxic effects on the liver and kidneys (Cantor et al., 2010; Villanueva et al., 2004). Therefore, the use of ballast water treatment systems that are not strictly controlled can threaten the safety of ship workers, ports, and coastal communities that depend on marine resources.

Furthermore, research by Banerji et al. (2012) suggests that many IMO-approved ballast water treatment systems still exhibit deficiencies in health risk assessment. Most only assess a few types of DBPs and do not consider the full range of hazardous compounds that may be formed during the disinfection process. The lack of toxicological information and exposure data under real-world conditions on ships results in incomprehensive risk assessments. Therefore, a more comprehensive approach is needed, encompassing active ingredient identification, toxicity assessment, and estimation of human exposure, both for ship workers and the port community.

In addition to heavy metals and chemical byproducts, a recent issue of concern is the presence of microplastics in ballast water. Ballast water is now recognized as a major vector for the spread of microplastics in the global ocean (Naik et al., 2021). Microplastics, defined as plastic fragments measuring less than 5 mm, have been found in almost all global waters, including polar regions and the Mariana Trench, the deepest point on Earth (Mendoza et al., 2018). With over 12 billion tons of ballast water exchanged annually, the potential for intercontinental transfer of microplastics via ships is substantial (GBWM IMO, 2001). Matiddi et al. (2017) reported that the number of microplastics in ballast water on a cargo ship from

Italy ranged from 100 to 1410 particles per cubic meter, with an average of 651 ± 160 particles/m³.

Exposure to microplastics and heavy metals in ballast water poses a dual risk to human health. Microplastics not only carry hazardous chemicals such as heavy metals and polymer additives, but can also serve as vectors for marine pathogens and invasive species (Naik et al., 2019). When microplastics enter the marine food chain, organisms such as plankton, fish, and shellfish can accumulate them, ultimately leading to human consumption. This biomagnification process increases the concentration of toxic materials at higher trophic levels and has the potential to cause endocrine disruption, oxidative stress, and carcinogenic effects (Rochman et al., 2015; Nelms et al., 2018).

According to the United Nations Environment Programme (UNEP), if current trends continue, the amount of plastic biomass in the ocean will exceed fish biomass by 2050 (Rocha-Santos, 2018). This indicates that ballast water management is not only a technical issue in the shipping world, but also a global environmental health issue. Direct exposure to heavy metals from ballast water can occur in ship and port workers through skin contact, aerosol inhalation, or consumption of contaminated seafood (Banerji et al., 2012). In this context, a multidisciplinary approach involving toxicology, ecotoxicology, occupational health, and maritime policy is crucial to minimize the negative impacts of shipping activities on the environment and humans.

Furthermore, significant challenges also arise from regulatory and technical implementation aspects. Although the IMO has established the G9 procedure for risk assessment for ballast water treatment systems, many countries still lack adequate monitoring infrastructure to assess exposure to hazardous materials in real time (International Maritime Organization, 2008b). GESAMP (Group of Experts on the Scientific Aspects of Marine Environmental Protection) also noted that most ballast water treatment systems have not fully assessed their long-term impacts on human health or marine biota (GESAMP, 2008). Therefore, improving evidence-based toxicity monitoring and evaluation methods is a crucial step in realizing sustainable and safe shipping practices for human health.

In this context, technological innovations such as the use of a three-layered screening chamber system proposed by Naik et al. (2021) offer a potential solution to reduce the spread of microplastics through ballast water. This system utilizes metal mesh with varying pore sizes (500 µm, 300 µm, and 100 µm) to separate microplastics based on their size before the water is discharged back into the sea. This approach is considered cheaper and more efficient than chemical treatment methods and can help reduce the burden of microplastics discharged from cargo ships into ocean waters.

2. RESEARCH METHODS

This study uses a qualitative approach with a literature review method to examine heavy metal contamination in ballast water and its implications for human health. This approach was chosen because it is relevant to integrate various previous research results and international regulations related to ballast water management. The main data sources were obtained from reputable international scientific journals, official reports of the International Maritime Organization (IMO), publications from Regulatory Toxicology and Pharmacology, and technical documents regarding risk assessment procedures for human health as regulated in the International Convention for the Control and Management of Ships' Ballast Water and Sediments (IMO, 2004; Banerji et al., 2012).

The research phase began with the collection of secondary data through a systematic review of relevant literature using keywords such as ballast water, heavy metal contamination, human health risk assessment, and IMO Ballast Water Management Systems. After the data was collected, a content analysis was conducted to identify general patterns, such as the types of heavy metals frequently found in ballast water, the toxicity levels of each element (e.g., Hg, Pb, and Cd), and the main routes of human exposure through inhalation, skin contact, and the food chain (Banerji et al., 2012; Tsolaki & Diamadopoulos, 2010).

The next step was a synthesis of the findings, where the results of the analysis from various sources were compiled to provide a comprehensive picture of the health risks from exposure to heavy metals and disinfection by-products (DBPs) in ballast water management systems. The study also reviewed IMO policies and standards, including Procedure G9, which governs the assessment of risks to ship safety, human health, and the marine environment (International Maritime Organization, 2008a).

In addition, a comparative analysis of various ballast water treatment technologies such as electrolysis, ozonation, and chlorination was conducted to assess their effectiveness in reducing heavy metal levels while minimizing the formation of hazardous DBPs (Echardt & Kornmüller, 2009; Richardson et al., 2007). The final results of this study are a conceptual synthesis and policy recommendations for improving ballast water management systems that are oriented towards protecting human health and the sustainability of the global maritime environment.

3. RESULT AND DISCUSSION

Ballast water plays a crucial role in maintaining the stability and balance of ships during navigation, but its use also carries serious consequences for the marine environment and human health. An estimated 3–10 billion tons of ballast water are transported globally annually (Globallast, 2000), creating a significant potential for the spread of pollutants, including heavy metals. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), copper (Cu), and zinc (Zn) are frequently found in ballast water originating from industrial ports, mining areas, and densely populated areas (Banerji et al., 2012). These metals are toxic and can cause long-term ecological and health impacts.

Types and Toxicity of Heavy Metals in Ballast Water

The types of heavy metals commonly found in ballast water generally reflect the characteristics of the marine or port environment where the water is loaded. Lead (Pb) is a heavy metal with high toxicity. This metal is known to be neurotoxic, especially in children and workers who are chronically exposed. Lead exposure can cause central nervous system disorders, cognitive decline, and behavioral disturbances (Asariotis et al., 2010). Furthermore, cadmium (Cd) is nephrotoxic and can impair kidney function even at very low levels. Cadmium is also carcinogenic, with strong evidence linking long-term exposure to the risk of lung and prostate cancer (Banerji et al., 2012).

Unlike these two metals, copper (Cu) and zinc (Zn) are essential metals that the body needs in small amounts for enzymatic and metabolic functions. However, if their levels are excessive in the marine environment or the human body, both can cause oxidative stress, cell damage, and metabolic disorders (Echardt & Kornmüller, 2009). Mercury (Hg) is one of the most dangerous heavy metals because it can biomagnify along the food chain, especially in the form of methylmercury, which is highly toxic to the human nervous system. Based on their toxicity levels, mercury, lead, and cadmium are categorized as metals with the highest risk to human health and the marine environment (International Maritime Organization, 2008).

In the context of ballast water management, the risk of heavy metal toxicity is increasing due to their interaction with chemical disinfection processes in ballast water management systems (BWMS). The electrolysis and ozonation processes used to inactivate organisms in ballast water often produce hazardous byproducts such as disinfection by-products (DBPs) that can react with heavy metals, forming new, more stable and potentially more toxic compounds (Richardson et al., 2007).

Exposure Routes and Health Impacts

Heavy metal exposure in maritime workers can occur through three main pathways: inhalation, direct skin contact, and indirect ingestion. The process of extracting and disposing of ballast water containing heavy metal particles can cause fine particles to be dispersed into the air. When inhaled, these particles can penetrate the respiratory system and enter the bloodstream, causing respiratory problems or systemic effects such as anemia and nervous system disorders (Banerji et al., 2012).

Direct skin contact is also an important route of exposure, particularly when workers maintain tanks or ballast systems. Metals such as nickel, copper, and chromium can cause contact dermatitis and significant transdermal absorption (Tsolaki & Diamadopoulos, 2010). Furthermore, indirect ingestion can occur when humans consume seafood contaminated with heavy metals due to ballast water discharge into coastal ecosystems. Over the long term, the accumulation of heavy metals in the body can lead to various chronic diseases such as kidney damage, neurological disorders, cancer, and reproductive dysfunction (Cantor et al., 2010; Villanueva et al., 2004).

Epidemiological studies have shown that chronic exposure to low levels of heavy metals can cause cumulative effects, especially when combined with exposure from other sources such as air or food. In addition to direct effects, the combination of heavy metals with oxidative chemicals produced by ballast water treatment processes (such as trihalomethanes and haloacetates) can increase the risk of genotoxicity and carcinogenicity (Richardson et al., 2007). Therefore, health risk assessment is an essential component of active substance-based ballast water management systems (IMO, 2008b).

Environmental Risks and the Food Chain

The environmental impacts of ballast water discharge containing heavy metals are no less serious than the impacts on human health. Heavy metals are persistent, non-biodegradable, and readily accumulate in sediments and marine life. When ballast water is discharged into the ocean, heavy metals can be absorbed by microscopic organisms such as phytoplankton and zooplankton, then transferred to higher trophic levels such as fish and shellfish, in processes known as bioaccumulation and biomagnification (Naik et al., 2021).

Bioaccumulation of heavy metals leads to increased toxin concentrations in organisms at the top of the food chain, including humans who consume seafood. Research shows that high levels of mercury and cadmium in fish in harbor waters are often associated with ballast water discharge from large ships (Matiddi et al., 2017). Furthermore, ballast water discharge also has the potential to exacerbate microplastic pollution in the ocean. Microplastics can act as vectors for heavy metal adsorption, thus extending the residence time of toxic metals in water and increasing the likelihood of their entry into the food chain (Naik et al., 2019).

The combination of heavy metals and microplastics in marine ecosystems creates a double risk (synergistic toxicity) that can reduce ecosystem productivity and damage biodiversity. In the long term, this contamination can impact coastal economies through reduced fisheries yields, damage to marine aquaculture, and risks to coastal community food security (Asariotis et al., 2010).

In response to these issues, the International Maritime Organization (IMO) in 2004 ratified the “International Convention for the Control and Management of Ships' Ballast Water and Sediments,” which sets maximum standards for the number of living organisms and chemical content before ballast water can be discharged into the sea (IMO, 2004). However, challenges remain in implementation, particularly in the control of non-biological toxic substances such as heavy metals and chemical by-products of disinfection.

Risk Mitigation and Evaluation Efforts

Efforts to control heavy metal pollution from ballast water must be carried out through technical, regulatory, and scientific approaches. From a technical perspective, the use of environmentally friendly Ballast Water Treatment Systems (BWTS), such as multi-layer filtration and corrosion-resistant metal-based microplastic filtration systems, can help reduce heavy metal loads in ballast water (Naik et al., 2021). From a regulatory perspective, improvements to the IMO G9 Procedure standard are needed to include risk assessments for carcinogenic, mutagenic, and reproductive toxicants (Banerji et al., 2012).

Furthermore, increased toxicology research is needed to understand the complex interactions between heavy metals, disinfection products, and microplastic particles in seawater. A risk-based monitoring approach that considers variations in location, water quality, and ballast discharge frequency will help determine more accurate safety limits for human health and marine ecosystems.

By understanding the complexity of the types, toxicity, exposure pathways, and ecological impacts of heavy metals in ballast water, effective ballast water management policies should not only focus on preventing bioinvasiveness, but also on controlling chemical pollutants that have the potential to cause a global health and environmental crisis.

Ballast Water Management Practices and Implementation Challenges

Ballast water is a crucial component of a ship's stabilization system, ensuring stability and safety during navigation. However, ballast water is also a source of marine pollution due to its potential to carry foreign organisms and hazardous chemicals, including heavy metals and toxic compounds from processing (International Maritime Organization, 2008a). To address these impacts, the International Maritime Organization (IMO) has established the Ballast Water Management Convention (BWMC), which regulates global ballast water management, with the aim of controlling the introduction of alien species and minimizing toxic risks to the environment and human health (Banerji et al., 2012).

One of the main principles of the IMO convention is the pre-discharge treatment of ballast water. Treatment technologies applied include mechanical filtration, ultraviolet (UV) irradiation, electrolysis, ozonation, and chlorination. These methods are effective in reducing the concentration of living microorganisms and pathogens, but have limitations in removing chemical contaminants such as heavy metals (Banerji et al., 2012). Heavy metals such as mercury (Hg), cadmium (Cd), and lead (Pb) tend to be chemically stable and difficult to decompose, so they can settle at the bottom of ballast tanks or be carried into seawater. Therefore, monitoring heavy metal levels through analytical techniques such as atomic absorption spectrometry (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) is crucial to ensure that ballast water discharge meets marine environmental quality standards (ECHA, 2008).

However, the main challenge in implementing this convention is the difference in technical capacity between countries and ship operators. The use of treatment technology requires significant investment and intensive maintenance, so not all ships are able to implement it optimally. Furthermore, research by Banerji et al. (2012) shows that most risk evaluation documents for ballast water management systems (BWMS) do not follow comprehensive exposure assessment procedures. Many systems only identify two or three exposure scenarios without considering all potential risks, such as exposure through inhalation of toxic gases, skin contact, or consumption of contaminated seafood.

In practice, IMO (2008a) recommends dividing the BWMS process into operating units such as: starting system, ballasting, deballasting, cruising, and maintenance. Each operating unit has different potential exposures. For example, during ballasting, the air in the tank can contain toxic gases from oxidation, while during deballasting there is a risk of exposure to hazardous aerosols. Furthermore, maintenance processes such as tank cleaning or filter replacement can also result in direct exposure to chemicals. In many cases, workers on board ships are not adequately trained to deal with emergency situations such as chemical leaks or ventilation system failures, which can increase long-term health risks such as lung disorders, skin irritation, and even carcinogenic effects (Banerji et al., 2012).

Another challenge is the differences in marine environmental conditions and water quality across regions. The effectiveness of treatment systems is highly dependent on parameters such as salinity, temperature, and the organic matter content of seawater. For example, electrolysis-based systems produce more harmful by-products (disinfection by-products – DBPs) in waters with high salinity (Banerji et al., 2012). DBP compounds such as trihalomethanes and haloacetates are known to be mutagenic and carcinogenic, meaning they can cause genetic mutations and cancer in humans (ECHA, 2008; Kogevinas et al., 2010). Therefore, the health risks to workers and coastal communities must be taken into account in the safety assessment of BWMS systems.

Weaknesses in global regulations also pose a significant obstacle. Although the IMO has provided guidance through its G9 Guidelines (IMO, 2008b), implementation remains voluntary and relies on national monitoring systems. Many developing countries lack laboratory facilities to verify the effectiveness of treatment systems and do not conduct routine marine environmental monitoring. Furthermore, monitoring of foreign vessels docking at domestic ports is limited due to limited human resources and equipment. As a result, the risk of transboundary pollution remains quite high, particularly in areas with heavy ship traffic.

Worker Prevention and Protection Strategy

In the context of occupational health and safety, shipworkers are the most vulnerable group to exposure to hazardous chemicals from ballast water management systems. Exposure can occur through various routes, such as inhalation of toxic gases, dermal contact with contaminated ballast water, or exposure to aerosols during deballasting. Therefore, prevention strategies must be implemented comprehensively, taking into account international safety standards and toxicology study results.

According to Banerji et al. (2012), the initial step that must be taken is the implementation of an Occupational Exposure Assessment according to the GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) methodology. This process includes identifying work activities that have the potential to cause exposure, determining the types of chemicals used in the BWMS, and quantifying exposure levels based on duration, frequency, and concentration of hazardous substances. The results of this assessment are used to determine the Derived No-Effect Level (DNEL), which is the exposure threshold that is still considered safe.

Key protective measures include the use of Personal Protective Equipment (PPE) such as chemical-resistant gloves, respirator masks, protective clothing, and safety glasses. Adequate ventilation systems should also be implemented in ballast water storage or processing areas to prevent the accumulation of hazardous gases such as chlorine or ozone. Furthermore, workers should receive regular training on chemical handling, emergency procedures, and regular health monitoring to detect long-term toxic effects such as liver, kidney, or reproductive system disorders (International Maritime Organization, 2012).

From a technological perspective, further research is needed to develop more environmentally friendly ballast water treatment systems that produce minimal DBPs or heavy metal residues. The use of a combination of biological and physical technologies, such as microbiological filtration with natural bioadsorbents (e.g., zeolite and activated charcoal), could be an efficient and low-cost alternative (Claxton et al., 2008). Furthermore, real-time sensor-based monitoring systems can be used to detect leaks or concentrations of hazardous chemicals in shipboard workspaces, allowing for more rapid risk management.

On the regulatory side, the application of the precautionary principle is crucial. Substances that are carcinogenic, mutagenic, or endocrine disrupting should be prohibited from ballast water treatment systems. The European Union, for example, through its pesticide regulations (European Parliament and Council, 2009), has banned the use of these substances on the basis of a non-threshold effect. A similar approach needs to be adopted in the context of ballast water management to minimize risks to worker and public health.

Ultimately, collaboration between regulators, the shipping industry, and research institutions is key to ensuring effective and safe ballast water management. Developing a global database on the toxic effects of chemicals, implementing a maritime safety certification system, and integrating monitoring results into national policies can improve the effectiveness of risk control. With the application of appropriate technology, strict regulations, and increased human resource capacity, ballast water management practices can be implemented sustainably without compromising worker health or the quality of the marine environment.

4. CONCLUSION

Ballast water management is a vital aspect of maintaining ship stability and a major challenge for environmental protection and human health. Improper management practices can lead to marine pollution by heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg), as well as the formation of toxic and carcinogenic disinfection by-products (DBPs). Although the Ballast Water Management Convention (BWMC), regulated by the International Maritime Organization (IMO), provides technical guidelines and regulations, its implementation still faces significant challenges, primarily related to technological limitations, high operational costs, and a lack of regulatory capacity in many countries.

From an occupational health perspective, shipworkers are at high risk of exposure to hazardous substances through inhalation, skin contact, and aerosols during the ballasting and deballasting processes. Therefore, implementing risk assessments and personal protection is a top priority. Preventive measures can be implemented through occupational safety training, the use of personal protective equipment (PPE), adequate ventilation systems, and regular monitoring of chemical exposure. Furthermore, environmentally friendly technological innovations such as biological filtration and real-time sensor systems need to be developed to reduce levels of heavy metals and toxic byproducts.

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