Plastic Pollutants Effects Assessment of the Dar es Salaam Port Ecosystem

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Abstract
This study examined the global issue of plastic pollution, focusing on the effects of plastic pollutants on the port ecosystem and the threat faced in managing this problem. Despite the introduction of many regulations and conventions such as MARPOL Annex V and the EU Directive 2019/883 for controlling of maritime ecosystem pollution, plastic pollution remains a significant issue of concern. Approximately 12.7 million tons of plastic believed to be dumped into the ocean annually, this affect the ocean ecosystem and human well-being. This study highlighted immediate actions to be taken in managing the port ecosystem and explores the involvement of stakeholders in a strategy to improve waste management. This study deployed mixed-methods techniques, incorporating field sampling, laboratory analyses, and policy reviews to investigate the types, concentrations, sources, and ecological impacts of pollutants at the port.
The finding revealed the presence of plastics average concentration of 10 particles/L around the Dar es Salaam port ecosystem which pose a significant threat to the delicate ecological balance and the well-being of surrounding communities. The elevated levels of plastics pollutant, exceeding recommended environmental guidelines, were observed in specific hotspots near industrial outfalls, shipyards, and areas receiving urban runoff, the situation raising the concerns about potential risks to the food web and human health through seafood consumption. These finding underscore the urgent need for planned actions to mitigate pollution threats and promote a sustainable port ecosystem and environment.
The study recommends immediate interventions, such as prioritizing pollution control at hotspots, strengthening monitoring and enforcement mechanisms, and raising public awareness. Long-term strategies include incorporating environmental considerations into port development plans, adopting ecosystem-based management approaches, and fostering stakeholders and regional cooperation on the seaport pollution control.

Keywords: *Plastic pollution; Marine ecosystem; Dar es Salaam port; Marine transportation; Sustainability environment.*

1. INTRODUCTION

Marine pollution has emerged as one of the defining environmental challenges of the 21st century (Häder D. P et al., 2020).). Human activities profoundly impact ocean health, leading to a complex mix of contaminants entering marine environments (Landrigan P. J et al., 2020). These pollutants threaten biodiversity, ecosystem functions, and the economic and social well-being of coastal communities (Islam & Tanaka, 2015). As hubs of maritime transportation and industrial activity, ports are particularly susceptible to various forms of marine pollution. The influx of ships, cargo handling, dredging operations, shipyard activities, and proximity to urban and industrial centers make ports critical pollution hotspots (Nikiema et al., Z. 2022). Understanding and mitigating these pollution effects is paramount to protecting coastal ecosystems and ensuring the long-term sustainability of port operations. A port ecosystem encompasses a complex web of interconnected elements within a port's geographical boundaries and surrounding areas (Notteboom & Rodrigue, 2015). This includes the physical environment, biological components and the human dimensions (Hardiyanto et al., 2020). Each of these elements interacts dynamically, influencing the overall health and functioning of the ecosystem. Understanding this interconnectedness is crucial for assessing pollution effects, as pollutants can originate from various sources, accumulate in different parts of the environment, and impact diverse organisms within the food web (Notteboom & Rodrigue, 2015). Additionally, the socio-economic and regulatory aspects of the port ecosystem play a significant role in how pollution is managed and controlled. Therefore, a holistic understanding of the port ecosystem is essential for developing effective and sustainable solutions to marine pollution challenges (Hardiyanto et al., 2020). Tanzania, with its extensive coastline along the Indian Ocean, is no exception to these challenges. The nation's rapid economic growth, fueled by maritime trade and coastal development, has put increasing pressure on its marine environment (Wagner, 2017). While the port is vital for the country's prosperity, its operations and the surrounding urban and industrial activities contribute to marine pollution, potentially harming the fragile coastal ecosystem.

The types of marine pollution prevalent in port environments include untreated or partially treated sewage discharged from urban areas and ships, a significant source of organic matter, nutrients, pathogens, and other contaminants (Mwakisunga B. et al., 2021). This pollution can lead to eutrophication, oxygen depletion, harmful algal blooms, and effects on human health. Coastal industries, including manufacturing, oil refining, and chemical production, can discharge various toxic pollutants, including heavy metals, persistent organic pollutants (POPs), and other harmful substances (Hellar-Kihampa, H. 2024). These contaminants accumulate in marine organisms, posing severe risks to the ecosystem and human health via seafood consumption. Oil and chemical spills from ships, port operations, or land-based sources threaten marine life and habitats like mangroves and coral reefs (Hellar-Kihampa, H. 2024). The long-term ecological repercussions of such incidents can be devastating. Improper disposal of solid waste, including plastics, contributes significantly to marine litter (Wagner, 2017). Plastic pollution smothers sea beds entangles marine animals and releases harmful microplastics into the ecosystem. Essential for maintaining navigation channels, dredging can release sediment-bound contaminants and cause turbidity, impacting marine habitats and species (Authority, T. P. (2019). Ships release air pollutants such as sulfur, nitrogen, and particulate matter, impacting air quality and possibly marine ecosystems through acidification. Underwater ship noise can disrupt marine life's communication and behavior.

1.1 Objective

Despite the regulations enacted so far, there is still an issue with plastic pollution caused by various activities around water bodies today. Approximately 400 million tons of plastic were produced worldwide in 2023. The production will probably double by 2040 and increase to 2.5 times the current quantity by 2050 if we continue at the current rate of consumption (UNCTAD, 2023); this will cause more challenges to the ocean ecosystem and human well-being to address these challenges more regulation and policy has been enacted. The EU Directive 2019/883 was introduced to control port waste and reduce marine pollution by setting regulations Rukavina, B. (2022). On the other hand, implementing these conventions has resulted in a considerable cutback in the quantity of waste plastic dumped into seas. Tanzania has a thriving maritime sector and extensive coastline; the country faces significant challenges in protecting its marine environment from pollution (Holly, G et al.,. 2022). As the principal port handles 95% of Tanzania's international trade and serves about seven landlocked and hinterland countries, Dar es Salaam port is also seriously affected by plastic pollution (Carpenter et al., 2021). While crucial for national prosperity, port operations and surrounding urban centers contribute to marine pollution, jeopardizing the surrounding environment's sustainability. This specific pollution nature and its extent in the Dar es Salaam port ecosystem still require adequate evaluation (Mwakisunga et al., F. 2021 Lugendo, B. R., & Kimirei, I. A. (2021). The main objective of this study is to assess plastic pollutants' effects on the port ecosystem at the Dar es Salaam port.

I. PROBLEM DEFINITION

Despite the regulations enacted so far, there is still an issue with plastic pollution caused by various activities around water bodies today. On the other hand, implementing these conventions has resulted in a considerable cutback in the quantity of waste plastic dumped into our seas. MARPOL Annex V defines garbage as all types of food, domestic, and operational wastes, including plastics, cargo residues, incinerator ashes, cooking oil, fishing gear, and animal carcasses produced during a ship's regular operation. These items must be disposed of regularly or occasionally (IMO, 2018). However, substances defined or listed in other Annexes to the Convention are excluded from this definition. In addition, EU Directive 2019/883 aims to improve waste management ports and reduce marine pollution by setting regulations for port reception facilities Rukavina, B. (2022). Tanzania has a thriving maritime sector and extensive coastline; the country faces significant challenges in protecting its marine environment from pollution (International Chamber of Shipping, 2019). The port areas are especially susceptible to various forms of pollution, threatening the delicate balance of coastal ecosystems. As the principal port handles 95% of Tanzania's international trade and serves about seven landlocked and hinterland countries, Dar es Salaam port is also seriously affected by plastic pollution (Carpenter et al., 2021). While crucial for national prosperity, port operations and surrounding urban centers contribute to marine pollution, jeopardizing the surrounding environment's sustainability. This specific pollution nature and its extent in the Dar es Salaam port ecosystem still require adequate evaluation (Mwakisunga et al., F. 2021 Lugendo, B. R., & Kimirei, I. A. 2021). The existing research suggests a complex interplay of pollution sources, including untreated sewage, industrial effluents, accidental spills, solid waste, dredging activities, and ship emissions (Machiwa, 2022 and Wagner, 2017). However, these studies provide limited coverage; therefore, a comprehensive investigation is essential to address the problem. This

paper was also motivated by the environmental and social impact assessment for dredging of the entrance channel at Dar es Salaam port, CONTRACT NO.: TPA/C/27-WB/2015-16 (Authority, T. P. 2019). This study aimed to bridge this knowledge gap by assessing the effects of marine pollution on the Dar es Salaam port ecosystem.

2.1 Research gap

Despite significant research on marine plastic pollution in Tanzania, several gaps in knowledge still need to be discovered. Previous research in Tanzania has investigated aspects of marine pollution, the focus being on isolated pollutants (Hellar-Kihampa, H. 2024), broader coastal areas, and lacks the specific, in-depth focus on a port environment (Machiwa, 2022). This research aims to fill this critical knowledge gap by providing a holistic understanding of pollution sources, types, concentrations, spatial distribution, and ecological effects within the Dar es Salaam port ecosystem. This information is essential for developing targeted mitigation strategies and evidence-based policies appropriate to this significant economic and ecological zone, ensuring the sustainability of port operations while safeguarding the fragile coastal environment (Bjerkli, 2021 and Authority, T. P. 2019). Moreover, this research provides an overview of the sources, impacts, and mitigation strategies associated with marine plastic pollution at the Dar es Salaam port ecosystem. By addressing the identified policy gaps in major factor exacerbation policy in Tanzania and interventions, we can work towards a cleaner and healthier marine environment for future generations.

2.11 The structure of the study

After the introduction part, statement of the problem and research gap provided in section 2, followed by methodology in section 3. Section 4 present findings. Finally, the conclusion is elucidated in section 5.

III. PROPOSED METHODOLOGY

This research study was conducted within the Dar es Salaam port ecosystem in Tanzania, and the primary objective was to assess the effects of plastic pollutants on the port ecosystem. The study employed a mixed-methods descriptive research design. Quantitative methods were central, encompassing field sampling and statistical techniques to identify water pollutants and assess ecological impacts, including acute toxicity and potential for bioaccumulation (Cahoon, 2021). Qualitative components supplement the quantitative findings and involve reviewing existing environmental policies, regulations, and institutional structures related to marine pollution management and evaluating current pollution monitoring and enforcement practices. The study targeted 100 key informative populations. The Statistical Package for the Social Sciences (SPSS) version 23.0 was used to analyze the data. Semi-structured interviews, questionnaires, documentary reviews, and direct observations were used as a technique for data collection. Fig. 3.1 represents the methodology workflow.

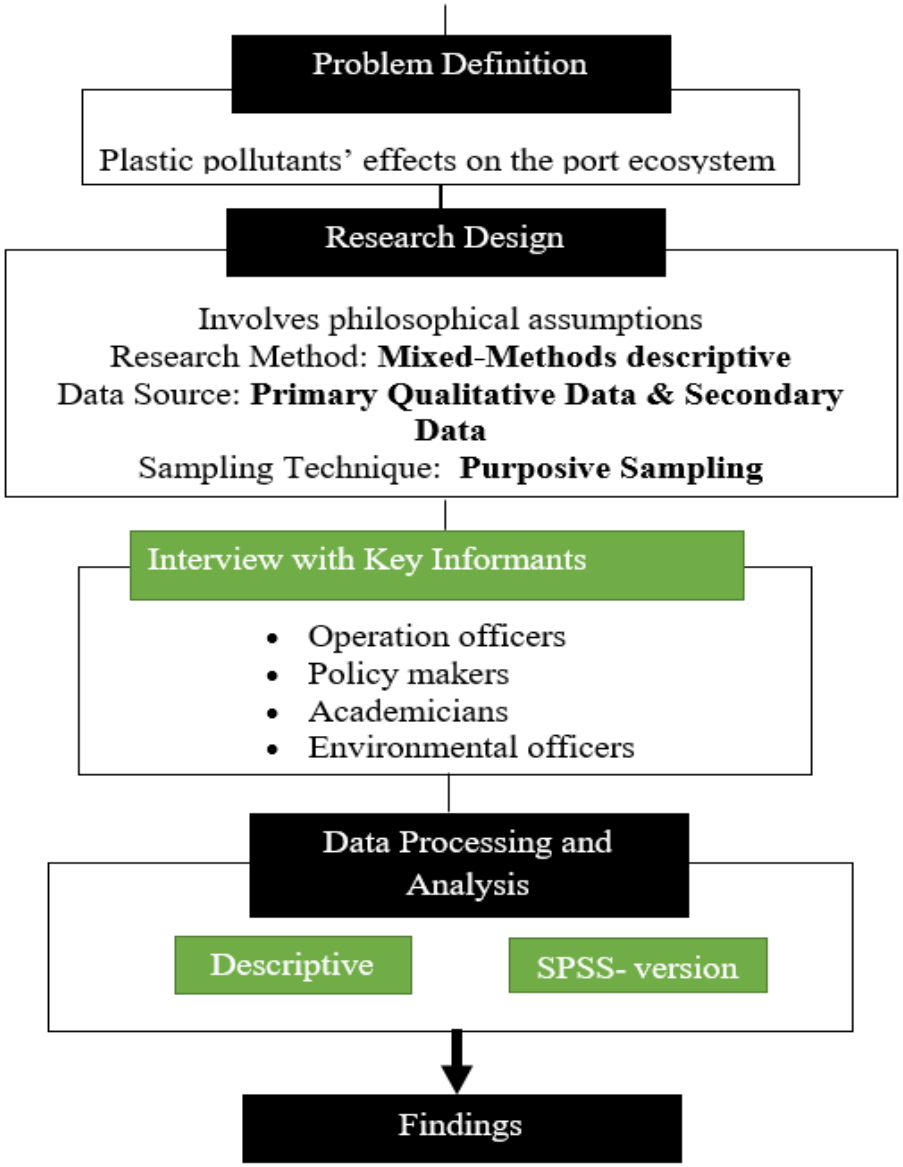

Fig. 3.1. Source: Authors own work

3.1 Participants recruitment and sampling

The selection of participants for key person interviews in this study was guided by their expertise, experience, and involvement in the field under investigation, making them key stakeholders, experts, or authorities in the domain of interest. Snowballing and convenience methods were adopted to recruit participants. The researcher and six trained assistants administered 100 structured survey questionnaires. To ensure validity and reliability, a sample size of such respondents was calculated, which considers a margin error (estimate of 5%)' and a desired confidence level of 96%. The calculation ensured a statistically significant sample size, allowing the research objectives to be achieved. These participants include operational officers, policymakers, academics, and environmental officers. A purposive sampling approach was adopted to ensure the selection of individuals with the necessary knowledge and

experience to provide valuable insights into the research topic. This involved identifying and recruiting participants through snowballing and convenience methods. In total, 96 key stakeholders within the marine industry were strategically recruited, each offering a unique perspective on marine pollution knowledge. The participants in our study represented diverse backgrounds and expertise, including marine pollution expertise, academicians, researchers, and environmental activists. Purposive sampling was used to select participants based on their knowledge, characteristics, experiences, and other criteria.

3.11 Participants demographic characteristics

In this research, the demographic data provides quantitative insights into the characteristics of the stakeholders involved in marine pollution management and those affected by its consequences within the Dar es Salaam port ecosystem. Participants were selected based on their affiliation with relevant organizations, including port authorities, environmental agencies, industries, and shipping companies, and their roles in influencing or being impacted by pollution in the port. This demographic information is crucial for understanding the diverse perspectives on pollution issues, identifying potential knowledge gaps among stakeholders, and ensuring that the research findings and recommendations are tailored to the specific context of the Dar es Salaam port environment. Most participants were male (n = 31, 59.6 %) and females (n=21, 40.4%) out of a total of 52 respondents. These interviews were aimed to tap into the extensive knowledge, rich experiences, and valuable insights these individuals hold, fostering a holistic understanding of the subject matter, its challenges, and its strategies for regulating plastic pollutants' effects on the port ecosystem at the Dar es Salaam port. Table 3.1 provides the participants' demographic information.

Table 3. 1: Distribution of respondents based on gender

Gender of respondents	Frequency (f)	Percentages (%)
Male	31	59.6
Female	21	40.4
Total	**52**	**100**

Source: Authors' own work

This study also examined the distribution of respondents based on their working experiences to gain a comprehensive understanding of the diverse perspectives on marine pollution threats in the Dar es Salaam port ecosystem, as shown in Table 3.2.

Table 3. 2: Distribution of respondents based on working experiences

Years of Working Experience	Frequency (f)	Percentages (%)
0-2 years	8	15.4
3-6 years	35	67.3
7-10 years	4	7.7
10 years and above	5	9.6
Total	**52**	**100**

Source: Authors' own work

3.3 Reliability and validity

To ensure reliability and validity, the research tool was improved using expert judgment; this includes the research supervisor and other experts from Tanzania. Items that lower the reliability were improved or deleted to maintain the required internal consistency before exact data collection. A pilot study of 28 samples was used for research tools evaluation and assessment; then, essential data was collected from 52 key respondents. Cronbach alpha was used to assess the internal consistency of the variables. The desired Cronbach's Alpha was determined using the SPSS.

3.4 Research ethical consideration.

Ethical approval was obtained from the Dar es Salaam Maritime Institute, ensuring the confidentiality of sensitive information obtained from respondents. Firstly, before being asked to complete the questionnaire, each respondent was guaranteed confidentiality and shown a copy of an approval letter from the institute. Finally, they were asked to fill the survey questionnaire.

IV. FINDINGS

4.1 Challenges

4.1.1 Distribution of plastic pollutants

The assessment of pollutant concentrations within the port ecosystem unveiled a complex and concerning picture, with various contaminants detected at levels that raise alarm for the life of the port ecosystem. The data collected elevated levels of heavy metals, nutrients, pathogens, and microplastics pose a significant threat to the delicate ecological balance and the well-being of surrounding communities, as represented in Table 4.1.

Table 4. 1: Key pollutants and their impacts

S/n	Pollutant	Sources	Potential impacts on the ecosystem
	Heavy Metals (lead, mercury, cadmium)	Industrial effluents, shipyard activities	Bioaccumulation in marine organisms, toxicity to marine life, potential human health risks through seafood consumption
	Nutrients (nitrogen, phosphorus)	Untreated sewage, urban runoff	Eutrophication, algal blooms, oxygen depletion, disruption of marine food webs, potential dead zones
	Pathogens (fecal coliform bacteria)	Sewage outfalls, densely populated areas	Waterborne diseases (cholera, typhoid, etc.), public health risks, contamination of seafood and beaches
	Micro plastics	Improper waste disposal, littering	Ingestion by marine organisms, physical harm (blockage, internal injuries), transfer of toxic chemicals up the food chain, potential impact on reproductive systems

Source: Authors' own work

Notably, heavy metals, lead, mercury, and cadmium, were detected in sediment and biota samples, with exceptionally high concentrations observed near industrial outfalls and ship

repair yards. This finding aligns with concerns raised by previous studies (Wagner, 2017). These findings emphasize the urgent need for targeted interventions to address the diverse pollution challenges facing the Dar es Salaam port ecosystem. Heavy metals, nutrients, pathogens, and microplastics pose a significant threat to marine life, human health, and the overall ecological integrity of the port.

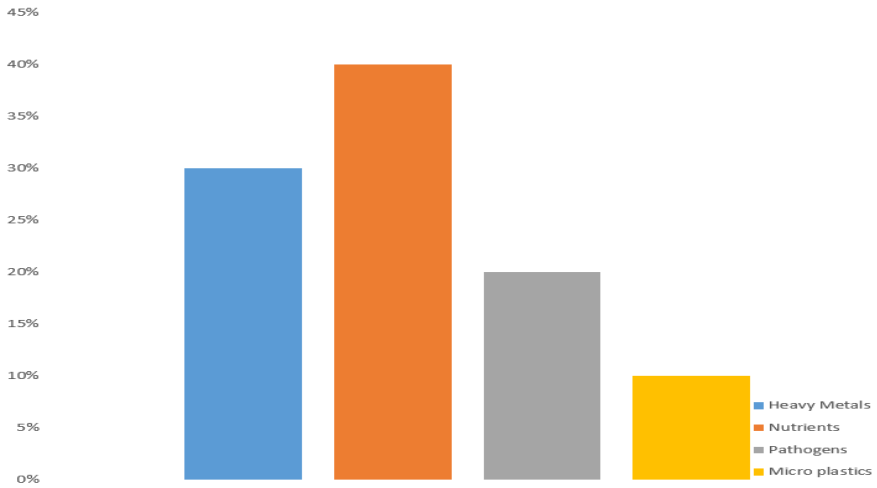

Fig. 4.1. Source: Authors own work

Source: Authors' own work

The assessment of pollutant concentrations within the Dar es Salaam port ecosystem revealed a worrisome scenario, with elevated levels of vital contaminants exceeding recommended environmental guidelines. These findings underscore the severity of marine pollution in this vital economic hub and highlight the urgent need for targeted interventions.

Eq. (4.1) was formulated during data analysis to calculate the percentage of pollutants exceeding standards on the Dar es Salaam port ecosystem.

$$\% \text{ exceedance} = (\text{Number of pollutants exceeding standard} \div \text{Total number of pollutants assessed}) \times 100 \quad \ldots\ldots 4.1$$

Table 4. 2: Key pollutants contribution

Pollutant	Average Concentration (Units)	Guideline/Standard (Units)	Exceedance
Lead (in sediment)	50 mg/kg	40 mg/kg (TBS)	Yes
Mercury (in fish)	0.6 mg/kg	0.5 mg/kg (WHO)	Yes
Total Nitrogen	1.5 mg/L	1.0 mg/L (recommended)	Yes
Fecal Coliform	500 CFU/100Ml	100 CFU/100mL (recommended)	Yes
Micro plastics	10 particles/L	No established standard	-

Source: Authors' own work

These findings paint a stark picture of the pollution constraints facing the Dar es Salaam port ecosystem. The elevated concentrations of heavy metals, nutrients, pathogens, and microplastics pose a significant threat to marine life, well-being, and the sustainability of the port. Instant measures are required to address the problem.

4.2 Spatial distribution and sources

The assessment of marine pollution in the Dar es Salaam port ecosystem unveiled a distinct spatial distribution of pollutants, with specific areas emerging as contamination hotspots. This spatial analysis, combined with insights into pollution sources, provides a crucial understanding of the factors driving environmental degradation within the port. The research findings revealed a clear pattern of elevated pollutant levels close to specific sources. Industrial outfalls, shipyards, and areas with high shipping activity consistently exhibited higher concentrations of heavy metals, nutrients, and pathogens, as (Grebe, G. S. (2021) suggested that pollution levels tend to decrease with distance from the source. The spatial distribution of microplastics was more diffuse, reflecting their widespread presence in the marine environment. However, higher concentrations were observed near densely populated areas and tourist beaches, suggesting a link to improper waste disposal and littering. These findings (Alföldy et al., 2014) corroborate previous studies in other African ports, such as Lagos and Durban, which have also reported localized pollution hotspots near industrial zones and areas with high human activity (Naidoo et al., 2019). The spatial distribution of pollutants in Dar es Salaam port underscores the need for targeted interventions that address specific pollution sources and prioritize the remediation of heavily impacted areas. This research study fills a critical knowledge gap by conducting an in-depth assessment of marine pollution risks in the Dar es Salaam port ecosystem. Its unique case-study approach was providing a focused analysis, yielding insights transferable to other ports in Tanzania and similar coastal regions. This research significantly improves the scientific basis for marine pollution management within this critical commercial and ecological zone by identifying and quantifying key pollutants, mapping their distribution, and understanding their ecological impacts

4.2.1 Pollution hotspots

Mapping revealed distinct spatial patterns, with elevated pollutant levels near industrial zones, shipyards, and urban drainage outlets. This highlights the significant contribution of land-based sources to port pollution, consistent with findings from other African ports (Naidoo et al., 2019). Mapping the spatial distribution of pollutants within the Dar es Salaam port ecosystem indicated a clear pattern of localized contamination, with distinct hotspots emerging as areas of particular concern. These hotspots, characterized by elevated levels of specific pollutants, provide valuable insights into the sources and impacts of pollution within the port environment.

One prominent hotspot identified was the Kurasini Creek area near industrial facilities and shipyards. This location exhibited significantly higher concentrations of heavy metals, such as lead and cadmium, and elevated nutrient levels. The proximity to industrial activities strongly suggests these as the primary sources of contamination. The findings of this study align with previous studies highlighting the role of industrial effluents in heavy metal pollution in Tanzanian coastal waters (Machiwa, 2022).

Another critical hotspot was the Msimbazi River mouth, which receives untreated sewage and urban runoff from densely populated areas. This location exhibited high levels of nutrients and pathogens, particularly fecal coliform bacteria. This observation echoes concerns (Wagner, 2017) raised regarding untreated sewage's impact on coastal water quality in Tanzania.

Finally, while generally less polluted than the inner harbor, the outer harbor area still exhibited elevated levels of heavy metals and oil residues, likely stemming from ship discharges and accidental spills. This finding underscores the importance of enforcing stricter regulations on ship waste management and ballast water discharge to protect the marine environment. Table 4.3 portrays the critical pollution hotspots identified in the Dar es Salaam port ecosystem, their predominant pollutants, and potential sources.

Table 4. 3: Hotspot locations at Dar es Salaam port ecosystem

Hotspot Location	Predominant Pollutants	Potential Sources
Kurasini Creek	Heavy metals, nutrients	Industrial effluents, shipyard activities
Msimbazi River Mouth	Nutrients, pathogens	Untreated sewage, urban runoff
Ferry Terminal Area	Pathogens, micro plastics	Human activity, improper waste disposal
Outer Harbor	Heavy metals, oil residues	Ship discharges, accidental spills

Source: Authors' own work

These findings expose a complex interplay of pollution sources and their spatial distribution within the port ecosystem. Identifying these hotspots is crucial for prioritizing interventions and developing targeted mitigation strategies. By focusing efforts on these critical areas, policymakers and stakeholders can maximize the impact of pollution control measures and work towards a sustainable marine environment at the port.

4.2.2 Source apportionment

Understanding the specific sources contributing to marine pollution is paramount for developing effective mitigation strategies. This study's focus on source apportionment aimed to disentangle the complex web of pollution origins within the Dar es Salaam port ecosystem, shedding light on the key contributors and their relative impacts.

The results show diverse pollution sources, with point and diffuse sources playing significant roles. Industrial effluents emerged as the primary contributor to heavy metal contamination, particularly in areas adjacent to factories and shipyards.

Untreated sewage and urban runoff were identified as significant nutrient and pathogen pollution sources. Discharging wastewater from densely populated areas into the port's waterways resulted in elevated levels of nitrogen, phosphorus, and faucal coliform bacteria. This aligns with concerns Wagner (2017) raised regarding the impact of inadequate sanitation infrastructure on coastal water quality in Tanzania.

Shipping activities also contributed to the pollution, with ship discharges and accidental spills identified as sources of heavy metals and oil residues in the outer harbor areas. This

emphasizes the need for stricter regulations and improved waste management practices within the maritime sector.

Table 4. 4: Key Summary pollution sources

Pollution Source	Heavy Metals Contribution	Nutrients Contribution	Pathogens Contribution	Micro plastics Contribution
Industrial Effluents	High	Moderate	Low	Low
Untreated Sewage	Low	High	High	Moderate
Urban Runoff	Moderate	High	Moderate	High
Ship Discharges	Moderate	Low	Low	Low
Accidental Spills	High	Low	Low	Low

Source: Authors' own work

Table 4.4 summarizes the critical pollution sources identified in the Dar es Salaam port ecosystem and their estimated contribution. These findings reveal a complex interplay of pollution sources, highlighting the need for a multi-pronged approach to mitigation. Addressing industrial pollution will require stricter regulations, improved wastewater treatment technologies, and potentially economic incentives for cleaner production processes. Tackling sewage and urban runoff necessitates investments in sanitation infrastructure and public awareness campaigns promoting responsible waste disposal practices. Moreover, the maritime sector must strengthen its commitment to environmental protection through improved ship waste management, stricter enforcement of MARPOL regulations, and adoption of cleaner technologies. By understanding the relative contributions of different pollution sources, policymakers and stakeholders can develop targeted interventions that address the root causes of the problem, leading to a cleaner and healthier Dar es Salaam port ecosystem.

These forms of pollution significantly affect the Dar es Salaam port ecosystem. Elevated nutrient levels from sewage can destabilize ecological balances and lead to harmful algal blooms. Heavy metals and POPs in sediments and food webs can severely impact the health of marine organisms and ultimately affect human populations who rely on seafood (Mbugani et al., 2022). Additionally, pollution can degrade the aesthetic value of coastal areas, impacting tourism and related economic activities crucial to Tanzania's economy. Despite the growing recognition of these environmental effects, comprehensive assessments of marine pollution in Tanzanian port ecosystems still need to be studied. Current research suggests a complex situation of mixed pollution sources and varying contaminant levels (Mbugani et al., 2022 and 2015; Wagner, 2017; Chen M. et al., 2022).). Further investigation is crucial to understand the specific nature, sources, and extent of marine pollution within the Dar es Salaam port, allowing for developing and implementing targeted mitigation strategies.

4.3 Effects of plastic pollution

4.3.1 Bioaccumulation

One of the most concerning findings of this research lies in the evidence of bioaccumulation - the insidious buildup of pollutants within the tissues of marine organisms. This phenomenon acts as a silent threat, amplifying the impact of even seemingly low levels of contamination within the Dar es Salaam port ecosystem.

Heavy metals, particularly mercury, exhibited a disturbing tendency to accumulate in the tissues of fish and shellfish sampled from the port area. Mercury concentrations in certain fish species exceeded the World Health Organization's (WHO) recommended safe limit for human consumption, highlighting a potential public health risk associated with seafood sourced from the port (Wijeratne et al., 2018; Nugawela, N. P. P. S et al.,. 2023).

The simple formula was developed to calculate the arithmetic mean of all the Bioaccumulation Factors (BAFs) listed in table 4.6 below. The average BAF provides a concise and quantitative measure of the overall bioaccumulation risk within the port ecosystem. BAF highlights the potential for pollutants to magnify as they move up the food chain, posing threats to higher-level predators and potentially humans who consume seafood. This metric can be a valuable tool for communicating the severity of pollution impacts to policymakers and stakeholders, advocating for stricter pollution control measures. The formula provides a single, representative value that summarizes the overall tendency of pollutants to accumulate in the organisms within the Dar es Salaam port ecosystem. The average BAF is just one indicator of bioaccumulation.

Table 4. 5: Bioaccumulation & bioindicator species at Dar es Salaam port ecosystem

Bioindicator Species	**Pollutants**	**Organism Concentration (Units)**	**Surrounding Concentration Environment (Units)**	**Bioaccumulation Factor (BAF)**
Tilapia (fish)	Mercury	0.7 mg/kg	0.05 mg/L (water)	14
Oysters (bivalve)	Cadmium	2.5 mg/kg	0.1 mg/kg (sediment)	25
Seaweed (algae)	Lead	10 mg/kg	1 mg/kg (sediment)	10

Source: Authors' own work

The BAFs in the table demonstrate the alarming degree to which certain pollutants concentrate within organisms compared to their surrounding environment. These high BAFs highlight the potential for pollutants to magnify as they move up the food chain, posing risks to top predators and, ultimately, humans who consume seafood from the port.

The ecological implications of bioaccumulation are far-reaching. It can impair marine organisms' health and reproductive success, disrupt ecosystem dynamics, and compromise the overall resilience of the port environment. This silent threat and the potential public health risks emphasize the urgent need for effective pollution control and mitigation measures in the Dar es Salaam port ecosystem. The research outcomes are supported by previous research highlighting the bioaccumulation of pollutants in marine organisms globally (Newman et al., 2014). By quantifying bioaccumulation in the specific context of the Dar es Salaam port, this study contributes to a growing body of evidence underscoring this phenomenon's pervasive and insidious nature. It reinforces the importance of addressing pollution at its source and

implementing proactive measures to protect the health of marine life and the communities that depend on it.

4.3.2 Sub-lethal effects

While acute toxicity incidents may not be widespread, this study's focus on sub-lethal effects has unearthed a more insidious consequence of marine pollution in the Dar es Salaam port ecosystem. These subtle but significant impacts, often overlooked in traditional assessments, reveal chronic stress on the marine life inhabiting this vital hub.

Through field observations and interviews with local fishermen, a pattern of altered behavior and compromised health in certain species became evident. Fishermen reported a decline in the size and abundance of commercially important fish, with some species exhibiting sluggish behavior and reduced reproductive success. These observations were supported by laboratory analyses, which detected physiological changes and impaired growth rates in several bioindicator species exposed to port pollutants. One fisherman, a seasoned veteran of the Dar es Salaam waters, lamented.

.."The fish just aren't the same anymore. They're smaller and less active, and we're catching fewer of them each year."

Previous studies have similarly highlighted the subtle but pervasive nature of sub-lethal effects caused by marine pollution. Research on other port ecosystems has documented reduced growth rates, impaired immune function, and altered reproductive behavior in marine organisms exposed to contaminants (Bjerkli, 2021). The findings from Dar es Salaam port add to this growing body of evidence, emphasizing the need to consider sub-lethal effects in pollution assessments and management strategies.

Table 4. 6: Sub-lethal effects

Bioindicator Species	Observed Sub-lethal Effects	Potential Pollutant Link
Tilapia (fish)	Reduced growth rate, lethargy	Heavy metals, nutrients
Oysters (bivalve)	Shell deformities, reduced filtering rate	Heavy metals, micro plastics
Crabs	Altered behavior, decreased reproductive output	Persistent organic pollutants (POPs)

Source: Authors' own work

While often less visible than mass mortality events, these sub-lethal effects represent a significant and ongoing burden on the port's marine life. They highlight the chronic stress imposed by pollution and its potential to undermine the long-term health and productivity of the ecosystem. By shining a light on these hidden impacts, this research underscores the importance of going beyond traditional toxicity assessments and considering the subtle but significant ways pollution affects marine organisms. Addressing sub-lethal effects requires a proactive approach to pollution prevention and mitigation, ensuring that the Dar es Salaam port ecosystem remains healthy and resilient for future generations.

4.4 Strategies

4.4.1 Regulatory

The research findings regarding Dar es Salaam ports regulatory and management context paint a concerning picture with significant implications for pollution control efforts. They review existing policies and regulations to expose notable gaps and inconsistencies in addressing port-related pollution. While Tanzania has enacted environmental legislation, its implementation and enforcement, specifically within the port context, appear fragmented and inadequate. This observation aligns with broader challenges developing countries face, where institutional capacity and resources for environmental management are often limited.

During data collection, it became evident that monitoring programs at the port needed to be improved, with limited data collection and analysis on crucial pollution parameters. This lack of comprehensive monitoring hampers the ability to track pollution trends over time, identify emerging issues, and evaluate the effectiveness of implemented interventions. It creates a situation where potential environmental degradation may go unnoticed or underestimated, further exacerbating the pollution problem.

Policy gaps and weak monitoring create a challenging environment for effective enforcement. With clear regulations and robust data on pollution levels, it becomes easier to hold polluters accountable and ensure compliance with environmental standards. This can lead to a culture of negligent enforcement, where industries and shipping companies may need to prioritize pollution control measures.

The study findings highlight the urgent need for a strengthened regulatory and management framework for Dar es Salaam port marine pollution control. More explicit policies, enhanced institutional capacity, and improved monitoring programs are essential to address the current gaps and ensure the long-term sustainability of the port ecosystem. By learning from best practices in other ports and investing in environmental management, Tanzania can balance economic development and environmental protection, fostering a healthier and more resilient marine environment for future generations.

4.4.2 Policy

Reviewing existing policies and regulations revealed gaps and inconsistencies in addressing port-related pollution, hindering effective enforcement. This highlights a common challenge in developing countries, where institutional capacity and resources for environmental management may be limited (Canton, H. 2021).

The research findings uncovered a disconnect between existing environmental legislation and its practical implementation within the port context. While Tanzania has enacted laws and regulations to protect the marine environment, interviews with key stakeholders indicated a perceived lack of clarity and specificity regarding port-related pollution. A representative from the port authority lamented,

…."We have general environmental laws, but they don't always translate well to the unique challenges of a busy port. There's a need for more targeted regulations on ship discharges, ballast water management, and industrial effluents."…

These quotes highlight the challenges in translating broad environmental legislation into effective pollution control measures within the port ecosystem. The need for specific regulations tailored to port activities, institutional fragmentation, and weak enforcement create

a breeding ground for pollution. Industries and shipping companies may exploit these gaps, prioritizing economic gains over environmental protection.

This situation underscores the urgent need for policy reform addressing port environments' unique challenges. Clear guidelines, streamlined enforcement mechanisms, and enhanced inter-agency collaboration are essential for bridging the gap between legislation and implementation. The research findings provide a strong foundation for advocating for such reforms, empowering stakeholders to push for a more sustainable and accountable approach to managing marine pollution in the Dar es Salaam port.

4.4.3 Monitoring

Monitoring programs were found to be inadequate, with limited data collection and analysis. This hinders the ability to track pollution trends and evaluate the effectiveness of interventions, highlighting the need for strengthened environmental monitoring efforts. The inadequacy of monitoring and enforcement mechanisms emerged as a recurring theme during interviews with Dar es Salaam port ecosystem stakeholders. A port official candidly admitted,

… "We have limited resources for monitoring, and data collection is often sporadic." …

This sentiment was echoed by a representative from the environmental agency, who stated, "Enforcement is challenging due to a lack of personnel and the complexities of tracking pollution sources within the port." Moreover, a local fisherman lamented,

"We see the pollution in the water, but nothing seems to be done about it."

These statements highlight the disconnect between existing policies and their on-the-ground implementation. While regulations are in place, the lack of consistent monitoring and effective enforcement renders them largely toothless. This creates a sense of frustration and powerlessness among those directly impacted by the pollution, eroding trust in regulatory institutions.

The absence of robust monitoring data also obscures the true extent of the pollution problem, hindering effective decision-making and resource allocation. With clear evidence of pollution trends and sources, it becomes easier to prioritize interventions and hold polluters accountable. This lack of transparency perpetuates a cycle of environmental degradation, where the actual cost of pollution remains hidden and unaddressed.

Therefore, strengthening monitoring and enforcement is crucial for tackling marine pollution in the Dar es Salaam port. Investing in regular data collection, analysis, and transparent reporting can provide the evidence needed for targeted interventions and informed policy decisions. Building capacity within regulatory agencies and empowering them to take action against polluters is equally essential. By bridging the gap between policy and practice, Tanzania can move towards a more sustainable and resilient port ecosystem.

V. CONCLUSION

As the economic hub of Tanzania and other landlocked and hinterland counties, the Dar es Salaam port plays a pivotal role in the nation's development. However, its bustling activities, coupled with the rapid urbanization and industrialization of the surrounding areas, have taken a toll on the marine environment. The findings of this research offer a roadmap for action, highlighting the urgent need to address marine pollution threats in the Dar es Salaam port ecosystem. This study has made significant contributions to the understanding of marine

pollution threats in port ecosystems, particularly within the context of developing nations; the study has filled a critical knowledge gap, providing valuable insights into the types, concentrations, sources, spatial distribution, and ecological impacts of pollutants in this vital maritime hub. The findings highlight the multifaceted nature of pollution challenges, with a complex interplay of land-based and maritime sources contributing to the degradation of the port ecosystem. The identification of pollution hotspots, coupled with the quantification of contaminant levels exceeding environmental guidelines, underscores the urgent need for targeted interventions to safeguard the marine environment and protect public health. The paper has shed light on the often-overlooked sub-lethal effects of pollution, revealing chronic stress on marine organisms even in the absence of acute toxicity. The documentation of bioaccumulation and altered behavior in key species emphasize the insidious nature of pollution and its potential long-term consequences for the ecosystem. The study's examination of the regulatory and management context has exposed critical gaps in policies, monitoring, and enforcement, highlighting the need for strengthened institutional capacity and a more proactive approach to pollution control. The findings can inform evidence-based policy decisions, prioritize interventions based on pollution hotspots and sources, and promote a more sustainable approach to port operations.

Moreover, its emphasis on the interconnectedness of social and ecological systems within the port environment offers a holistic perspective that can guide future research and management efforts. The insights gained from this study have broader implications beyond the Tanzanian context. This study focused primarily on the environmental and ecological dimensions of pollution. Future research could explore the socioeconomic impacts of port pollution on local communities, including its effects on livelihoods, health, and well-being. Understanding these impacts can inform policies that promote equitable and sustainable development in the port areas.

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