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Research Article

Assessment of water quality and heavy metal contamination in ballast water: Implications for marine ecosystems and human health

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Abstract

The global menace of non-compliance with ballast water management poses a pressing environmental threat, as it facilitates the transfer of harmful organisms and sediment contaminants. This study investigates the environmental impact of ballast water discharged by ships, focusing on water quality and heavy metal concentrations. The release of ballast water, often containing elevated levels of heavy metals like mercury, lead, and cadmium, poses a significant threat to marine ecosystems. The research, involving water sample collection from ten different vessels across various countries, assesses physicochemical parameters and heavy metal concentrations. Results indicate variations in temperature, turbidity, conductivity, dissolved oxygen, and pH levels among samples. Turbidity values surpassing WHO limits suggest potential anthropogenic pollution. The study identifies significant differences in pH values, potentially influencing microbial populations. Total dissolved solids and total suspended solids values vary, affecting the distribution of potential pathogens. The results reveal varying total concentrations of heavy metals (mg/L) in the following decreasing order: SA>SE>SF>SB>SC>SD>SH>SI>SG>SJ(6.07 >4.95 > 2.07 > 1.59>0.24>1.22>0.09>0.04>0.03>0.01). The highest concentration of heavy metals is recorded for iron (SA= 5.78), zinc (mg/L) (SB = 1.36, SE = 1.30, and SF = 1.35) and lead (Pb) (SE = 2.39). The elevated iron levels in vessels from SA are potentially linked to corrosion processes. Cadmium, lead, and nickel were not detected, except for lead in the sample from SE. Copper concentrations were aligned with EU standards in the vessels. Proper ballast water management is vital for monitoring water qualities, preventing environmental spread of heavy metals, ensuring marine ecosystem health, and developing compliance strategies for ships docking in ports.

1. Introduction

The release of ballast water containing degraded water quality and elevated levels of heavy metals, such as mercury, lead, and cadmium, into the ocean by ships can have severe effects for marine ecosystems (Dobaradaran et al., 2018). The bioaccumulation of these heavy metals in marine organisms poses a significant threat to organism health and survival, as they can enter the food chain and cause detrimental effects on biodiversity and ecosystem functioning. Moreover, the presence of pollutants such as oil, chemicals, and microplastics in ballast water can exacerbate these negative

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impacts (Naik et al., 2019; Velusamy et al., 2014). The introduction of these pollutants can disrupt the delicate balance of marine ecosystems, leading to a decline in biodiversity and the loss of important habitats.

Heavy metals can affect the reproductive capabilities of marine organisms, impair their immune systems, and cause genetic mutations, with far-reaching consequences for both the immediate environment and human health. For instance, the consumption of contaminated seafood can pose serious health risks to humans (Chris et al., 2023; Onyena et al., 2024). Several sources contribute to the release of heavy metals into coastal environments, including anthropogenic activities, industrial and urban wastewater, dredging and reclamation, nuclear weapons, power plants, sea traffic, and bilge and ballast water disposals related to port services (Dobaradaran et al., 2018). The international maritime industry accounts for approximately 90 % of the world's commodities transported, with unintended consequences being the transport of heavy metals via ballast water (IMO, 2017). Ships carry ballast water to control draft, constancy, and trim, which can result in the discharge of heavy metals into the marine environment, posing a threat to human and marine ecosystem health (Velusamy et al., 2014). Studies have shown that heavy metals can be present in ballast water and sediment samples taken from ships' ballast tanks (Hasanspahić et al., 2022). The Ballast Water Management Convention was adopted in 2017 to regulate ship ballast water management and prevent the spread of aquatic invasive species. All ships, including existing ones, are required to have a ballast water treatment system onboard by September 8, 2024 (Pitana & Handani, 2023; Ivče et al., 2021). The convention also requires ships to have a ballast water management plan, a ballast water record book, and an International Water management certificate. The treatment of ballast water with active substances can have significant and harmful effects on the marine environment (Ivče et al., 2021). The quantity of heavy metals carried in ballast water can vary, and is dependent on factors such as the origin of the water, the type of vessels, and the geographical locations where the water is collected (Tolian et al., 2020a).

Heavy metal pollution in marine ecosystems has become a serious worldwide concern. Some heavy metals are toxic even at low concentration levels (Onyena et al., 2024). Cadmium, for instance, exhibits toxicity at the remarkably low level of 0.005 mg/L, according to EU standards. Lead and nickel become harmful at concentrations as low as 0.5 mg/L. The existence of heavy metals at certain elevated concentrations in the marine environment creates a societal health risk which is harmful for fisheries and human nutrition (Chris et al., 2023). These heavy metals demand attention due to their potential health risks, emphasizing the importance of monitoring and adherence to safety standards to mitigate their adverse effects. While marine transportation provided by the shipping industry is crucial to global trade, with economic growth and development, it also has significant environmental impacts. Therefore, the aim of this study is to evaluate the water quality and heavy metal concentrations in ballast water from different vessels across different countries.

2. Materials and methods

2.1 Study area

Ten (10) different vessels, labelled Samples A to J, were selected for this study; Sample A- Lome, Sample B- Atlantic, Sample C- Philippine, Sample D- Switzerland, Sample E- Senegal, Sample F- Indian, Sample G- Cameroon, Sample H- Lagos Anchorage, Sample I- Escravos River Nigeria, Sample J- South Africa (**Figure 1**).

2.2 Sample collection

Ten (10) samples of ship ballast water were collected from the 10 different vessels through an open manhole from a single tank per vessel. The samples were collected from 12th -22nd December 2023. The ten water samples from conveyor vessels were collected in 2 liter sterilized polythene bottles each, and transported in ice blocks to ANALAB Laboratory Services Limited (RC: 1794471) Ibadan for water analysis.

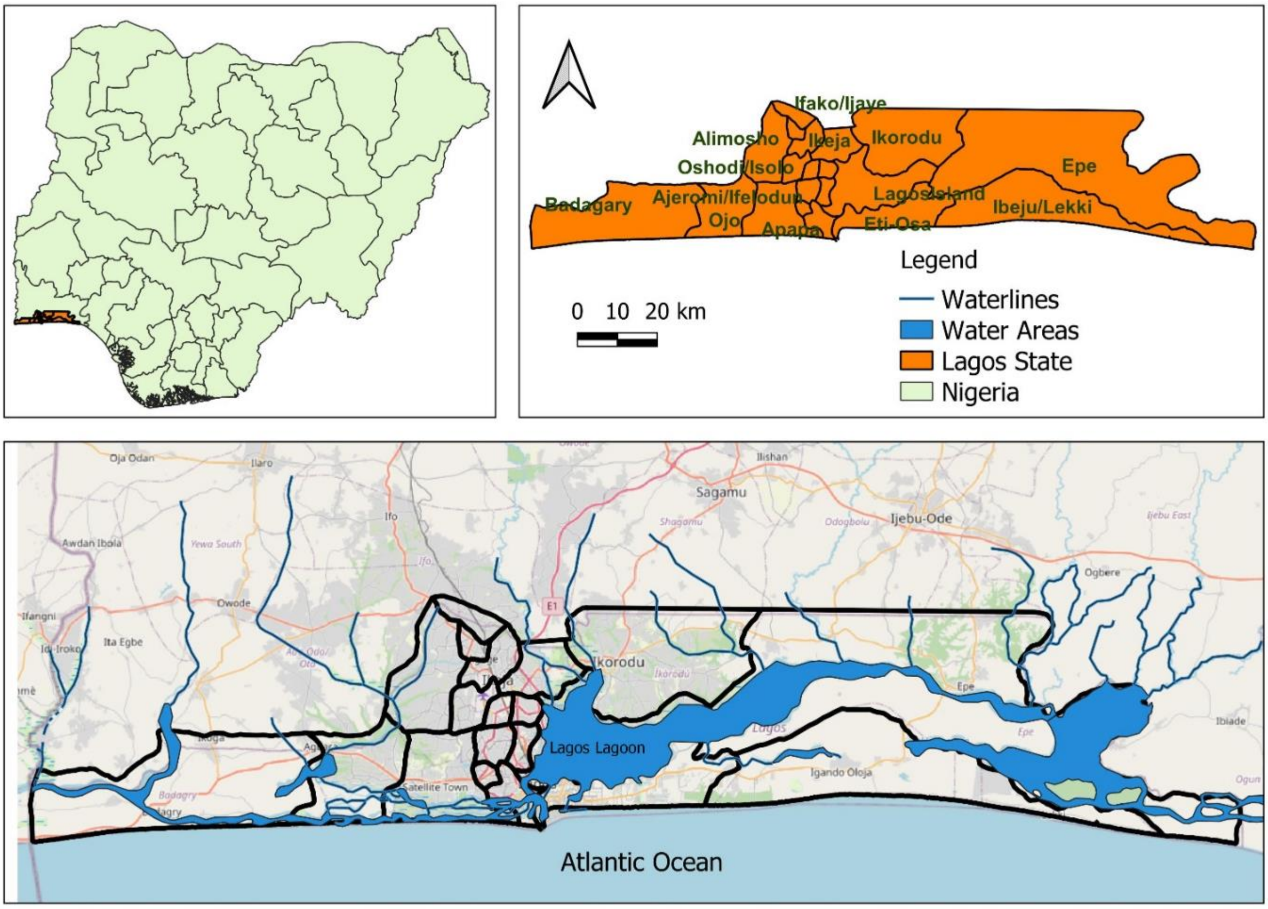

Figure 1 Map showing the Lagos Waterways and Ships.

2.3 Physicochemical analysis of ballast water samples

Physicochemical analysis of the water samples was carried out *in situ* using different measuring meters. The physicochemical parameters were determined using known standard methods, and analyses were carried out in triplicate. Temperature, water conductivity, pH, and total dissolved solid (TDS) were quantified *in-situ* at each site using a handheld electronic multipurpose meter (EZ9908 model). Turbidity using a turbidimeter (TDR-Z200 model), dissolved oxygen (DO) using a DO meter (AZ8403 model), and biochemical oxygen demand (BOD) were carried out in the laboratory, and all analyses followed the guide of the American Public Health Association (APHA, 2017).

2.4 Determination of heavy metal concentration in ballast water samples

The selected heavy metals, including copper (Cu), iron (Fe), lead (Pb), zinc (Zn), cadmium (Cd), and nickel (Ni), were analyzed and determined by Atomic Absorption Spectrophotometry (AAS-model AA-7000), according to method described by Dobaradaran et al. (2018).

2.5 Digestion of samples for heavy metal analysis with nitric acid

Suitable volumes of the water samples were added in evaporating dishes and acidified to methyl orange with concentrated nitric acid (HNO_3). Furthermore, 5ml concentrated HNO_3 was added and evaporated to 10ml. Then, it was transferred to a 125 ml conical flask. 5ml of concentrated nitric acid and 10ml of perchloric acid (70 %) were added. This was heated gently until white dense fumes of $HClO_4$ appeared. The digested samples were cooled at room temperature and filtered through Whatman no. 41 or a sintered glass crucible, and finally the volume was made up to 100 ml with distilled water. Then, this solution was boiled to expel oxides of nitrogen and chlorine. This solution contained 0.8N in $HClO_4$. The solution was used for the use of determination of heavy metals.

2.6 Quality control and quality assurance

The accuracy, precision, and reliability of the heavy metal analysis results in the ballast water included a blank extraction, and were checked with standard reference material. The standard concentrations and absorbance values for each metal are documented in **Table 1**. Quality control samples yielded analytical results that demonstrated satisfactory performance in determining heavy metals. These results fell within the range of certified values, showing a recovery rate between 90.4 and 97.5 % for all metals. To avert contamination risks, precautionary measures were taken, including the prior washing of all plastic labware in diluted nitric acid and distilled water. Additionally, all chemicals utilized in the experiments were sourced from Merck, ensuring high purity standards.

Table 1 Standard and absorbance values of the metals employed in this research.

Fe		Cu		Zn		Cd		Pb		Ni	
Conc. (ppm)	Abs.	Conc. (ppm)	Abs.	Conc. (ppm)	Abs.	Conc. (ppm)	Abs.	Conc. (ppm)	Abs.	Conc. (ppm)	Abs.
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.00	0.23	1.60	0.14	1.60	0.32	4.00	0.06	4.00	0.04	4.00	0.10
8.00	0.18	0.80	0.07	0.80	0.16	3.00	0.05	3.00	0.03	3.00	0.08
4.00	0.09	0.40	0.04	0.40	0.08	2.00	0.04	2.00	0.02	2.00	0.05
2.00	0.05	0.20	0.02	0.20	0.04	1.00	0.01	1.00	0.01	1.00	0.03

2.7 Data analysis

Statistical analysis was performed using Windows-based SPSS version 20 (IBM Corp). Results of physicochemical and heavy metals were presented as Mean ± Standard deviation and all the determinations were in triplicate. One-way ANOVA was used to evaluate differences between the samples; p-value of less than ($p < 0.05$) was considered to be statistically significant.

3. Results and discussion

3.1 Results of physicochemical parameters of ballast water

The physicochemical parameters of ship ballast water samples collected from various vessels in a maritime environment are presented in **Figure 2** and **Tables 2** and **3**. The concentration of each parameter varied, resulting in different levels of ship ballast water pollution in the maritime environment. The ANOVA findings revealed statistically significant differences among the parameters examined ($P < 0.05$).

3.2 Comparative analysis of ballast tank parameters across different samples from various regions

Distinct characteristics emerged, indicating variations in water quality and potential deviations from international standards. Samples A to F exhibited a consistent absence of objectionable odor and were characterized by being either salty or tasteless. While the appearance was generally clear, Sample F stood out with a slightly cloudy appearance. Temperature values for

Samples A to E remained within a close range, with Sample F showing a lower temperature. Turbidity levels varied, with Sample A surpassing standard limits. Sample E exhibited significantly higher conductivity and total dissolved solids (TDS), indicating potential concerns. Dissolved oxygen (DO) levels across all samples were within acceptable ranges, although Sample D showed a slightly elevated biochemical oxygen demand (BOD). pH levels for Samples A to F generally adhered to standards, except for Samples E and F, displaying minor deviations.

Table 2 Results of water-quality parameters of the ballast water samples collected from maritime environments.

Parameter	**Sample A Lome**	**Sample B Atlantic**	**Sample C Philippine**	**Sample D Switzerland**	**Sample E Senegal**	**Sample F Indian**
Odor	Un-object	Un-object	Un-object	Un-object	Un-object	Un-object
Taste	Salty	Salty	Tasteless	Tasteless	Salty	Salty
Appearance	Clear	Clear	Cloudy	Clear	Clear	Clear
Temperature (°C)	27.30±0.10	27.27±0.058	27.33±0.058	27.00±0.20	27.20±0.10	25.20±0.1
Turbidity NTU	7.54±0.16	3.74±0.18	3.689±0.18	4.438±0.04	3.583±0.10	2.529±0.31
Conductivity (µS/cm)	200.00±0.00	194.70±0.58	93.00±0.00	121.0±0.00	579.3±1.16	207.3±0.58
DO (ppm)	4.17±0.21	3.84±0.072	4.013±0.081	3.86±0.096	3.53±0.040	3.90±0.035
BOD (ppm)	0.61±0.12	0.21±0.086	0.63±0.04	1.057±0.1301	0.31±0.012	0.39±0.03
pH	5.70±0.015	5.75±0.005	5.78±0.0300	6.20±0.015	5.75±0.0058	5.48±0.025
TDS (mg/L)	100.00±0.00	97.07±0.060	46.33±0.58	40.17±0.21	31.50±1.14	33.80±0.72
TSS (mg/L)	40.17±0.72	18.24±0.21	10.74±1.10	16.95±0.36	19.83±3.04	17.53±3.56
TS (mg/L)	140.17±0.72	115.31±0.15	57.073±1.01	57.12±0.16	51.33±4.16	52.33±3.16

Table 3 Results of water-quality parameters of the ballast water samples collected from maritime environments.

Parameter	**Sample G Cameroon**	**Sample H Lagos Anchorage**	**Sample I Nigeria Escravos River**	**Sample J South Africa**
Odor	Un-object	Un-object	Un-object	Un-object
Taste	Tasteless	Salty	Tasteless	Salty
Appearance	Clear	Clear	Clear	Cloudy
Temp (°C)	27.80±0.55	26.90±0.070	27.77±0.09	28.37±0.18
Turbidity (NTU)	4.82±0.084	6.65±0.12	6.31±0.058	3.64±0.058
Conductivity (µS/cm)	308.7±1.20	238.00±0.00	350.3±0.88	296.3±0.67
DO (ppm)	3.120±0.011	2.31±0.035	2.53±0.012	3.400±0.021
BOD (ppm)	1.048±0.030	0.97±0.030	0.10±0.023	1.26±0.032
pH	8.36±0.014	8.28±0.013	7.82±0.0033	7.82±0.0033
TDS (mg/L)	154.0±1.00	119.00±0.00	125.00±1.20	124.00±0.58
TSS (mg/L)	55.69±0.77	44.200±1.34	65.00±1.001	41.63±0.33
TS (mg/L)	209.69±1.77	163.200±1.34	190.00±2.20	165.63±0.90

Samples G to J shared commonalities, featuring an absence of objectionable odor and a clear appearance. Taste varied, with Samples G and I being tasteless, while Samples H and J were salty. Temperature values were consistent, with Sample J showing a slightly higher temperature. Turbidity levels in Samples G, H, I, and J fell within acceptable ranges. Conductivity and TDS levels for these samples were also within standard limits. DO and BOD values were within acceptable ranges, showcasing water quality compliance. pH levels for all of these samples were within the acceptable range.

The water samples analyzed in this study exhibited a clear appearance, no objectionable taste or odor, and conformed to the permissible limits for these parameters. The mean temperature of all samples was within the range of 26.90 to 28.70 °C. However, there was a slight increase in the temperatures recorded for Samples J and H, which showed no significant difference ($P > 0.05$) compared to other samples. The mean temperature of the water samples could be attributed to variations in weather conditions and time of sampling. Ballast water samples collected from three vessels with voyages within the Middle East and Asian regions recorded higher temperatures, ranging from 29.8 to 30.5 °C (Ng et al., 2015).

The mean turbidity (NTU) measured in samples was within the range of 3.52 - 7.54. There was a significant increase in the turbidity mean values of Samples A, H, I, and J compared to other samples. The turbidity values were higher that the threshold limits of 5NTU set by the WHO (WHO, 2011). The increase in turbidity mean values in Samples A, H, I, and J suggests that there may be anthropogenic activities causing pollution and potential contamination in those samples. Turbidity, while not directly harmful to health, can impair ship movement due to water cloudiness, and may indicate the presence of invasive species and contaminants of concern. High turbidity values can result from anthropogenic activities that cause pollution, which can affect the turbidity level of water samples. Various activities, like urban development, industrial discharges, agriculture, and dredging, introduce pollutants into water bodies, such as sediments, chemicals, nutrients, and pathogens, leading to increased turbidity (Chawla et al., 2024). Ships contribute to this by taking on ballast water in one location and discharging it elsewhere to maintain stability. These actions, combined with other human activities, can cumulatively increase turbidity levels. This increased turbidity can hinder light penetration, disrupt photosynthesis, and affect aquatic plants, and alter water temperature, nutrient availability, and habitat structure, ultimately impacting the behavior and composition of aquatic organisms (Bulmer et al., 2018; Boyd & Boyd, 2015).

The mean value of water sample conductivity ranged from 93.00 (Sample C) to 579.3 (Sample E). There was no significant decrease in the conductivity value recorded for Samples C and D compared to other samples, but there was a significant increase in Sample E compared to the standard range limit. The conductivity values for the water samples were found to be significantly below the permissible limit of 1,000 µS/cm, as established by the WHO (2011). The low conductivity values in the ballast water samples could be attributed to the presence of natural organic matter, minerals, or organisms that hinder the movement of electricity (Heyer et al., 2013). Studies have identified various bacteria, including *Pseudomonas fluorescens*, *Vibrio campbellii*, and *Escherichia coli*, in ballast water (Kumar et al., 2021; Sun et al., 2021). These organisms could have contributed to changes in water quality, including alterations in conductivity.

The dissolved oxygen and biochemical oxygen demand measured in samples varied in mean value. The DO (ppm) recorded ranges within 2.31 in Sample H to 4.17 in Sample A, and there were no significant differences ($P > 0.05$) in DO between the samples, but there were slight decreases in the mean values of DO recorded in sample H and I, while slight increases were observed in Sample A, C, and F (4.17, 4.01 and 3.90), respectively. These concentrations were lower than the 6 mg/L of the WHO (2011). There were slight decreases in the BOD recorded in samples B, E, and F, and increases in samples D, G, and J, though they were not significantly different ($P > 0.05$) from each other. Reduced dissolved oxygen in ballast water can have various effects on the ecosystem. It can cause behavioral and distributional shifts of organisms, alter ecological processes, and impact predator-prey interactions (Moriarty et al., 2020). Additionally, the discharge of ballast water can transfer nonindigenous aquatic species, including invasive species, from one region to another, leading to reduced DO levels and, thus, ecological damage (Saglam & Duzgunes, 2018).

The reduced BOD could be attributed to the release of microorganisms from ballast water, particularly the regrowth of heterotrophic microorganisms in ballast tanks (Fujiwara et al., 2020). Thus, the introduction of non-indigenous species through ballast water can lead to competition with native species, the decline or extinction of indigenous species, and disruption of the ecosystem (Hess-Erga et al., 2019). The conditions of the Lagos Coastal Waters reveals low dissolved oxygen and high biochemical oxygen demand at certain stations (Ajani et al., 2021). Nkwoji et al. (2020) revealed in their study of the coastal Lagos Lagoon that the inflow of pollutants from land-based sources resulted in degraded water quality, and low diversity and abundance of benthic macroinvertebrates.

The pH recorded in sample A, B, C, D, E, and F tends to be acidic, with mean values of (5.70; 5.75; 5.78; 6.20; 5.75, and 5.48), and alkaline in other samples (G - J). There were significant ($P < 0.05$) differences in values of pH of different samples. An increase in hydrogen ions and a decrease in pH values can indeed affect the pattern of microbial populations. Studies have shown that acidification can alter the activities, structures, and functions of bacterial and fungal communities in estuarine sediments (Su et al., 2021). Acidification has been found to inhibit the activities of extracellular enzymes related to nutrient cycling and decrease basal respiration rates (Franzo et al., 2011). Acidification can increase the abundance of potential animal pathogens in sediments (Krause et al., 2012), and the introduction of invasive species. Acidification also disrupts bacteria-mediated nutrient cycling, as the relative abundances of functional genes associated with nutrient cycling in bacterial communities are decreased (Ratzke & Gore, 2018).

The mean levels of total dissolved solids (TDS) (mg/L), total suspended solids (TSS) (mg/L) and total solids (TS) mg/L of Sample A were (100.00; 40.17, and 140.17), Sample G (154.00; 55.69, and 209.90), sample H (119.00; 44.20, and 163.20), sample I (125.00; 65.00, and 190.00), and Sample J (124.00; 41.63, and 165.63), respectively, showed significant increases compared to other samples. The presence of these substances in ballast water can affect the distribution and diversity of potential pathogens in the water (Ardura et al., 2021). For example, the abundance of certain potential pathogenic genera, such as Pseudoalteromonas and Bacteroides, can vary depending on the ballast holding time (Hess-Erga et al., 2019). Additionally, the levels of TSS, total organic carbon, and particulate organic carbon in ballast water have been found to have a positive correlation with most potential pathogens (Wang et al., 2020). Elevated TDS in ballast water indicates the presence of salts, minerals, and other dissolved materials, which can create conditions for pathogen survival (Kuroshi, 2012). Similarly, increased TSS provides a substrate for microorganisms, including potential pathogens, and creates an environment conducive to the persistence of harmful agents (Walters et al., 2014). High levels of TOC suggest the presence of organic materials, which serve as nutrients for microorganisms and raise the risk of contamination (Perwira et al., 2020). Increased POC levels may contribute to nutrient availability and provide surfaces for potential pathogen attachment and growth (Olilo et al., 2017).

3.3 Results of heavy metal concentrations in ballast water samples

The results of the heavy metal concentration from different ship ballast water from different vessels are presented in **Figure 3** and **Table 4**. The ANOVA findings revealed statistically significant differences among the heavy metals examined ($P < 0.05$). Heavy metal analysis in ship ballast water sampled from ten different vessels showed that concentrations of iron (Fe) present in water samples ranged from 0.00 to 5.78, but in sample G, I, and J, iron was not detected. However, the concentration level of iron found in Sample A (5.78) was significantly higher than other samples, though the level of iron found in sample B, D, and H (0.14; 0.04, and 0.01, respectively) were below the permissible limits of the WHO of 0.1 (WHO, 2011). In contrast, Sample C (0.58); Sample E (0.84), and Sample F (0.68) were increased and above the threshold limit. However, only Sample A exceeded the 3 mg/L permissible limit for EU estuary and harbor basin water standards. Iron is an important element for the human body, especially in the blood, but if it exceeds the limit, it will become a radical that is capable of doing damage to human tissue cells (Skalnaya & Skalny, 2018). The elevated levels of Fe in Sample A may be attributed to the corrosion process, which is caused by electrochemical reactions involving ionic content in seawater, such as Fe^{2+} ions withdrawn from the ballast tank surface. Although the typical corrosion rate for iron in ballast is between 0.1 and 0.3 mm/y, contamination with other corrosive materials can increase it to 2 to 4 mm/y, leading to higher Fe concentrations in the collected samples (Valdez et al., 2016). High iron levels in ballast water can have potential long-term effects on the marine environment. These effects include damage to ecosystems and negative impacts on human health (Nwigwe & Kiyokazu, 2023). Iron can act as a nutrient for certain organisms, leading to excessive growth and the formation of harmful algal blooms (Yarimizu et al., 2018). These blooms can deplete oxygen levels in the water, leading to hypoxic conditions that can harm marine life. Additionally, high iron levels can contribute to the introduction and spread of nonindigenous aquatic species, which can disrupt native ecosystems and threaten biodiversity.

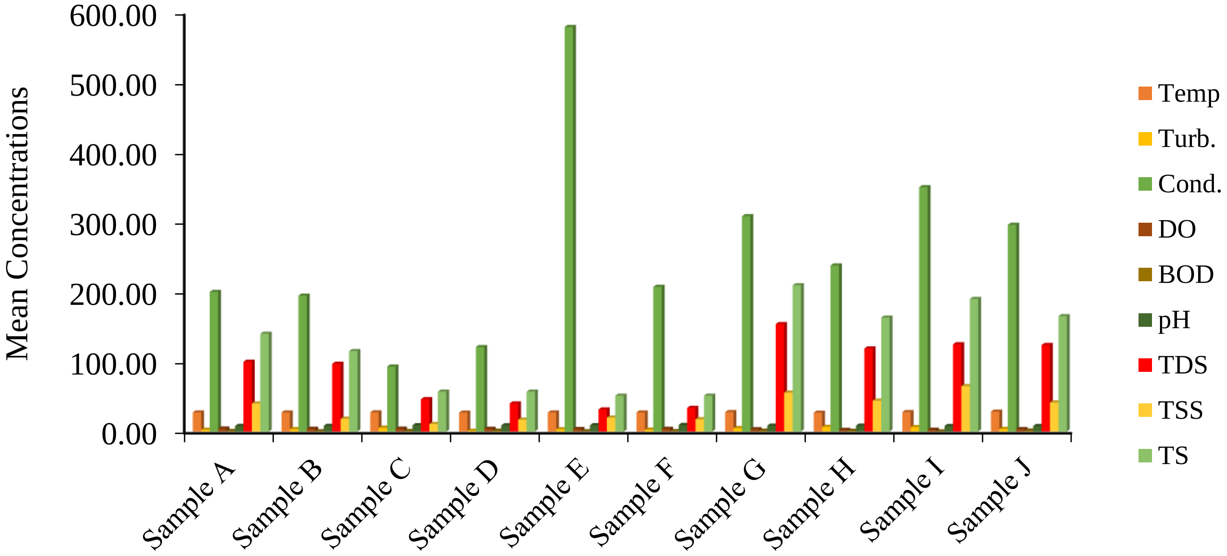

Figure 2 Water-quality parameters of the ballast water samples collected from ballast water vessels. This figure illustrates the characteristics and composition of the collected ballast water samples in terms of their quality-related attributes.

Sample A- Lome, Sample B- Atlantic, Sample C- Philippine, Sample D- Switzerland, Sample E- Senegal, Sample F- Indian, Sample G- Cameroon, Sample H- Lagos Anchorage, Sample I-Nigeria Escravos River, Sample J- South Africa

The study recorded that no cadmium (Cd), lead (Pb) or nickel (Ni) were found in any of the collected samples. However, only Sample E contained lead concentrations of 2.39 mg/L, which is above the WHO permissible limit of 1.0 mg/l (**Table 4**) and above the 0.5 mg/L EU estuary and harbor basin waters standards. This result contrasts with the findings from a study conducted in the Port of Tanjung Emas Semarang, Indonesia, where the average Pb content in ballast water tanks was determined to be 0.37 mg/L (Tjahjono et al., 2017). Their study showed that the content of Cd was about 0.001 - 0.46 mg/L, and Zn was about 0.001 - 2.464 mg/L. The concentration levels of copper in the ballast samples analyzed in this study were within the 0.5 mg/L EU estuary and harbor basin waters standards. A study conducted on ships entering the Bushehr port, Iran, found that the heavy metals concentrations in the water samples exceeded the quality standard values for Cu and Ni, and for Cd in some samples (Tolian et al., 2020b).

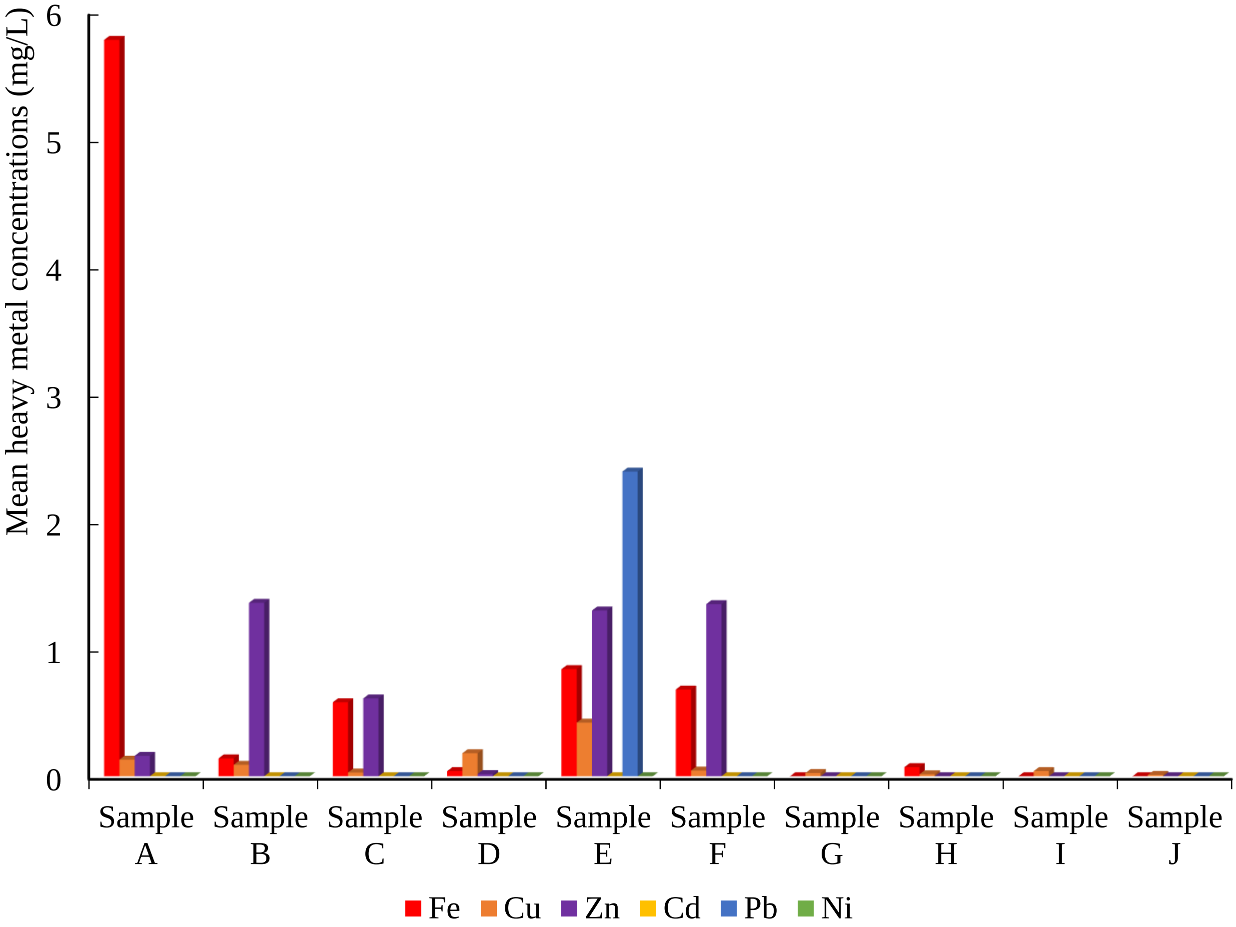

Figure 3 Mean heavy metal concentrations in ship ballast water from maritime environments. This figure depicts a visual representation of heavy metal concentrations found in ballast water collected from various vessels.

Key: Sample A- Lome, Sample B- Atlantic, Sample C- Philippine, Sample D- Switzerland, Sample E- Senegal, Sample F- Indian, Sample G- Cameroon, Sample H- Lagos Anchorage, Sample I-Nigeria Escravos River, Sample J- South Africa.

Table 4 highlights the concentrations of heavy metals from ballast tanks from different regions.

The presence of lead concentrations in Sample E is an indication that the ballast water contained some possible contaminants. Lead is a toxic pollutant that can disrupt the entire food chain and is lethal even at low concentrations. When lead is present in ballast water, it can lead to chlorosis in aquatic plants, decrease in growth and biomass productivity, and inhibition of root length. Lead can also be bioconcentrated in aquatic species over time, leading to chronic toxicity and potential harm to internal organs (Mishra et al., 2014). Exposure to lead can cause hematological disruption, anemia, kidney dysfunction, brain damage, and adverse effects on the kidney, heart, and blood-forming organs (National Research Council, 1993). Lead is a major factor in symptoms such as hyperactivity, behavioral aberrations, and learning difficulties in children (Dórea, 2019).

Copper (Cu) is an essential element for human life at moderate levels, and all samples in this study were found to be within the standards set. The major sources of Cu in ballast water are electrolysis units used in ballast water treatment systems and hot water from the cooling water overboard discharge associated with the propulsion plant of a vessel (Werschkun et al., 2014). The concentrations detected in this study are consistent with the findings of Dobaradaran et al. (2018). It is worth noting that Zn, Fe, and Cu were the heavy metals most frequently detected in both seawater and ballast water, and were within the standards set by the International Maritime Organization (IMO). While Zn and Cu are essential minerals for the human body, excessive amounts can lead to health issues such as skin diseases and anemia. Excessive absorption of zinc suppresses copper and iron absorption (Fosmire, 1990). Excessive copper intake can cause nausea, vomiting, abdominal pain and cramps, headache, dizziness, weakness, diarrhea, and a metallic taste in the mouth (Osredkar & Sustar, 2011).

Table 4 Mean heavy metal concentrations in ship ballast water from maritime environments.

Code	Name	mg/L Fe	mg/L Cu	mg/LZn	mg/LCd	mg/LPb	mg/L Ni	Total (mg/L)
Sample A	Lome	5.78	0.13	0.16	0.00	0.00	0.00	6.07
Sample B	Atlantic	0.14	0.089	1.36	0.00	0.00	0.00	1.59
Sample C	Philippine	0.58	0.029	0.61	0.00	0.00	0.00	1.22
Sample D	Switzerland	0.04	0.18	0.017	0.00	0.00	0.00	0.24
Sample E	Senegal	0.84	0.42	1.30	0.00	2.39	0.00	4.95
Sample F	Indian	0.68	0.044	1.35	0.00	0.00	0.00	2.07
Sample G	Cameroon	0.00	0.025	0.00	0.00	0.00	0.00	0.03
Sample H	Lagos Anchorage	0.071	0.015	0.00	0.00	0.00	0.00	0.09
Sample I	Nigeria Escravos River	0.00	0.04	0.00	0.00	0.00	0.00	0.04
Sample J	South Africa	0.00	0.01	0.00	0.00	0.00	0.00	0.01
EU standard		3	0.5	-	0.005	0.5	0.5	

Zn and Fe were the most commonly detected heavy metals in ballast water samples, while Nwigwe and Kiyokazu (2023) recorded Zn and Pb from selected ships docked in the Onne River, Nigeria. The major sources of Zn in ballast water include the sacrificial anode used for ship propeller shafts and the pipes of seawater cooling systems (Kim et al., 2015). Additionally, Fe can be present in ballast water due to corrosion of a ship's hull and machinery. These heavy metals pose a significant threat to marine ecosystems, as they can disrupt the balance of nutrients and harm aquatic organisms. Therefore, proper ballast water management and treatment methods are essential to prevent the spread of these harmful contaminants.

While Samples A and E exhibited potential variations in turbidity, conductivity, and TDS, Samples G to J generally aligned with international quality standards. In addition, most samples aligned with EU standards for copper, zinc, cadmium, and nickel concentrations. The elevated lead levels in Sample E highlight the significance of vigilant monitoring and robust ballast water management practices to prevent environmental degradation and ensure compliance with international quality standards. Continuous scrutiny of heavy metal concentrations remains imperative for maintaining water quality integrity during maritime operations. Continuous monitoring and stringent ballast water management practices are vital to ensure compliance, protect marine ecosystems, and maintain the integrity of water quality during shipping operations. The findings necessitate the need for a comprehensive approach to address variations in water parameters and uphold environmental standards across different regions.

4. Conclusions

The study highlights the critical issue of ballast water pollution, emphasizing its potential to introduce elevated levels of heavy metals, such as iron, copper, and lead, into marine ecosystems. The physicochemical analysis of the ballast water samples revealed variations in temperature, turbidity, conductivity, dissolved oxygen, biochemical oxygen demand, pH, total dissolved solids, total suspended solids, and total solids among the different vessels. Notably, the increased turbidity in certain samples indicated potential anthropogenic activities causing pollution.

The heavy metal concentrations in the ballast water samples, particularly iron, exhibited significant variability among the vessels. While some vessels adhered to permissible limits for iron, others, like Sample A, exceeded these limits, pointing to potential corrosion issues. Fortunately, cadmium, lead, and nickel were not detected in any of the samples, except for minimal lead content in Sample E, emphasizing the need for ongoing monitoring and control measures to prevent the introduction of toxic pollutants.

The study highlights the global concern of heavy metal pollution in marine organisms, emphasizing the potential risks to both marine ecosystems and human health. The findings contribute to the growing body of knowledge on the environmental impacts of the international maritime industry which, while vital for global trade and economic growth, necessitates effective management strategies to mitigate its ecological footprint. As the shipping industry continues to play a crucial role in trade and development, ongoing research and regulatory efforts are imperative to ensure sustainable practices and prevent further degradation of marine environments. The results of this study provide valuable insights for policymakers, environmentalists, and industries alike, emphasizing the urgency of addressing ballast water pollution to safeguard the health of our oceans and the well-being of future generations.

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