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Marine Pollution Crisis

Understanding Impacts and Innovating Solutions

Edited by Tirivashe Phillip Masere



Marine Pollution Crisis - Understanding Impacts and Innovating Solutions

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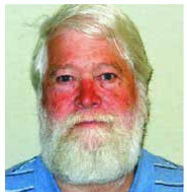
Volume 34

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editor



Tirivashe Phillip Masere (Ph.D.) is a dedicated environmental scientist and academic specializing in agriculture and natural resources management. He currently serves as the Acting Deputy Dean of the Faculty of Agriculture, Environment, and Natural Resources Management at Midlands State University in Zimbabwe, where he teaches Environmental Water Quality, Soil and Water Conservation, Environmental Education and Extension, among other subjects. Dr. Masere has published widely on water quality, climate change and land degradation. A Fellow of the Environmental Professionals Council of Zimbabwe and Professional Extension Scientist of the South African Society for Agricultural Extension, he has led and collaborated on regional research, consultancies, and innovations on critical environmental and agricultural initiatives.

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Preface

The marine environment is under increasing pressure from human activities that compromise the ecological integrity and sustainability of ocean systems. Among the most pressing threats is marine pollution, originating from plastics, heavy metals, industrial runoff, and untreated wastewater, which has intensified ecological degradation and public health concerns globally. This edited volume, *Marine Pollution Crisis – Understanding Impacts and Innovating Solutions*, presents interdisciplinary and geographically diverse research addressing both the scope and solutions to marine contamination. The collection aims to inform scholars, practitioners, and policymakers by presenting evidence-based insights and innovative pathways rooted in current marine science.

The volume opens with Chapter 1, "Introductory Chapter: Navigating the Marine Pollution Crisis – From Microplastics to Metal Contamination and Community Resilience", which lays a conceptual foundation by outlining the types, causes, and impacts of marine pollution while emphasizing systemic responses that integrate technological innovation, governance reform, and participatory approaches. The chapter also highlights the critical role of interdisciplinary science in addressing the multiscale complexities of ocean degradation.

Chapter 2, "Microplastics and Sea Urchin Life: A Review of Distribution and Implications in Indonesia", shifts focus to the biological impacts of microplastic contamination. This systematic review (guided by PRISMA methodology) evaluates how ingestion of microplastics affects the physiology and reproduction of sea urchins, with implications for marine food webs and sediment ecosystems. The study identifies the types of polymers, particle shapes, and exposure routes, situating Indonesia's experience within the global research on microplastic pollution in echinoderms.

In Chapter 3, "Assessment of Metal Contamination in the Gabes Gulf (Tunisia): Contribution of Comparative and Chemometric Methods", the volume moves into the North African context, where advanced geo-statistical tools are applied to assess sediment contamination by cadmium (Cd), copper (Cu), and zinc (Zn). Using enrichment factors and geoaccumulation indices, the study maps spatial disparities in pollution, revealing the legacy of industrial phosphate discharge in the Gulf of Gabes. This chapter offers methodological insights into localized monitoring strategies and highlights the need for more robust geochemical background baselines.

Chapter 4, "Marine Pollution and Environmental Sustainability: Challenges and Solutions for Karachi, Pakistan", provides an in-depth case study of the Sindh coastline, where weak regulatory enforcement has led to dangerous levels of contamination in Karachi Harbour. The authors assess physicochemical parameters, including temperature, turbidity, salinity, COD, BOD, and TDS, as well as toxic heavy and trace metals (Pb, Cd, Ni, and Hg), across various tidal conditions and distances from the coast.

The study finds that pollutant levels consistently exceed safe thresholds, highlighting urgent regulatory gaps. Importantly, the chapter proposes strategies for more stringent monitoring, public education, and policy reform aligned with the UN Decade of Ocean Science for Sustainable Development (2021–2030). The findings make a significant contribution to understanding the dynamics of pollution in urbanized coastal zones of South Asia.

Chapter 5, "Socio-Economic Impacts of Climate Change and Marine Pollution on Fish-Dependent Communities of Southern Africa", explores the intersection of ecological degradation and community well-being in one of the world's most vulnerable regions. Drawing on a systematic review of 30 peer-reviewed studies, the authors reveal how marine pollution and climate-driven changes in fish populations are reducing catches, depleting incomes, and eroding food security. The socio-economic consequences are particularly severe for women and marginalized groups who are often excluded from adaptation decision-making. The chapter highlights critical pathways for strengthening resilience, including climate-adaptive fisheries management, livelihood diversification, and improved access to climate information. The study's findings underscore the urgency of safeguarding coastal livelihoods in the face of converging environmental pressures.

Taken together, these five chapters represent a comprehensive synthesis of marine pollution challenges, impacts, and proposed innovations across different regions and analytical frameworks. Each chapter contributes to a collective vision of restoring ocean health through rigorous science, inclusive policy, and strategic investment in research and monitoring systems. The volume emphasizes that addressing marine pollution necessitates a collaborative effort among nations and sectors.

We would like to express our sincere gratitude to the contributing authors for their timely and valuable contributions. We also acknowledge the peer reviewers and technical staff whose efforts ensured the quality and consistency of this volume. Special appreciation goes to the editorial assistants for their diligence in managing references and coordinating correspondence across institutions.

We hope that this volume will serve as a meaningful contribution to marine science, inspire further research, and support global efforts to protect and sustainably manage marine ecosystems.

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Chapter 1

Introductory Chapter: Navigating the Marine Pollution Crisis – From Microplastics to Metal Contamination and Community Resilience

Tirivashe Phillip Masere

1. The scope of marine pollution

The oceans, covering about 70% of our planet, are essential for life, regulating climate, supporting biodiversity, and providing livelihoods for millions. They are often regarded as the "lungs of the Earth". Yet, the health of the world's oceans is increasingly under threat from a wide range of pollutants, placing ecosystems, economies, and communities at risk. Marine pollution is a multifaceted global issue that encompasses the introduction of harmful substances or energy into the marine environment, resulting in deleterious effects on marine life, human health, and ecosystem services [1]. Marine pollution encompasses a range of contaminants, from microplastics to heavy metals like lead, mercury, and cadmium.

Recent studies indicate that approximately 11 million tons of plastic enter the oceans annually [2], with microplastics becoming ubiquitous in marine food webs. Microplastics, defined as plastic particles smaller than 5 mm, have infiltrated marine environments, impacting marine life and human health. These tiny particles can be found in the deepest sea trenches and even in Arctic ice [2]. Microplastic concentrations across the five principal oceanic basins were reported to range between 0.002 and 62.50 particles per cubic meter, yielding a global mean concentration of approximately 2.76 particles/m^3 [3]. Among these, the Atlantic Ocean exhibited the highest average microplastic load at 4.98 particles/m^3; and the Southern Ocean recorded the lowest mean value, at 0.04 particles/m^3 [3].

The ingestion of microplastics by marine organisms is a widespread phenomenon, affecting a significant number of species, including those of commercial importance. A global synthesis by Barboza et al. [4] reported that microplastics have been recorded in 830 wild fish species, including 606 species of interest to commercial and subsistence fisheries. This further underscores the extensive reach of microplastic contamination in marine ecosystems. The ingestion of these particles can lead to toxicological effects, bioaccumulation and potential biomagnification up the food

Organism	Microplastic ingestion rate	Reference
Plankton	12 particles per individual	[5]
Fish (e.g., sardines)	3–5 pieces of microplastics per stomach	[6]
Sea turtles	Up to 74% of individuals sampled	[7]

Table 1.
Microplastic ingestion rate across different marine species.

chain. **Table 1** illustrates the prevalence of microplastics in various marine species, highlighting the alarming rates of ingestion across different trophic levels.

While microplastics garner significant attention, metal contamination poses a severe threat to marine ecosystems. Heavy metals such as mercury, lead, and cadmium enter the marine environment through industrial discharges, mining activities, and agricultural runoff [8]. These contaminants can be highly toxic, even at low concentrations, affecting the health and survival of marine organisms. A study by Martínez–Salcido et al. [9] revealed that coastal regions near industrial hubs exhibit alarming levels of metal contamination, with mercury levels in fish exceeding safety thresholds established by the World Health Organization (WHO). Similarly, WHO found mercury pollution to be particularly concerning, as it can biomagnify in fish, posing serious health risks to humans who consume them [10].

2. The human dimension of marine pollution

The ramifications of marine pollution extend beyond ecological concerns; they directly impact human health and community resilience. Coastal communities, often reliant on fishing and tourism, are particularly vulnerable to the consequences of polluted waters. As already discussed in the previous section, fish caught in polluted waters often contain mercury levels exceeding safe consumption thresholds, thereby endangering local fishermen, their families and their customers [8–11].

Research indicates a strong correlation between marine pollution and public health issues. Contaminated seafood can lead to significant health risks, including neurological disorders and reproductive issues, linked to heavy metal exposure. This is particularly concerning for communities that depend on fish as a primary source of protein.

Moreover, the economic implications of marine pollution are profound. A report by the World Bank estimated that marine pollution costs the global economy approximately $1.3 billion annually due to lost fisheries, decreased tourism, and health-related expenditures [12]. The impact on livelihoods can be devastating, leading to social dislocation and increased poverty in affected regions.

3. Community resilience

Amidst the challenges posed by marine pollution, communities worldwide are exhibiting remarkable resilience. Community resilience refers to the ability of communities to withstand, adapt to, and recover from environmental shocks. Initiatives focused on education, sustainable practices, and local governance can enhance resilience in the face of marine pollution. Grassroots organizations and local leaders

Strategy	Description	Example
Education and Awareness	Raise awareness about pollution impacts on health and livelihoods	Community workshops
Sustainable Practices	Promote sustainable fishing and waste management	Local fishery cooperatives
Policy Advocacy	Advocate for stricter regulations on industrial pollutants	Environmental NGOs

Table 2.
Key strategies for enhancing community resilience against marine pollution.

are pioneering solutions that not only address pollution but also empower their communities. For instance, in the coastal town of Gokarna, India, local fishermen have initiated a community-led clean-up initiative that not only removes plastics from the beach but also raises awareness about sustainable fishing practices and promotes stewardship and resilience. **Table 2** summarizes key strategies for enhancing community resilience against marine pollution centered on capacity building, advocating for policy change and partnering with environmental NGOs to secure funding and expertise for clean-up and conservation projects.

Moreover, the integration of traditional ecological knowledge with modern science is proving essential. In Alaska, Indigenous communities are documenting changes in marine ecosystems, helping scientists understand the impacts of pollution and climate change on local resources [13].

4. Conclusion: Navigating forward

As we sail through the complexities of marine pollution, a multifaceted approach is essential. Addressing the dual crises of microplastics and metal contamination requires collaboration among scientists, policymakers, and communities. By leveraging research to inform innovative solutions, we can enhance community resilience and work toward healthier oceans for future generations as we aim to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water).

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Chapter 2

Microplastics and Sea Urchin Life: A Review of Distribution and Implications in Indonesia

Vanela Chatrin Lekatompessy, Aprilia Paskarani Molle, Agung Pramana Warih Marhendra and Dion Dollan Awayal

Abstract

This article delves into the impact of microplastics on Sea urchins in Indonesia, focusing on their distribution and ecological consequences in marine environments. Microplastics, pervasive pollutants, are increasingly found in Indonesian waters, posing significant threats to the health and behavior of sea urchins. Studies on MP contamination distribution in Sea Urchins in Indonesia were conducted using the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analysis). Data were collected from various sources such as Google Scholar, PUBMED, BASE, Garuda, DOAJ, ScienceDirect, and Researchgate. Keywords used in the search included accumulation, abundance, contamination, microplastics, impact, physical, chemical, sea urchin, and Indonesia. Studies show that ingesting microplastics can disrupt vital physiological functions, hinder reproductive abilities, and change social dynamics among sea urchins. These disruptions can have far-reaching effects on marine ecosystems, impacting biodiversity and ecological equilibrium. The article underscores the pressing need for effective mitigation measures and advocates for more extensive research to fully grasp the long-term effects of microplastics on marine life in Indonesia.

Keywords: microplastics, sea urchin distribution, ecological impact, recommendation and mitigation, Indonesia

1. Introduction

Microplastics, which are pollutants in the form of particles smaller than 5 mm, have become a significant environmental issue in the twenty-first century. They come in various forms such as fibers, fragments, microbeads, pellets, and foam, posing a threat to aquatic ecosystems and potentially impacting the food chain and human health [1, 2]. Monitoring the presence and impacts of microplastics is a global priority due to their ability to carry heavy metals and other organic pollutants [3, 4].

Microplastics in water float based on the density of the polymer. This floating ability affects their position in the water and their interaction with organisms [5]. Microplastics with a higher polymer density than seawater will sink, while those with a

lower density will float. Smaller microplastic particles are more likely to be consumed by marine organisms, leading to potential negative effects on their health [6]. Sea urchins are crucial benthic organisms in marine ecosystems. They act as first-order consumers and help maintain ecosystem balance, particularly in the Indo-Pacific region.

Microplastics can enter the bodies of deposit feeder biota, like sea urchins, through two main pathways: the digestive system and the water vascular system [7]. Microplastics can accumulate in body tissues of sea urchins, impacting their physiological processes, growth, and reproduction [8, 9]. This exposure can also disrupt species interactions within ecosystems, potentially altering the structure of biotic communities [5].

The impact of microplastics on marine ecosystems is significant, especially for sensitive marine species like sea urchins. Sea urchins can be used as bioindicators of pollution due to their vulnerability to environmental changes [10]. Sea urchins are at risk of exposure to microplastics through accumulation in sediments, suspension in the water column, and uptake in tissues. This can disrupt ecosystem function [11]. It is crucial to study the distribution of microplastics in Indonesian waters and their effects on sea urchins.

This article explores the presence of microplastics in Indonesian waters and their effects on sea urchins, which serve as indicators of marine ecosystem health. Drawing on recent studies, it examines how microplastics are distributed, accumulate, and interact with sea urchin populations in different Indonesian waters. The article also delves into case studies that highlight the environmental impacts of microplastics on sea urchins and proposes mitigation strategies, waste management solutions, and policy recommendations to tackle the microplastics problem in Indonesia effectively.

2. Methodology

A study on the distribution of microplastic contamination in Sea Urchin in Indonesia was conducted using the PRISMA method. Data was collected from various sources such as Google Scholar, PUBMED, BASE, Garuda, DOAJ, ScienceDirect, and Research gate using keywords like Accumulation, Abundance, Contamination, Microplastics, Sea Urchin, and Indonesia. Out of 369 articles related to Sea Urchin in Indonesia, nine articles (five conference articles and four research articles) were selected for analysis to map the distribution of microplastic contamination in sea urchins across major islands in Indonesia. The study focused on types of Sea urchins contaminated with microplastics, organs dissected, contamination levels, types of microplastics, polymer types, and contaminant sources.

Additionally, 422 articles were reviewed to understand the effects of microplastic physical and chemical properties on sea urchins. Keywords such as impact, microplastics, physical, chemical, and sea urchin were used to identify relevant articles. The selected articles were analyzed descriptively using Microsoft Excel to present the findings effectively.

3. Physical characteristics and fate of microplastics in the environment

3.1 Types of microplastics

The shape of microplastics plays a role in how organisms absorb them. Microplastics come in different forms such as fibers, pellets, filaments, fragments,

films, foams, micrograins, and granules. Low-density fibers and films tend to float easily due to their high buoyancy and slow settling velocity. The shape and surface area of microplastics are important factors in their movement, with fibers, films, and foams having a higher tendency to aggregate and sink compared to larger plastic particles due to their high surface area to volume ratio [12]. Research has shown that microplastics with uniform shapes, like polypropylene, can travel longer distances due to their low surface area to volume ratio. In contrast, microplastics with irregular shapes, such as fragments, have shorter transport distances. Spherical particles have fewer exposed surfaces, resulting in lower shear resistance and requiring less drag force to move. Fibers, on the other hand, need higher shear stress to initiate movement as they are more firmly embedded in sediment. The geometry of microplastics influences erosivity, shear stress, drag, and lift. During transportation in aquatic environments, microplastics undergo natural processes like aggregation, degradation, biofouling, and flocculation.

3.2 Size of microplastics

The toxicity of microplastics on organisms is strongly influenced by their size. Smaller particles have a greater toxic impact on organisms compared to larger ones. Microplastics that are less than 5 mm in size are most commonly reported to be toxic. Nano-sized particles are easily ingested by organisms, as they can bypass the mouth-size limitations of the species. These smaller particles can reach subcellular levels and potentially cause various harmful effects on organisms. Moreover, the ability of organisms to expel particles is affected by particle size, retention time, and toxicity. Smaller particles have longer retention times and can be more harmful even at low concentrations. Therefore, smaller microplastics and nanoplastics have the potential to cause a range of adverse effects on organisms at subcellular level.

3.3 Color of microplastics

Organisms tend to consume microplastics that resemble the color of their prey. Color is a significant factor in the ingestion of microplastics by marine organisms, with black, red, and blue being the most prevalent [5]. White or transparent microplastics can confuse natural predators, leading to unintended consumption by marine life. Green fluorescence is the most common color, making up 47% of the samples. Fluorescent plastics are chemically stable and remain intact in organisms for extended periods. Furthermore, fluorescence particles are easily detectable and measurable under a microscope [13].

3.4 Microplastics density

The distribution and bioavailability of microplastics are influenced by their density, which can impact how they are ingested by organisms at different trophic levels. Microplastics with higher density are more likely to be consumed by marine biota compared to floating particles due to their wider distribution in the water. Low-density microplastics like polyethylene (PE) and polypropylene (PP) are often ingested by small fish, bivalves, and planktivores. On the other hand, microplastics with a higher density tend to sink further into the water column. Microorganisms and biofouling processes contribute to the deposition of microplastics in the marine environment, with the extent of biofouling influenced by the size of the microplastics.

Microplastics can be found in the tissues or digestive tracts of organisms. However, accurately measuring microplastic density is challenging, and different sampling and analysis methods can yield varying results.

3.5 Microplastic particle settling velocity

The settling velocity of microplastics can help us understand how they move in the environment. By calculating this velocity, we can study how microplastics are transported, distributed, and concentrated. The settling velocity of spherical particles in fluid flow can be determined using the equation:

$$ws = \left(RgD\,\hat{}\,2\right) / \left(\mathrm{C_1\,v} + \sqrt{\left(0.75\mathrm{C_2}\,RgD\,\hat{}\,3\right)}\right) \quad (1)$$

where.
R is the damped relative density.
g is the gravitational constant.
D is the diameter of the particle.
C1 is a constant of 18 while C2 is a constant of 1.

The damped relative density is calculated as (ρs - ρf)/ρf, where ρf is the sediment density and ρs is the fluid density (in this case, seawater with a density of 1026.2 kg/m^3).

The settling speed of microplastics, like polyurethane, is slower than that of sand grains. For example, a 0.5 mm diameter polyurethane particle settles at a similar speed to a 0.15 mm diameter quartz grain (fine sand), and a 5 mm diameter polyurethane particle settles at a similar speed to a 0.75 mm diameter quartz grain (coarse sand). However, due to variations in shape and surface roughness between natural and plastic particles, the settling velocity for spherical shapes is typically higher than the actual settling velocity.

4. Distribution of microplastics in sea urchins in Indonesian waters

The distribution of sea urchins in Indonesia is significantly influenced by environmental conditions that are impacted by human activities (**Table 1**). Research on the effects of microplastics on sea urchins is particularly important in areas with high levels of contamination, such as small islands like Tidung and Gili Labak. In these locations, sea urchins may be vulnerable to the harmful effects of microplastics, which could jeopardize their health and the overall health of the marine ecosystem. Microplastic pollution is often more severe on small islands due to human activities like tourism and improper waste disposal, making these areas crucial for studying the impacts of pollution.

Research on the impact of microplastics on large islands is limited compared to coastal areas. This could be due to a lack of resources and a focus on other issues like natural resource management. There is a perception that microplastic pollution is lower on large islands, leading to less research in these areas. Collaboration between researchers, government, and local communities is essential to raise awareness and address pollution on large islands. Further research is needed to understand the full impact of microplastics on the environment and ecosystems of large islands (**Figure 1**).

Location	Types of Sea urchin	Dissected organs	Contaminant level of MPs	Types of MPs	Types of polymers	Contaminant source	References
Java							
Untung Jawa island	*D. setosum*	Digestive tract	2175.55 ± 584.26 particles.ind^{-1}	Fiber, film, fragment, granular	No Identified	Domestic waste, human activities	[14]
Tidung island	*D. setosum*	Digestive tract	1786.66 ± 451.17 particles.ind^{-1}			Waste from tourism, human activities	
Porok beach	*T. gratilla*	Digestive tract	165 particles	Fragment, film, monofilament, fiber	No Identified	Domestic waste, human activities	[15]
		Gonad	75 particles				
Nglolang beach	*T. gratilla*	Digestive tract	222 particles			Waste from tourism, human activities	
		Gonad	182 particles				
Sepanjang Timur beach	*T. gratilla*	Digestive tract	210 particles				
		Gonad	74 particles				
Sepanjang Barat beach	*T. gratilla*	Usus	383 particles				
		Gonad	48 particles				
Pari island	*E. mathaei*	Digestive tract	3.93 ± 2.25 particle/g dry weight	Fragment (75%) Fiber (59%)	Polyethylene, Polyester, Polypropylene	Accumulation of microplastic-exposed sediments during sea urchin foraging (biomagnification)	[16]
Harapan beach	*D. setosum*		0.27 ± 0.28 particle/g dry weight				
Gili Labak island	*Diadema* sp.	Digestive tract	15,5 particles.ind^{-1}	Fiber, film, fragment, microfiber	No identified	Fishing activities, plastic waste	[17]
Tidung Island	*Diadema* sp.	Mouth and digestive tract	Mouth: 0.552 ± 0.42 particle/gr (2021) Digestive: 0.6 ± 0.16 particle/gr (2021) Mouth: Not found (2022) Digestive: 0.16 ± 0.19 particle/gr (2022	Serat, Fragment, Foam	Polyethylene polypropylene, polyvinyl polyamide, polyurethane, rubber	Plastic waste from human activities	[18]

Location	Types of Sea urchin	Dissected organs	Contaminant level of MPs	Types of MPs	Types of polymers	Contaminant source	References
Sulawesi							
Barranglompo Island	*D. setosum*	Internal organs	23.70 ± 2.99 particles.ind^{-1}	Fiber	No Specified	Anthropogenic activities and plastic debris accumulation in seagrass ecosystems	[19]
Kodingareng Lompo, Bone Tambung, Langkai (Spermonde Archipelago)	*T. gratilla*	Internal organs and digestive tract	23.53%	Fiber	No Specified	Anthropogenic activities and plastic debris accumulation in seagrass ecosystems	[20]
Barrang Lompo	*T. gratilla*	Digestive tract	3.4 ± 0.29 particles.ind^{-1}	Fiber, Fragment	Semi-synthetic (Cotton)	Plastic waste from human activities	[21]
Badi			14.8 ± 0.98 particles.ind^{-1}				
Kondong Bali			9.5 ± 2.11 particles.ind^{-1}				
Maluku							
Laha Beach	*T. gratilla*	Digestive tract	28 particles	Fiber, fragment, film, pellet	No identified	Domestic waste, fishing activities	[22]
		Gonad	45 particles				
Tawiri Beach		Digestive tract	80 particles				
		Gonad	22 particles				
Hative Besar Beach		Digestive tract	40 particles				
		Gonad	40 particles				
Erie Beach		Digestive tract	85 particles				
		Gonad	98 particles				

Source: Compiled by the author.

Table 1.
Distribution and microplastic contamination of sea urchin in Indonesian coastal sites.

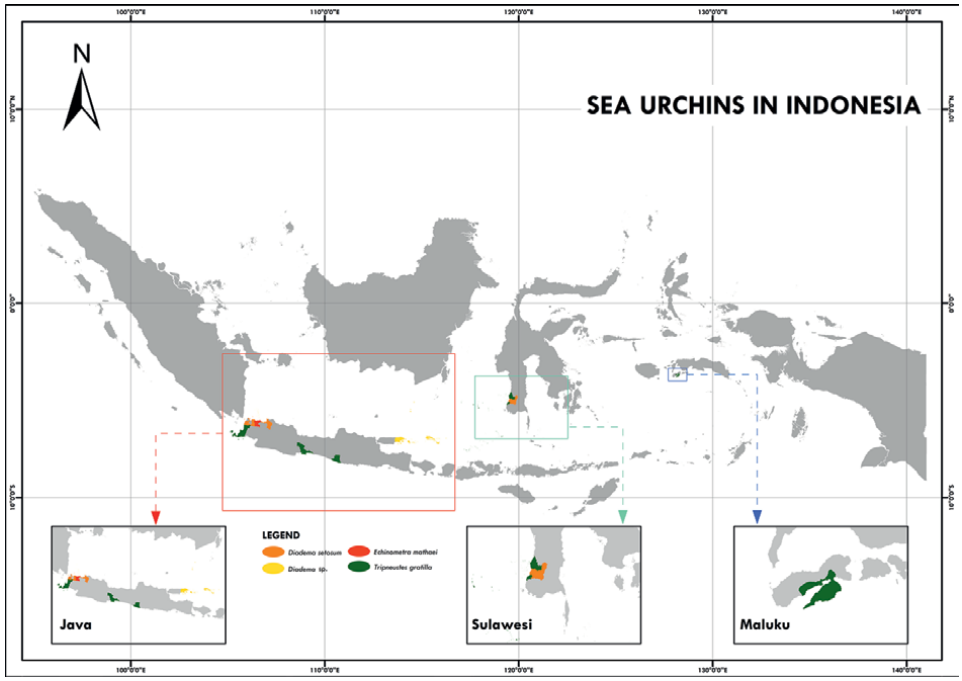


Figure 1.
*Distribution map of microplastic research in sea urchin samples in Indonesia. This figure shows the distribution of microplastic research on sea urchins in various regions of Indonesian waters based on data collected in 2025. The map identifies locations on several major islands in Indonesia where sea urchin populations are found, as well as indicating the levels of microplastic accumulation in their organs (*Source: Compiled by the author*).*

5. Case studies and research on the impact of microplastics on sea urchins

A study conducted by Lekatompessy et al. [22] revealed that sea urchins can accumulate microplastics in their bodies. The study observed that sea urchins exposed to microplastics had high levels of microplastics in their gonad tissue, which is a commonly consumed part. The accumulation of microplastics could potentially disrupt the physiological functions of sea urchins, such as reproduction and growth, and may also pose health risks to humans who consume them [23].

Microplastics can have various negative effects on sea urchins, including disrupting their foraging behavior [24], causing satiation delution, reducing energy reserves [5], and impacting reproductive success and survival [22]. Impaired foraging behavior leads to decreased feed consumption, which may be a response to digestive distress caused by the presence of microplastic particles in the intestines. Changes in lipid-linked mRNA proteins suggest impaired fatty acid metabolism and reduced energy intake, potentially affecting reproduction. The disruption of gonadal pathways, such as p53-mediated apoptosis, can lead to decreased gametogenesis and infertility. Antioxidant systems like catalase and glutathione peroxidase help mitigate the effects of Reactive Oxygen Species (ROS). Exposure to microplastics can also alter testicular morphology and decrease testicular basement membrane thickness. The fertilization success rate of sea urchins exposed to microplastics larger than 0–80 μm for 10 minutes was only 56–58%. The microplastic particles did not adhere to the membrane of gametes or zygotes, and the growth of larvae exposed to microplastics significantly decreased.

A study by [25] reported that 0.5 μm polystyrene microbeads significantly decreased mitochondrial membrane potential and suggested that microplastics may indirectly affect the outer mitochondrial membrane through increased Reactive Oxygen Species (ROS) presence in cellular compartments outside, but around the mitochondria. Exposure of mitochondria to excessive oxidative stress in the cytosol can trigger the opening of several transmembrane Na/K mitochondrial channels. The increased ion flux through membrane channels can subsequently lead to the collapse of the mitochondrial membrane potential and release of Reactive Oxygen Species through the "ROS-induced ROS-release" (RIRR) mechanism, which is responsible as a mediator between intracellular microplastic presence and inhibiting the observed mitochondrial membrane potential [26].

Furthermore, tissue damage due to inflammation also supports other research on biota exposed to microplastics at the cellular level. Polystyrene microparticles (5 μm) and nanoplastics (70 nm) accumulated in the gills, liver, and intestines of zebrafish after 7 days of exposure, causing typical inflammatory damage in the liver (vacuolation, leukocyte/neutrophil infiltration, necrosis, and lipidosis) [27].

6. Implications for marine ecosystems and coastal communities

Indonesia, with its rich marine biodiversity and status as the world's largest archipelago, faces significant challenges from the impact of microplastics on both ecosystems and public health. The potential economic benefits of sea urchin fishing are promising, but unsustainable fishing practices pose a threat to sea urchin populations and marine ecosystems. Overfishing can lead to a decline in sea urchin populations, which in turn can disrupt the balance of marine ecosystem. Research conducted in Eastern Indonesia revealed overfishing of sea urchins at 12 sites across four regions [28].

In Sulawesi, the city of Makassar is a hub for collecting sea cucumbers, with an average of 32 individuals captured per collection reported by respondents. Another location in Sulawesi, Pangkep, recorded collections of 81 individuals per trip, thanks to the presence of seagrass and coral reefs. Selayar Island also showed significant activity, with respondents reporting 81 individuals collected, locally known as "tie-tie." In Muna, the average collection reached 40 individuals, while in Wakatobi, known for its marine biodiversity, respondents reported 82 individuals per trip. In the Maluku region, Ternate is one of the islands with considerable sea cucumber collections, where respondents reported 55 individuals per trip. Central Maluku showed the highest number, with an average of 169 individuals collected, while in Buru, respondents reported collecting 42 individuals. In West Nusa Tenggara, Bima recorded collections of around 88 individuals per trip, mostly for household consumption. In Dompu, the number of sea cucumbers collected reached 73 individuals, and in Kupang, the capital of East Nusa Tenggara Province, respondents reported around 47 individuals per trip. In Papua, Manokwari recorded the collection of 36 sea cucumbers per trip, with a primary focus on consumption. The overexploitation of sea cucumbers in these areas indicates the local communities' dependence on marine resources for food and income, where local knowledge and traditions play a crucial role in these collection practices.

The impact of microplastics is not limited to marine ecosystems; communities relying on marine resources are also affected. Seafood contaminated with microplastics can pose health risks to humans. Research shows that microplastics can contain

harmful chemicals, such as polychlorinated biphenyls (PCBs) and heavy metals, which can transfer to human tissues through seafood consumption [29]. Long-term exposure to these substances can contribute to health issues, including hormonal disruptions and cancer [30].

The local economy, which relies on the fishing and tourism sectors, is also affected by the issue of microplastics. The decrease in the quality and quantity of marine resources due to microplastic pollution can reduce fish catches, harm fishermen, and impact the tourism industry, which depends on the beauty of nature. The costs of cleaning up and mitigating plastic pollution can drain government and community budgets, as well as disrupt social well-being.

7. Policy and mitigation recommendations

Public awareness campaigns and education programs can help inform the public about the dangers of microplastics and encourage responsible consumption and disposal practices. Collaboration between government, industry, and civil society is essential to effectively tackle this issue and protect the environment for future generations [4]. Educating the public about the use of plastic and its impact on the environment is also important to build collective awareness. Further research on the impact of microplastics in Indonesia's marine ecosystems is crucial to inform effective policies and mitigation strategies.

In an effort to reduce plastic usage, various countries have implemented policies that can serve as references [31]. Kenya was one of the first countries to enforce a total ban on plastic bags in 2017 [32, 33]. This policy prohibits the production, sale, and use of plastic bags, with penalties of up to 4 years in prison or fines of up to US$ 40,000 for violators [34].

Costa Rica's government has launched a pilot project to capture and recycle plastic waste before it reaches the sea. This project involves installing barriers in rivers to trap plastic waste, with a target to recover 200,000 tons of plastic waste by 2030. Additionally, Costa Rica is committed to developing a circular economy by transforming low-value plastic into building material [35].

The European Union has adopted strategies to reduce single-use plastic and increase recycling. In 2018, they proposed a ban on several single-use plastic products, such as straws, stirrers, and food containers. Australia has also implemented various policies to reduce single-use plastic, including banning plastic bags in some states. The Australian government promotes recycling initiatives and environmentally friendly alternatives, such as reusable shopping bags, with the goal of reducing plastic waste and raising awareness of the environmental impact of plastic [36].

The Canadian government announced plans to ban single-use plastics, including plastic bags, straws, and utensils, in 2021. This plan is part of efforts to reduce plastic pollution in the environment and protect marine ecosystems [37]. Meanwhile, Singapore has launched initiatives to reduce single-use plastic involving the private sector and the community. The government encourages companies to reduce plastic packaging and provide more environmentally friendly alternatives, accompanied by public awareness campaigns on the importance of reducing plastic use.

Germany is known for its highly efficient recycling system, implementing the "WEEE" (Waste Electrical and Electronic Equipment) and "Grüner Punkt" (Green Dot) systems that require producers to be responsible for the waste they generate. This policy has successfully increased the plastic recycling rate in Germany to over

60% [38, 39]. France has also taken initiative by banning single-use plastic products, including plates, cups, and straws, since 2020 [40]. This policy aims to reduce plastic waste and promote more sustainable alternatives, and is committed to achieving 100% plastic recycling by 2025.

In India, bans on single-use plastic have been announced in several states, including Delhi, to reduce plastic pollution and raise awareness of its negative impact [41, 42]. The government also promotes the use of environmentally friendly alternatives, such as cloth bags [43, 44]. Lastly, New Zealand has announced plans to ban single-use plastics, including plastic bags and utensils, in 2020 [44]. This policy is part of efforts to reduce plastic waste and protect the environment, as well as increase plastic recycling and waste management [31].

8. Challenges, research limitations, and strategies for future research

Research on microplastics in sea urchins in Indonesia has significant shortcomings and gaps. Existing studies are limited, with many remote islands not yet studied. Geographical variations in microplastic concentrations and their impact on sea urchins are not well understood. The diverse methodologies used in different studies make it challenging to compare results. Most studies do not include data on the types of polymers found in the microplastics, limiting our understanding of their origin and behavior. Long-term impacts of microplastic exposure, such as sub-lethal effects and behavioral changes, are often not evaluated. There is a lack of biological data on sea urchin populations and other environmental factors that may interact with microplastics. Low public awareness and limited resources for further research hinder mitigation efforts and a deeper understanding of the issue.

Future research on the impacts of microplastics on sea urchins and marine ecosystems in Indonesia is crucial for a better understanding of this issue. Longitudinal studies should be conducted to monitor the accumulation of microplastics in sea urchins at different locations, including analyzing the type and size of microplastics present. Further investigation into the physiological effects of microplastics on sea urchins, such as changes in metabolism, growth, and reproduction, is necessary. Exploring the interaction of microplastics with pathogens and their impact on sea urchin health and ecosystem health is also important. Research on how microplastics affect the marine food chain can provide insights into the consequences for predators and other herbivores. Evaluating the effectiveness of plastic waste management policies and public education programs is essential to reduce microplastic pollution. Collaborative efforts involving scientists, local stakeholders, and comparative studies across different regions in Indonesia can enhance our understanding of microplastic impacts. By taking a comprehensive approach, we can develop effective solutions to safeguard marine biodiversity and ensure the sustainability of coastal resources for communities.

Developing consistent methodological standards for microplastic research in marine biota and ecosystems in Indonesia is crucial. These standards will enhance research quality, support evidence-based decision-making, and aid in addressing the growing issue of microplastic pollution in our waters.

First, establishing clear methodological standards will ensure uniformity in sampling, analysis, and reporting practices. This includes guidelines for identifying, measuring, and categorizing microplastics, as well as protocols to prevent contamination during fieldwork and laboratory analysis. By implementing standardized

procedures, research findings can be compiled into a national database, facilitating the monitoring of microplastic pollution trends over time [10].

Secondly, the development of consistent standards also enables multidisciplinary research involving ecology, chemistry, and health sciences. This research can provide a more holistic understanding of the impacts of microplastics on marine biota and humans. For example, by combining data on microplastic accumulation in specific species and analysis of human health related to consumption of those species, researchers can provide more informed and evidence-based policy recommendations.

Thirdly, consistent methodological standards will improve collaboration between research institutions, governments, and local communities. With clear guidelines in place, all parties can work together to address the microplastics issue more effectively. For example, local fishermen can be involved in data collection and monitoring, which not only improves research capacity but also raises public awareness of microplastic pollution issues [5].

It is important to develop methodological standards that take into account the local context, such as environmental conditions, affected species, and cultural practices. By tailoring research methodologies to suit the specific conditions in Indonesia, the research can be more relevant and have a greater impact.

9. Conclusions

This review highlights the significant impact of microplastics in Indonesian waters, particularly on sea urchins, which are key indicators of marine ecosystem health. Sea urchins accumulate microplastics through feeding, which can affect their growth and reproduction and also pose risks to human health. To address this issue, the review suggests implementing improved waste management practices, conducting public education campaigns on plastic use, and conducting further research on the effects of microplastics. Collaboration among researchers, policymakers, and communities is crucial to mitigate plastic pollution and protect Indonesia's marine resources. Addressing microplastic pollution is essential for preserving marine ecosystems and the health of coastal communities.

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Conflict of interest

The authors declare no conflict of interest.

Appendices and nomenclature

MPs	microplastics
HPG	hypothalamic-pituitary-gonadal
ROS	reactive oxygen species
PE	polyethylene
PP	polypropylene
PCBs	polychlorinated biphenyls
WEEE	waste electrical and electronic equipment

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Chapter 3

Assessment of Metal Contamination in the Gabes Gulf (Tunisia): Contribution of Comparative and Chemometric Methods

Dorra Gargouri and Habib Abida

Abstract

The aim of this work is to present a global view of metal contamination in surface marine sediments of the Gabes Gulf. This study is based on descriptive and chemometric methods. Heavy metal concentrations were found to be variable. The examined sites, classified in an increasing order of contamination are: southern coast of Sfax (Zn: 39–117, Cu: 13–28.8, Cd: 5.5–7.2 mg kg^{-1} dry weight), northern coast of Sfax (Zn: 3.6–2077, Cu: 1–81.4, Cd: 0.1–35.9 mg kg^{-1} dry weight), and the coast of Gabes (Zn: 25–3920, Cu: 5–490, Cd: 0.1–732 mg kg^{-1} dry weight). Metal contamination is mainly related to the industrial activity of phosphate treatment. Phospho-gypsum is evacuated directly into the sea along the Gabes coast, while small quantities were evacuated into the sea in the northern coast of Sfax. In the southern coast of Sfax, only a part of the phospho-gypsum leaching water is drained into the sea. The pollution indices were calculated using two different methods. The method based on regional natural concentrations of metals was shown to better characterize sediment contamination. Indeed, surface sediments of the southern coast of Sfax are characterized by a moderate enrichement and contamination. Nevertheless, sediments of the northern coast of Sfax show EF and Igeo values generally higher than those of the southern coast. The obtained indices show a very to extremely severe enrichment and moderate to extreme contamination. Gabes coast is characterized by very high EF and Igeo, implying very to extremely severe metallic enrichment and heavy to extreme contamination.

Keywords: Gabes gulf, marine sediments, metals, pollution indices, principal component analysis

1. Introduction

Coastal environments represent transition zones between oceans and continents. The opportunities of these ecosystems, in terms of resources (fishing), transport (navigation), or trade (tourism), have for centuries encouraged humans to occupy

these areas. Nearly half of the world's population lives less than 200 km from the coast [1]. High population density in coastal areas resulted in the development of infrastructure and industrial activities as well as significant economic progress. Despite the control carried out by environmental management regulatory bodies to protect the environment, industries take the advantage of their proximity to the sea to discharge its rejects. These discharges, heavily loaded with organic and inorganic pollutants, are responsible for clear damage of the coastal ecosystem [2].

Numerous scientific studies dealt with the environmental problems that affect coastal ecosystems and may threaten current life conditions on Earth. Since the end of the twentieth century, several Tunisian researchers have been interested in examining the contamination of coastal ecosystems, especially in the Gabes Gulf. The latter is characterized by low hydrodynamic conditions, resulting in an increased sensitivity to contamination. The Gabes Gulf is recognized for its high marine productivity. Indeed, it represents the main fishing zone in Tunisia and one of the most important in the Mediterranean Sea [3–5]. Nevertheless, due to rapid and uncontrolled industrialization, continued and increasing degradation of the coastal ecosystem has been reported for several decades [6, 7]. The resulting contamination is attributed not only to industrial waste but also to domestic disposals rejected in the marine environment.

Several studies attempted to cover the Gabes Gulf through regional studies [8–10] and local studies [10–12]. The latter were selected because of their proximity to pollution sources or their particular hydrodynamic conditions. These studies contribute to the assessment of metal contamination of coastal sediments through descriptive and chemometric methods that include contamination indices (Enrichment Factor and Geo-accumulation Index) and statistical methods. This synthetic work, based on previous regional works, is interested in the global assessment of metal contamination in the Gabes Gulf and its relationship with anthropogenic sources.

2. Study area

The main sources of pollution of the coastal marine ecosystem are domestic and industrial solid waste; contaminated groundwater; contaminated surface waters in streams whose beds have become, in places, illicit dumps for domestic and industrial waste; atmospheric emissions that far exceed standards, maritime transport, and urban wastewater exceeding the capacity of wastewater treatment plants. Intense industrial development in the Gabes Gulf generated high anthropogenic pressure [13, 14]. In fact, diversified industrial activities are mainly located in the urban areas of Sfax and Gabes cities. The region of Skhira is also the seat of an important industrial activity (**Figure 1**).

In Sfax City, the most important industries, representing more than 80% of the industrial sector, are installed along the coast. The highly diversified industrial activities are responsible for the discharge into the sea of enormous quantities of wastewater [15]. Skhira Region is marked by an industrial pole, where the essential activity is represented by the treatment of phosphates (SIAPE II), the storage of oil, and the management of liquids (PAKTANK Mediterranean Company) [16]. In Gabes City, many industrial activities, especially concentrated in the commercial port, are encountered. The corresponding liquid and solid effluents are known as gypsum waters [8]. They are collected in the same channel and rejected into the sea in the vicinity of the commercial harbor.

Despite the diversity of industrial activities in the Gabes Gulf, phosphate treatment is the most important industry in the region (**Figure 1**). Phosphate rocks are treated with sulfuric acid to produce phosphoric acid. This reaction generates a large

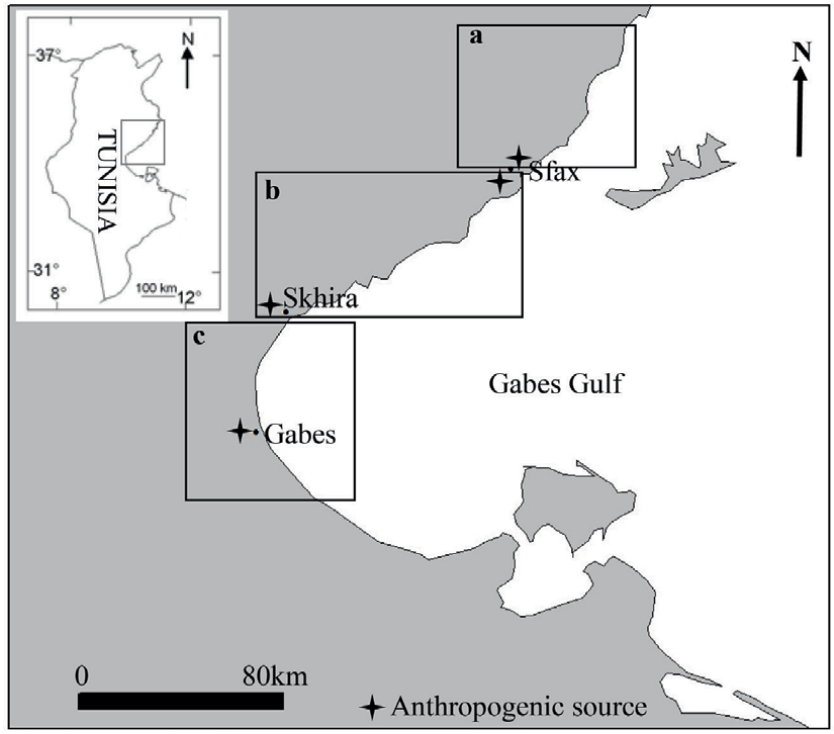


Figure 1.
Location of study areas in Gabes Gulf (a- Northern coast of Sfax, b- Southern coast of Sfax, c- Gabes coast).

amount of phosphogypsum (PG), which is the main product causing the degradation of seawater environment [13].

Phospho-gypsum wastes, formed mainly by Ca and SO_4, contain harmful various components, including metals, especially Zn, Cu, and Cd, which exist with high concentrations [17–19], impurities, residual acids, fluorides, organic matter, and radioactive elements [20–23].

In Sfax City, the production of phosphate fertilizers began in 1952, where two production plants were installed in the urban zone. SIAPE A (Industrial Company of Phosphoric Acid and Fertilizers) is located in the southern coast of Sfax. SIAPE B (former NPK), whose activity was stopped in 1992, was located in the northern coast of Sfax. In Skhira Region, which is a rural zone, the SIAPE II plant began its activity in 1988. In Gabes City, the production of phosphate fertilizers began in the 1970s.

The generated Phospho-gypsum is removed in two different ways. While it is rejected directly into the sea in Gabes City, it is piled on the ground surface in open air in Sfax City. In the northern coast of Sfax (SIAPE B), a part of Phospho-gypsum was directly rejected into the sea. However, in the southern coast of Sfax, heaping was performed *via* dry (SIAPE II) or wet mode (SIAPE A). In the latter case, Phospho-gypsum mixed with water (70% water-30% dry matter) is deposited in settling tanks. Part of the infiltrated water and part of the runoff water are collected and reused by the plant. The rest is drained to the sea [24].

Metal contamination of surface sediments in the Gabes Gulf was studied in three regional sites, including the northern coast of Sfax (**Figure 1a**) [9], the southern coast of Sfax (**Figure 1b**) [25].and the Gabes coast (**Figure 1c**) [8].

3. Relevant setting, material, and methods of study areas in Gabes Gulf

In the summer of 2010, a total of 20 surface coastline marine sediment samples were taken from each site (Southern Coast of Sfax, northern coast of Sfax, and Gabes coast (**Figure 1a–c**)) in one cruse (14/08/2010–16/08/2010). Sampling was limited to the coastline because coastal sedimentary transport of solid wastes is specially limited at ~ 10 km far from their source [2]. Dried sediment samples were sieved to collect the fine fraction (<63 μm) to which metals are most often associated [26]. Then, selected trace metals (Zn, Cu, Cd and Fe) were determined by Inductively Coupled Plasma-Atomic Emission Spectrometry [8, 9, 25].

This study includes both descriptive and chemometric analyses. The first is essentially based on a comparison of the concentrations of metals to regional natural concentrations, to the mean concentration of the continental crust and to those of other sites around the world. Chemometric methods correspond to the application of mathematical tools, to obtain the maximum of information from chemical data. In this work, the database available for the three studied areas (northern coast of Sfax, southern coast of Sfax, and Gabes coast) was used to calculate Enrichment Factors (EF) and Geo-accumulation Indices using two different methods. Indeed, background values corresponding to both regional natural concentrations and mean continental crust concentrations were adopted for the calculation of these indices. These later were used to assess metal contamination in the Gabes Gulf.

To highlight the existence of anomalous enrichment related to the abundance of metals [27], the EF was calculated for all samples. Commonly, geochemical normalization of metal data to conservative elements is used to identify anomalous metal concentrations. In this study, Fe was considered as a conservative element because: (i) the levels of Fe are lower than regional natural concentrations, (ii) unlike other metals, Fe concentrations do not vary significantly, (iii) the spatial distribution of iron does not depend on anthropogenic sources, (iv) Iron has no significant correlation with other metals, and finally, (v) Iron is the most used normalizer in other works around the world.

According to Ergin et al. [27], the metal EF is defined by Eq. (1):

$$EF = \frac{\left(C_x / C_{Fe}\right)_{\text{sample}}}{\left(C_x / C_{Fe}\right)_{\text{background}}} \tag{1}$$

Where $(C_x/C_{Fe})_{\text{sample}}$ is the ratio of concentration of the element being tested (C_x) to that of Fe (C_{Fe}) in the sediment sample and $(C_x/C_{Fe})_{\text{Background}}$ is the same ratio in uncontaminated reference baseline. Values were interpreted according to the ranges mentioned in **Table 1**.

The Geo-accumulation Index (I_{geo}) expressed by Eq. (2) may contribute to the estimation of the degree of sediment contamination.

$$I_{geo} = \log_2\left(\frac{C_n}{1.5B_n}\right) \tag{2}$$

Where C_n is the measured concentration of the analyzed metal (n) in the sediment sample and B_n is the geochemical background concentration of the metal (n). Values were interpreted according to the ranges mentioned by Müller's classification

I_{geo} value	Class quality of sediment
EF < 1	No enrichment
1 < EF < 3	Minor enrichment
3 < EF < 5	Moderate enrichment
5 < EF < 10	Moderate to severe enrichment
10 < FE < 25	Severe enrichment
25 < FE < 50	Very severe enrichment
EF > 50	Extremely severe enrichment

Table 1.
Classification for enrichment factor [28].

Igeovalue	Quality of sediment
$I_{geo} < 0$	uncontaminated
$0 < I_{geo} < 1$	uncontaminated to moderately contaminated
$1 < I_{geo} < 2$	moderately contaminated
$2 < I_{geo} < 3$	moderately contaminated to heavily contaminated
$3 < I_{geo} < 4$	heavily contaminated
$4 < I_{geo} < 5$	heavily to extremely contaminated
$I_{geo} > 5$	extremely contaminated

Table 2.
Classification for geo-accumulation Index (modified after [29]).

(**Table 2**). It is worth noting that the term pollution has been replaced in this table by the term contamination, which is more appropriate according to Chapman [30].

In this work, the calculation of EF and I_{geo} was performed using two different methods. In the first method, background values correspond to the natural regional metal concentrations [31]. We also found it useful to calculate these indices using the mean crust values [32].

Principal Component Analysis (PCA) permitted to synthesize information from many quantitative data sources. This statistical tool was used to better understand the behavior of metallic elements.

4. Results and discussion

4.1 Metal contamination in the Gabes Gulf region

4.1.1 Southern coast of Sfax

Table 3 shows that the selected metals present concentrations exceeding by far the regional natural concentrations, defined by Serbaji [31], implying metal enrichment of sediments. An exception is made for Fe, where concentrations are in agreement

	Cu	Zn	Cd	Fe
Sfax Southern coast [a]	13.11–28.80	39–117	5.51–7.17	41,011–51,163
Sfax Northern coast [b]	1–81.4	3.6–2077.3	0.1–35.9	8812.5–8831.6
Gabes coast [c]	5–490	25–3920	0.1–732	8800–9600
Regional natural concentration [d]	13	39	5.5	52,000
Mean continental crust concentration [e]	32	127	0.2	35,900
Quintero bay (Chile) [f]	41–1776	65–167	—	—
Valencia coast (Espagne) [g]	28.8	88.6	0.38	—
Yellow sea (Chine) [h]	5.93–25.7	21.9–96.2	0–8.21	—
Zhelin bay (Chine) [i]	50.9–144.5	175–251.2	—	—
Finland Gulf (Finlande)[j]	42.1–76.3	—	0.8–2.69	—

[a]*Gargouri et al. [33].*
[b]*Ghannem et al. [9].*
[c]*Gargouri et al. [8].*
[d]*Serbaji, [31].*
[e]*Martin and Whitfield [28].*
[f]*Parra et al. [34].*
[g]*Hernandez-Crespo and Martin [35].*
[h]*Jiang et al. [36].*
[i]*Gu et al. [37].*
[j]*Vallius et al. [38].*

Table 3.
Metal concentrations (mg kg^{-1} dry weight) from various sources.

with natural levels. Compared to the mean continental crust concentrations, all samples had high Cd contents. However, Cu and Zn contents were relatively low.

Compared to other sites around the world, surface sediments in the southern coast of Sfax (SIAPEA in urban area and SIAPE II in Skhira) are characterized by moderate to high metallic concentrations. These results may be explained by the relatively large amounts of the selected metals present in Phospho-gypsum.

4.1.2 Northern coast of Sfax

Similar to the southern coast of Sfax, metals generally present concentrations varying widely over large intervals in the northern coast (**Table 3**). Compared to regional natural concentrations and mean levels in the continental crust, 70% of the samples present high concentrations, except for Fe. In fact, Fe levels are lower than both the natural regional concentrations and the average concentrations of the continental crust. Compared to other sites around the world, the northern coast of Sfax is generally characterized by pronounced contamination (**Table 3**). The corresponding maximum concentrations are much higher than those recorded in the southern coast of Sfax. This may be explained by the industrial activity of phosphate treatment, responsible for the evacuation into the sea of a part of Phospho-gypsum produced by SIAPE B (former NPK).

4.1.3 The Gabes coast

Metal concentrations in surface marine sediments are highly variable. However, 95% of the examined samples show concentrations above regional natural levels and

mean crust values. These results clearly show the enrichment of the majority of the samples. An exception is made for Fe (natural tracer) for which concentrations are relatively low. The Gabes coast is generally characterized by relatively much higher maximum concentrations compared not only to the coast of Sfax but also to other sites around the world. These results may be explained by the disposal of the totality of Phospho-gypsum into the sea (**Table 3**).

Furthermore, it is worth noting that local studies were carried out in areas, characterized by the lack of neighboring anthropogenic sources and low hydrodynamic conditions. These zones are characterized by high concentrations of metals in Gabes Gulf. Indeed, low oxygen levels favor the accumulation of organic matter that has an affinity with metals [39]. These sites can be considered as vulnerable areas which deserve particular attention.

4.2 Metal enrichment factors, geo-accumulation index, and component analysis of surface marine sediments

4.2.1 Enrichment factor

The EF of surface sediments in the southern coast of Sfax was firstly calculated based on regional natural levels (**Table 4**). The corresponding mean values vary between 1 and 2, implying a minor enrichment. However, maximum values show a moderate local enrichment for Zn (**Table 4**). For northern coast of Sfax, mean values generally indicate moderate to severe enrichment. Maximum values, which are higher than those recorded in the southern coast of Sfax, show very severe to extremely severe restricted enrichment. Values of EF calculated for the Gabes coast are much higher than those recorded in the coast of Sfax (**Table 4**). They generally show very severe to extremely severe enrichment.

The EF values *of Cu and Zn*, calculated with mean crust values (**Table 5**), are lower compared to those calculated based on regional natural levels. This would imply

Study area	Element	Mean	Standard deviation	Extent
Sfax southern coast	Zn	1.53	0.47	0.9–3.54
	Cu	1.28	0.3	0.93–2.65
	Cd	1.08	0.41	0.87–2.24
	Zn	7.54	62.88	0.43–284.66
Sfax northern coast	Cu	4.24	7.21	0.40–33.11
	Cd	8.62	2.51	0.10–35.33
Gabes coast	Zn	95.30	117.37	3.23–532.63
	Cu	34.06	42.48	1.91–197.44
	Cd	102.20	154.15	0.09–712.80

Table 4.
Metal enrichment factors in surface marine sediments from the Gabes Gulf based on natural regional concentrations.

Study area		Zn	Cu	Cd
Sfax southern coast	a	0.9–3.54	0.93–2.65	0.87–2.24
	b	0.22–0.66	0.29–0.64	25.8–71.8
Sfax northern coast	a	0.43–284.66	0.40–33.11	0.10–35.33
	b	0.1–66.5	0.1–10.3	2.2–731.8
Gabes coast	a	3.23–532.63	1.91–197.44	0.09–712.8
	b	0.75–124.5	0.59–61.8	1.06–14,763

Table 5.
Ranges of enrichment factors in the Gabes Gulf calculated based on (a) natural regional concentrations and (b) mean crust values.

an underestimation of the metallic enrichment of sediments. However, the calculation of the EF of Cd led to an excessive overestimation.

4.2.2 Geo-accumulation index

Average I_{geo} values calculated based on regional natural levels show that the surface marine sediments of the southern coast of Sfax are generally not contaminated. The maximum values, varying between 0 and 2 (with the exception of Fe) attest local moderate contamination (**Table 6**). Average values calculated for the northern coast of Sfax show that the surface marine sediments are not contaminated. However, the maximum values that are higher than those of the southern coast of Sfax indicate a more pronounced contamination. In fact, sediments are, in places, extremely contaminated with Zn and moderately to heavily contaminated with Cu and Cd. The average values of I_{geo} calculated for Gabes coast reflect uncontaminated to moderately contaminated sediments with Cd, moderately contaminated with Cu and moderately to heavily contaminated with Zn (**Table 6**). The maximum values are higher than those calculated for the Sfax Coast. It shows heavy to extreme restricted contamination. I_{geo} values calculated using the mean crust levels are summarized in **Table 7**. They show an underestimation of the contamination for Zn and Cu. However, the use of the mean crust values resulted in an excessive over estimation of contamination for Cd.

Study area	Element	Mean	Standard deviation	Extent
Sfax southern coast	Zn	−0.1	0.4	−0.6 → 1
	Cu	−0.3	0.3	−0.6 → 0.6
	Cd	0.1	0.3	−0.3 → 0.9
	Zn	−3.06	2.20	−4.02 → 5.15
Sfax northern coast	Cu	−1.79	1.46	−4.24 → 2.06
	Cd	−2.87	2.00	−6.36 → 2.12
Gabes coast	Zn	2.55	1.87	−1.22 → 6.06
	Cu	1.28	1.55	−1.96 → 4.65
	Cd	0.68	4.28	−6.36 → 6.47

Table 6.
Geo-accumulation index of surface marine sediments of the Gabes Gulf based on natural regional concentrations.

Study area		Zn	Cu	Cd	Pb	Cr
Sfax Northern coast	a	−0.6 → 1	−0.6 → 0.6	−0.3 → 0.9	−0.6 → 1.7	−0.6 → 0.4
	b	−2.28 → -0.7	−1.87 → -0.73	4.19 → 4.57	−0.39 → 1.86	−1.37 → -0.38
Sfax southern Coast	a	−4.02 → 5.15	−4.24 → 2.06	−6.36 → 2.12	−15.22 → 2.21	−5.35 → 1.67
	b	−5.7 → 3.4	−15.6 → 0.8	−1.5 → 6.9	−14.6 → 2.4	−16.7 → 0.9
Gabes coast	a	−1.22 → 6.06	−1.96 → 4.65	−6.36 → 6.47	-	-
	b	−2.92 → 4.36	−3.26 → 3.35	−1.58 → 11.25	-	-

Table 7.
Ranges of geoaccumulation index for surface sediments in the Gabes Gulf based on (a) natural regional concentrations and (b) mean crust values.

4.2.3 Component analysis

The results of the PCA applied to the coast of Sfax prove the existence of a natural component that corresponds to Fe and several anthropogenic components [10, 25]. These results show the existence of several anthropogenic sources enriched with heavy metals. These sources are concentrated in the urban area. In the coast of Gabes, the existence of a single anthropogenic component proves that the gypsum water constitutes the main source of metal contamination.

5. Conclusion

This study represents a first synthesis work that provided an overview of metal contamination in the Gulf of Gabes. Metal concentrations in surface marine sediments of the Gabes Gulf were shown to be variable. Metal enrichment is more or less important and varies from a site to another. An exception is made for Fe, chosen as a natural tracer, whose content is in agreement or lower than natural regional concentration and mean continental crust concentration. Compared to the Sfax coast, surface marine sediments in the Gabes coast are characterized by higher levels of metals. These results are directly related to gypsum water directly discharged into the sea along the Gabes coast. The EF and the I_{geo} values, calculated based on regional natural concentrations, resulted in the characterization of the metal contamination. Surface sediments of the southern coast of Sfax are characterized by moderate enrichment and moderate contamination. However, sediments of the northern coast of Sfax show EF and I_{geo}values generally higher than those of the southern coast. These indices show very severe to extremely severe enrichment and moderate to extreme contamination. As for the Gabes coast, very high EF and I_{geo} values were obtained, implying very severe to extremely severe metallic enrichment and heavily to extreme contamination. The use of EF and I_{geo} was shown to be useful in the assessment of contamination in such environments around the world. Nevertheless, index values calculated with mean continental crust concentrations resulted in different values, showing thereby the limitation of this semiquantitative approach. Indeed, the use of regional natural concentrations in the calculation of these indices is in our opinion better to characterize the marine sediments in the Gabes Gulf. However, the use of mean crust concentrations is more adequate in order to compare results against those of other areas worldwide. PCA proved the existence of several anthropogenic sources

concentrated in the urban area of Sfax coast, while the coast of Gabes is characterized by a single main anthropogenic source that corresponds to the gypsum water.

This work should be used as a support tool to decision-makers to take effective measures and develop integrated management plans. This approach should correct the negative impacts of the phosphate treatment industry. Solutions are needed, such as treatment procedures that allow the reduction of the metallic element content in the marine sediments and/or the valorization of Phospho-gypsum, which constitutes the main source of metallic contamination in the Gabes Gulf.

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Chapter 4

Marine Pollution and Environmental Sustainability: Challenges and Solutions for Karachi, Pakistan

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Abstract

Marine water pollution is a significant global issue, and the Sindh coastline in Pakistan, particularly the Karachi Harbor area, has become a hotspot due to weak regulatory enforcement. This poses serious risks to the coastal ecosystem and human health. This study aimed to assess the levels of pollutants in the Karachi Harbor and Sindh coastline by measuring various physicochemical parameters, including temperature, turbidity, total dissolved solids (TDS), salinity, chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Additionally, trace metals such as Pb, Cd, Ni, and Hg were analyzed from marine coastal waters at different distances (20-, 50-, and 100-m offshore) and at varying tides (low and high) to assess pollution levels. The study also evaluated the effectiveness of current regulations by comparing pollution data with regulatory actions. The results revealed pollutant concentrations exceeding safe limits, indicating an urgent need for stricter regulations and better enforcement. The study provides recommendations for improved pollution control measures to mitigate environmental and health risks. It highlights the importance of continuous monitoring and research to track pollution trends, assess long-term impacts, and implement effective strategies. This research aligns with the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), contributing to global efforts for better ocean science and informed policy decisions. It also advocates for public awareness of marine pollution's dangers and promotes sustainable environmental practices to ensure the future health of marine ecosystems.

Keywords: marine pollution, regulations, coastal ecosystem, marine biodiversity, sustainable development

1. Introduction

Marine pollution has become an increasingly urgent issue, attracting significant attention due to its detrimental effects on coastal ecosystems and the broader marine

environment. The growing concerns surrounding climate change, coastal pollution, overfishing, greenhouse gas emissions, and coastal development have underscored the need for robust, science-based policies and measures to safeguard oceans and coasts. Monitoring marine pollution is particularly critical as the world's oceans and coastal ecosystems are undergoing rapid changes driven by anthropogenic pressures.

In Pakistan, marine pollution is primarily concentrated in areas receiving waste from municipal, industrial, agricultural, and oil spill sources. Karachi, as the economic hub of the country, is at the forefront of this challenge. The city's coastal areas, including the Karachi Harbor and regions along the adjacent river estuary, are particularly vulnerable to pollution due to continuous discharges from both domestic and industrial activities. Karachi generates approximately 472 million gallons per day (MGD) of wastewater, with only 55 MGD being treated [1]. The remaining untreated wastewater is discharged directly into the sea through various drains, exacerbating the pollution load on the coastal environment.

Approximately 262 million gallons per day (MGD) of sewage is produced in Karachi from both industrial and domestic sources, with 111 MGD originating from municipal sources and the remainder from industrial activities, involving around 6000 units. Only 20% of this wastewater undergoes treatment, while the rest is released untreated into coastal waters [1, 2]. The adjacent rivers account for 60 and 25% of Karachi's total pollution load, respectively, with the remaining 15% being discharged directly into the nearby open sea or into the Gizri, Korangi, and Gharo creeks [2].

The Karachi coastline in Sindh is contaminated by a range of hazardous materials originating from industrial, municipal, and agricultural sources. This pollution is exacerbated by the absence of adequate monitoring systems and treatment facilities to reduce their detrimental impacts [1]. Pollutant concentrations, especially heavy metals, have already surpassed natural oceanic levels in areas near Karachi, such as Karachi Harbor [3].

The primary waste-receiving zones in and around Karachi, especially from industrial sites, discharge into the harbor and coastal waters of Sindh. Coastal regions near Karachi, including Karachi Harbor, which is situated at the estuary of the adjacent river, are significantly impacted by land-based pollution. Karachi produces approximately 472 million gallons of wastewater per day [4]. The operational capacities of the current sewage treatment plants (STP) are detailed in **Table 1** and illustrated in **Figure 1**.

Out of the 472 MGD of wastewater generated by the city, only 55 MGD undergoes treatment, while the rest flows untreated into the Arabian Sea through natural and nallah drains, severely impacting the marine environment [2]. The existing sewage treatment plants operate below capacity due to the inadequate transmission

Sewerage treatment plants	Optimum design capacity	Actual treatment
STP-I – SITE	51 MGD	20 MGD
STP-II –Mehmoodabad	46.50 MGD	00 MGD
STP-III – Mauripur	54 MGD	35 MGD
Total capacity	**151.50 MGD**	**55 MGD**

Table 1.
Sewerage Treatment Plants (STP) in Karachi [4].

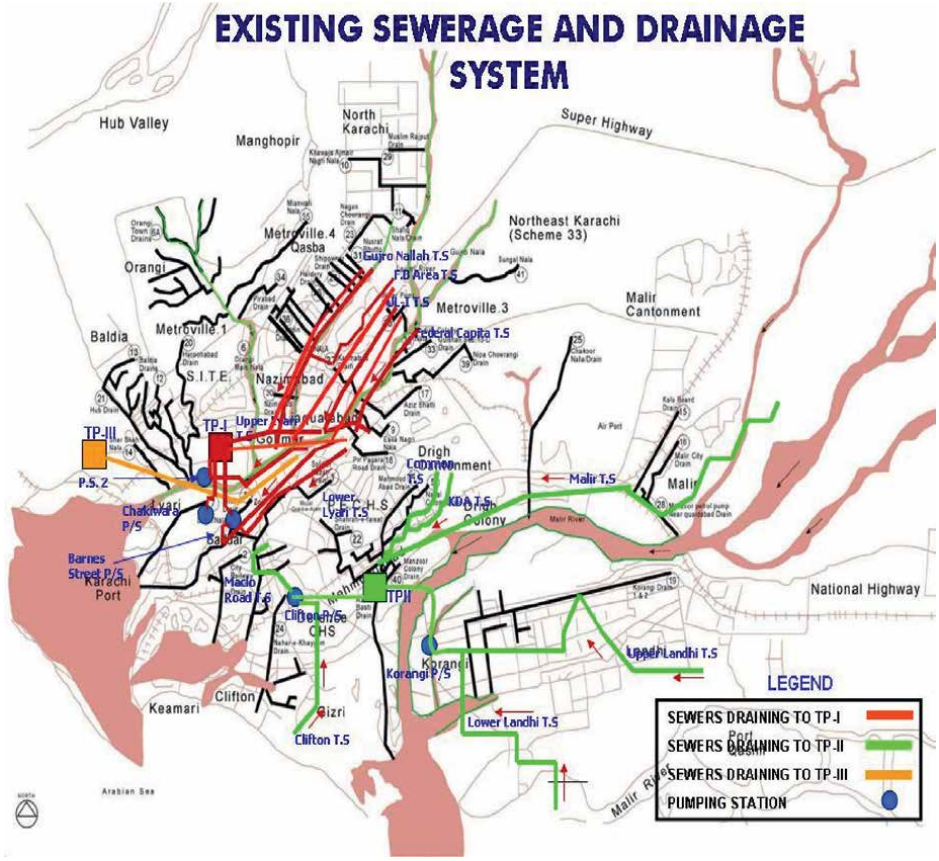


Figure 1.
Map of sewerage treatment plant of Karachi. Sources: https://techno-consult.com/?post_type=portfolio&p=876&gallery=current-projects

capabilities of interceptors [5]. The primary aim of this study is to collect and analyze marine water samples from different offshore distances (20 m, 50 m, and 100 m) along the Sindh and Karachi coastlines, focusing on physicochemical parameters and selected heavy metals to assess the pollution load.

Untreated wastewater presents a significant risk to mangroves, aquatic life, and the broader marine coastal ecosystem, while also potentially causing damage to ships and associated infrastructure. To address this threat, it is crucial to examine all relevant factors, including the chemical composition, physical characteristics of the area, and the impact of contaminated water on the offshore marine ecosystem.

This chapter aims to highlight the severity of the marine pollution crisis in Karachi, focusing on the impacts of industrial and domestic effluents on water quality, ecosystem health, and local communities. It underscores the need for immediate remedial action to mitigate the ongoing degradation of Karachi's coastal and marine environments. Without effective regulatory mechanisms and sustainable waste management practices, the health of the marine ecosystem, including fish habitats, mangroves, and human health, will continue to suffer. Collaborative efforts from both government agencies and the industrial sector are essential to combat this growing

pollution challenge and ensure environmental and socioeconomic sustainability for Karachi's coastal communities.

The Karachi coastline and the harbor areas are facing rapidly escalating pollution at an alarming rate, primarily driven by industries, harbor operations, and metropolitan sewerage discharge. A significant portion of this pollution, approximately more than 90%, stems from terrestrial activities, encompassing both municipal and industrial sources. The Layari and the Malir Rivers, which were once the perennial channels, are now carrying millions of gallons of polluted water into the Arabian Sea. Despite the severity of the problem, there are currently no effective or worthwhile remedial measures in place to properly address this growing environmental crisis. The lack of action underscores the urgent need for comprehensive strategies to mitigate the pollution and protect the marine ecosystem.

The main and primary objective of this study was to pool the representative marine water samples from various areas around Karachi Harbor, as well as the coastal water along the 300-kilometer coastline of Sindh at multiple offshore points. These samples were analyzed for physiochemical parameters and selected heavy and trace metal species to examine the contamination levels. Finally, the data of examined samples was compared with available national quality standards to evaluate compliance and identify potential environmental concerns.

2. Adopted methodology to conduct research work

2.1 Study areas and sampling framework for marine pollution assessment

This study encompasses two primary research areas. The first is Karachi Harbor, where 10 samples were collected and analyzed to assess marine pollution and its impacts. The laboratory analysis parameters for this site were tailored to the specific pollution sources, including industrial effluents, urban wastewater, and municipal sewage. The second research area covers the Sindh coastline-Pakistan, with a total of 30 samples collected for laboratory analysis. The analytical parameters for this site were determined based on the nature and intensity of pollution sources and loads characteristic of the region. Certain physical and chemical properties of water, such as pH, temperature, salinity, and total dissolved solids, were noted at the sampling location with the help of portable equipment, the HACH SensION 156 device. Chemical parameters were determined by HACH BOD and COD Track. Metal contents (Pb, Cd, Ni, and Hg) in the samples were determined with the help of the Thermo Ice 3000 Atomic Absorption Spectrophotometer. Testing and sampling procedures are conducted in accordance with the standards set forth by APHA and ASTM [6, 7].

2.1.1 Sampling procedure for Karachi Harbor

Seawater samples were collected from a range of predetermined coastal locations, as detailed in **Table 2**. To ensure comprehensive data, samples were collected twice at each location, once during high tide and once during low tide. This approach was designed to capture the average pollution load and the temporal variation of pollutants within the marine environment.

Sr. No.:	Sample location	Sample number	Coordinates	
1	River sample	River sample	24°52′16.80″N	66°58′30.61″E
2	River outfall area	LS-1	24°50′46.82″N	66°58′21.65″E
		LS-3	24°50′35.14″N	66°58′1.16″E
3	Shipyard area	S-1 A	24°50′19.58″N	66°58′18.17″E
		S-1 C	24°50′17.49″N	66°58′3.74″E
4	Karachi Port Trust (KPT) area	S-2 A	24°49′17.34″N	66°58′22.00″E
		S-2 C	24°49′6.41″N	66°58′13.48″E
5	Kemari Harbor area	S-3 A	24°49′3.18″N	66°58′32.03″E
		S-3 C	24°48′51.26″N	66°58′23.54″E
6	Dockyard area	S-4 A	24°49′44.19″N	66°58′6.92″E
		S-4 C	24°49′39.63″N	66°57′53.80″E

Table 2.
Sampling location with coordinates.

Samples were taken from two specific depths at each location: the sea surface and a depth of 10 feet. This dual-depth sampling was essential to analyze both surface and subsurface water conditions, providing a more holistic understanding of pollution dispersion and concentration.

2.2 Sampling procedure for the coastline of Sindh-Pakistan

As shown in **Figure 2**, the sampling procedure for the coastline of Sindh, Pakistan, the marine coastal water sampling was conducted at thirty (30) sites along the 300-kilometer, focusing on various offshore points at distances of 0–20 m, 20–50 m, and 50–100 m. Each sample was collected in replication from the sea surface as well as at depths of 6 and 12 feet. Before analysis, a composite sample is prepared of these depths at each point, and standard sampling procedures have been followed.

2.3 Laboratory analysis for both study area's sampling

The collected samples were analyzed for a range of physicochemical parameters and the presence of selected heavy metals. All analyses were conducted at the Environmental Research Center, which is certified by the Sindh Environmental Protection Agency (SEPA) and ISO standards. This laboratory, located at the Bahria University Karachi Campus, ensured the reliability and accuracy of the results through standardized procedures and modern analytical techniques.

For the determination of chemical parameters, the HACH BOD and COD Track were utilized to assess the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels in the samples, which are critical indicators of organic pollution.

The presence of selected heavy metals—including lead (Pb), cadmium (Cd), nickel (Ni), and mercury (Hg)—was determined using the Thermo Ice 3000 Atomic

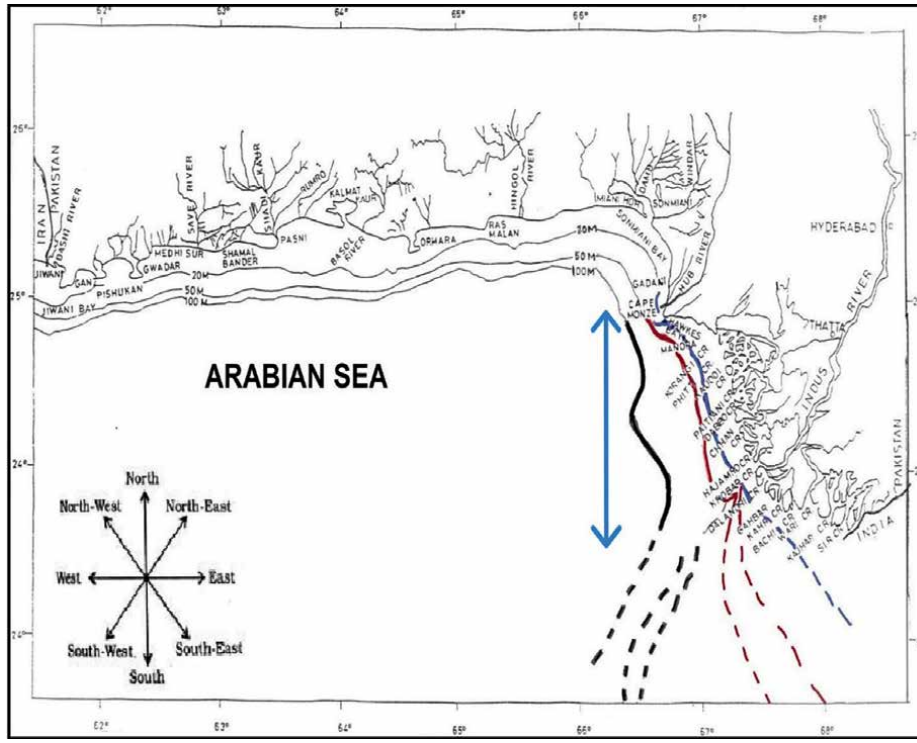


Figure 2.
Showing the offshore coastline of Sindh-Pakistan and the distance from the coastal sampling lines area (blue line 20 m, red line 50 m, and black line 100 m).

Absorption Spectrophotometer. This advanced equipment allowed for precise detection of metal concentrations in the water samples, providing valuable insights into potential contamination sources and their environmental impact.

The selection of these specific parameters was based on their significance to the marine and coastal environment, with a focus on pollutants that have a substantial impact on the health of the ecosystem and the organisms that rely on it.

By utilizing this methodology, the study aimed to deliver a detailed, scientifically rigorous assessment of Karachi Harbor and the Sindh-Pakistan coastline's marine water quality, offering critical insights for future management and policy interventions in the region's marine and coastal environments.

2.4 Field analysis for both study area's sampling

Samples were collected from various locations within Karachi Harbor and Coastline Sindh at strategically selected points, as depicted in **Figures 2** and **3**. To maintain the integrity of the collected samples and ensure the accuracy of the test results, standard sampling procedures were strictly followed at each designated sample point.

At each sampling location, certain physical and chemical properties of the water, including pH, temperature, salinity, and total dissolved solids (TDS), were recorded using portable equipment. These parameters provided essential baseline data for evaluating the environmental conditions of the sampled waters.

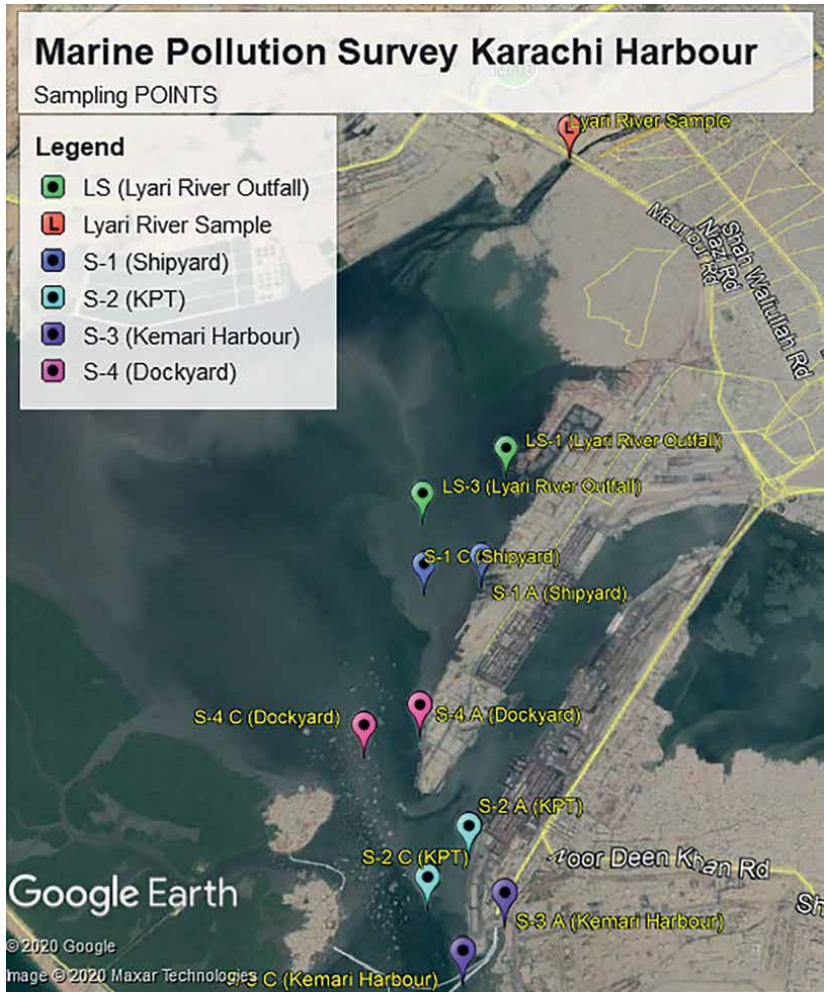


Figure 3.
Marine pollution survey Karachi Harbor sampling points.

3. Results and discussion of Karachi Harbor and Sindh coastline-Pakistan

The results and discussions are presented step by step, focusing on harbor sample analysis along with Sindh coastline-Pakistan sample analysis. For each sampling site, two sections have been designated to systematically discuss the analytical results.

3.1 Physicochemical characteristics of Karachi Harbor

3.1.1 Analysis of river samples adjacent to Karachi Harbor

Temperature: The temperature of the River tail samples was 26.1°C during high tide and 31.6°C during low tide, as shown below (**Tables 3** and **4**; **Figures 4** and **5**). The SEQS permissible limit for temperature is 40°C. Both samples were within the permissible temperature range, suggesting that effluent influx may not have adverse effects on coastal water temperatures.

Sr. No:	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp ^{0}C	pH --	TDS (mg/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
SEQS standard (Into sea)		40 ≤ 3	6–9	3500	—	400	80	0.5	0.1	1.0	0.01
1	River sample	26.1	7.71	2810	2.8	654	362	0.1328	0.1276	5.6598	0.0176

Table 3.
River sample-1 data (high tide).

S. No.	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp °C	pH --	TDS (mg/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
SEQS standard (Into sea)		40 ≤ 3	6–9	3500	—	400	80	0.5	0.1	1.0	0.01
1	River sample	31.6	8.22	2196	2.19	572	291	0.1055	0.1009	3.5914	0.0118

Table 4.
River sample-2 data (low tide).

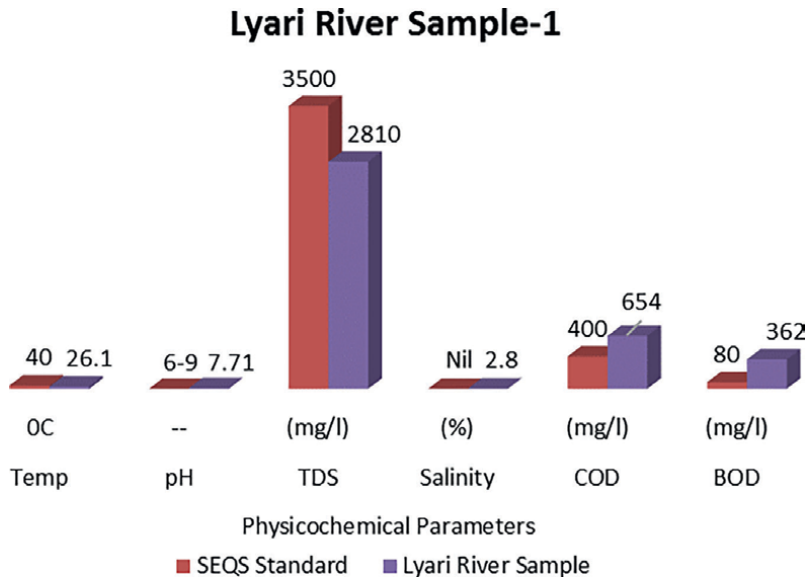


Figure 4.
Physicochemical parameters of river sample 1 (high tide).

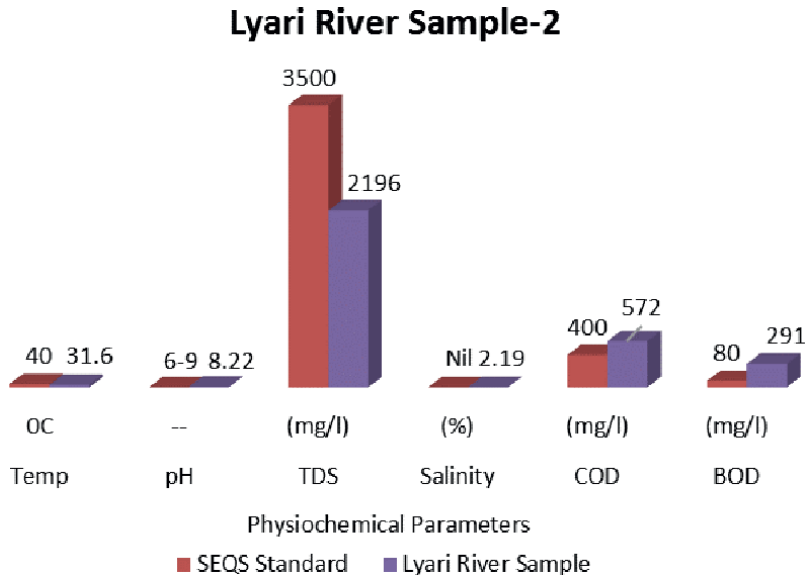


Figure 5.
Physicochemical parameters of river sample-2 (low tide).

pH: The pH of river samples was found to be 7.71 during high tide and 8.82 during low tide (**Tables 3** and **4**; **Figures 4** and **5**). The variation in pH values is negligible and within the SEQS permissible range of 6–9. Therefore, the influx of effluent into the coastal areas of Karachi is unlikely to cause significant changes in pH.

Salinity: The salinity of river samples was 2.8% during high tide and 2.19% during low tide (**Tables 3** and **4**; **Figures 4** and **5**). There is no specific limit for salinity under

SEQS. Given that natural seawater has a high salinity, the effluent influx from rivers does not pose a significant risk to salinity levels.

Chemical oxygen demand (COD): The COD of river samples was 654 mg/l during high tide and 572 mg/l during low tide (**Tables 3** and **4**; **Figures 4** and **5**). The SEQS limit for COD is 400 mg/l, indicating that the COD values were significantly higher than permissible limits. This elevated concentration is attributed to the mixing of industrial effluents from the SITE area with municipal effluents, which eventually discharge into the sea.

Biochemical oxygen demand (BOD): The BOD of river samples was 362 mg/l during high tide and 291 mg/l during low tide (**Tables 3** and **4**; **Figures 4** and **5**). The SEQS limit for BOD is 80 mg/l, indicating that the BOD values far exceed the permissible limits. This elevated BOD is likely due to the influx of untreated municipal and industrial effluents from the river and surrounding areas.

Lead (Pb): Lead concentrations were 0.1328 mg/l during high tide and 0.1055 mg/l during low tide, as shown below (**Figures 6** and **7**). The SEQS permissible limit for Pb is 0.5 mg/l, and both samples were within the acceptable range.

Cadmium (Cd): Cadmium concentrations were 0.1396 mg/l during high tide and 0.1009 mg/l during low tide (**Figures 6** and **7**). The SEQS permissible limit for Cd is 0.1 mg/l, and both samples exceeded the permissible limit.

Nickel (Ni): Nickel concentrations were 5.6598 mg/l during high tide and 3.5914 mg/l during low tide (**Figures 6** and **7**). The SEQS permissible limit for Ni is 1.0 mg/l, and both samples were significantly higher than the permissible limit. High concentrations of Ni are likely due to effluents from electroplating industries in the SITE area.

Mercury (Hg): Mercury concentrations were 0.0176 mg/l during high tide and 0.0118 mg/l during low tide (**Figures 6** and **7**). The SEQS permissible limit for Hg is 0.01 mg/l, and the mercury concentrations in both samples were within the allowable limits.

3.1.2 Analysis of seawater samples adjacent to Karachi Harbor

Temperature: The seawater temperature ranged from 22.9 to 23.6°C (surface) and 22.6 to 23.4°C (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low

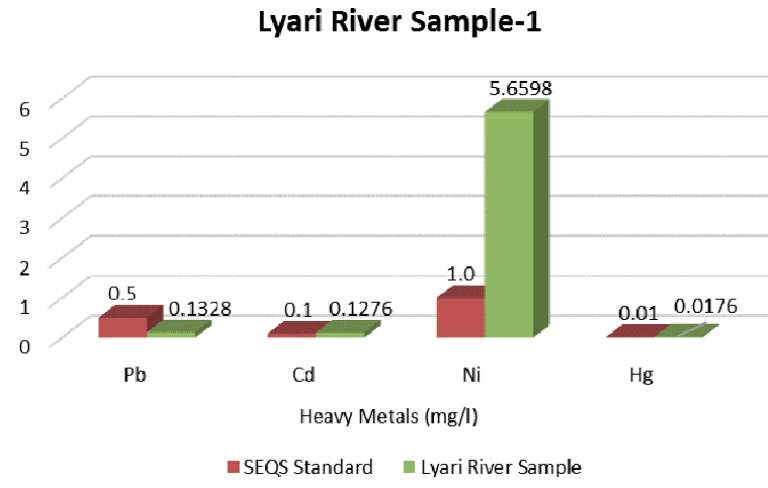


Figure 6.
Heavy metal concentration in river sample 1 (high tide).

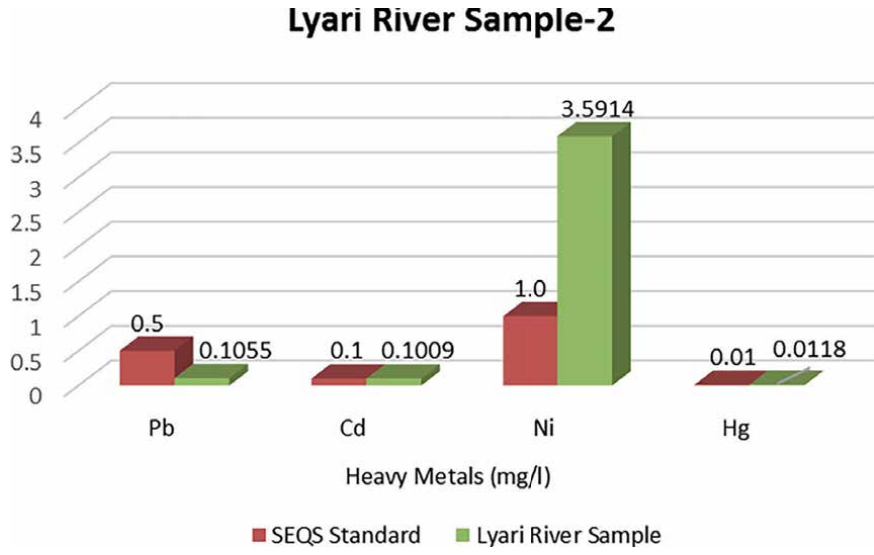


Figure 7.
Heavy metals river sample-2 (low tide).

tide, the temperature ranged from 31.8 to 32.8°C (surface) and 31.5 to 32.6°C (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

Turbidity: Turbidity ranged from 0.45 to 1.57 NTU (surface) and 0.52 to 1.78 NTU (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low tide, turbidity ranged from 1.20 to 2.05 NTU (surface) and 1.53 to 6.32 NTU (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

Total dissolved solids (TDS): TDS ranged from 30.8 to 36.5 g/l (surface) and 33.8 to 36.9 g/l (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low tide, TDS ranged from 30.1 to 34.4 g/l (surface) and 30.3 to 34.4 g/l (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

Salinity: Salinity ranged from 32.5 to 38.0% (surface) and 35.2 to 36.9% (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low tide, salinity ranged from 31.5 to 35.9% (surface) and 31.6 to 36.1% (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

COD: The COD ranged from 56 to 24 mg/l (surface) and 297 to 28 mg/l (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low tide, COD ranged from 2120 to 390 mg/l (surface) and 2240 to 94 mg/l (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

BOD5: BOD5 ranged from 27 to 14 mg/l (surface) and 172 to 16 mg/l (depth) during high tide (**Tables 5** and **6**; **Figures 8** and **9**). During low tide, BOD5 ranged from 910 to 174 mg/l (surface) and 1030 to 97 mg/l (depth) (**Tables 7** and **8**; **Figures 10** and **11**).

3.1.2.1 Lead (Pb)

High tide: Pb concentrations in seawater ranged from 0.1226–0.8838 mg/l (surface) and 0.0757–0.9925 mg/l (depth) (**Figures 12** and **13**).

Low tide: Pb concentrations ranged from 0.2122–0.9024 mg/l (surface) and 0.4128–0.9764 mg/l (depth) (**Figures 14** and **15**).

S. No:	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp ^{0}C	Turbidity NTU	TDS (g/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
1	LS-1	23.6	1.34	31.2	32.5	45	23	0.8838	0.8241	15.2370	0.0118
2	LS-3	23.3	0.62	32.3	33.6	37	19	0.5910	0.5804	12.0776	0.0103
3	S-1 A	23.4	0.52	30.8	32.8	24	14	0.6991	0.8656	13.0730	0.0089
4	S-1 C	23.1	0.58	32.5	33.7	29	15	0.4397	0.6859	10.8965	0.0062
5	S-2 A	22.9	1.57	34.5	36.8	56	27	0.2706	0.4032	10.8209	0.0125
6	S-2 C	22.9	0.49	33.4	34.7	48	25	0.1693	0.2005	8.8788	0.0119
7	S-3 A	23.4	0.63	32.8	34.1	46	24	0.4241	0.6768	12.7695	0.0117
8	S-3 C	23.2	0.45	36.5	38.0	47	24	0.1226	0.2673	11.3096	0.0013
9	S-4 A	23.2	0.69	32.6	33.9	49	26	0.5732	0.6607	13.3241	0.0016
10	S-4 C	22.9	0.51	33.0	34.2	38	21	0.3278	0.5891	9.9213	0.0011

Table 5.
Seawater surface sample data (high tide).

S. No:	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp 0C	Turbidity NTU	TDS (mg/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
1	LS-1	23.4	1.78	34.4	35.7	106	61	0.9925	0.8995	18.8420	0.0339
2	LS-3	23.0	1.67	35.1	36.1	297	172	0.8211	0.6879	14.5810	0.0284
3	S-1 A	23.4	0.76	33.8	35.2	28	16	0.7220	0.9709	16.9945	0.0171
4	S-1 C	22.9	0.67	34.8	36.2	33	19	0.6713	0.7520	11.3778	0.0086
5	S-2 A	22.6	0.59	35.6	37.9	41	24	0.5670	0.5868	13.9862	0.0192
6	S-2 C	22.7	0.52	36.5	37.9	53	28	0.2459	0.4474	10.8365	0.0115
7	S-3 A	23.1	1.35	36.8	38.3	57	31	0.6133	0.8715	12.9784	0.0162
8	S-3 C	23.0	0.77	36.9	38.8	62	34	0.1997	0.6688	9.3925	0.0150
9	S-4 A	22.9	0.87	35.0	36.4	71	39	0.0906	0.7583	15.2275	0.0297
10	S-4 C	22.7	1.17	36.4	36.7	79	42	0.0757	0.6075	11.7331	0.0211

Table 6.
Seawater 10 feet depth sample data (high tide).

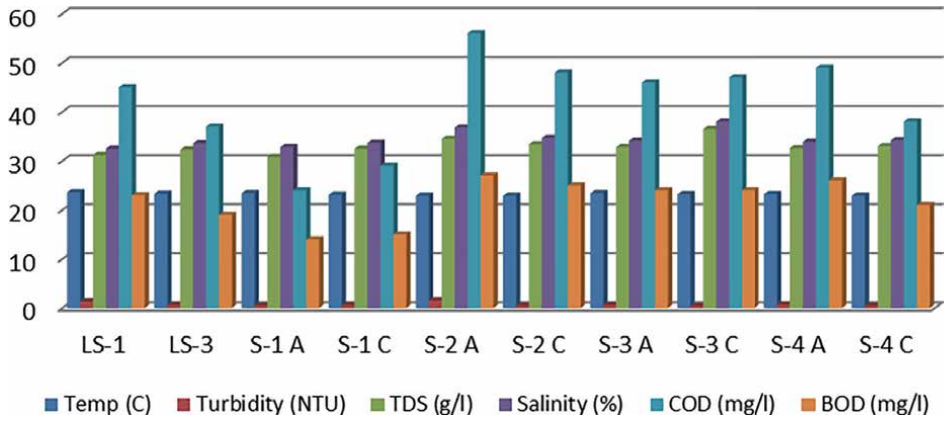


Figure 8.
Physicochemical parameters of seawater surface samples (high tide).

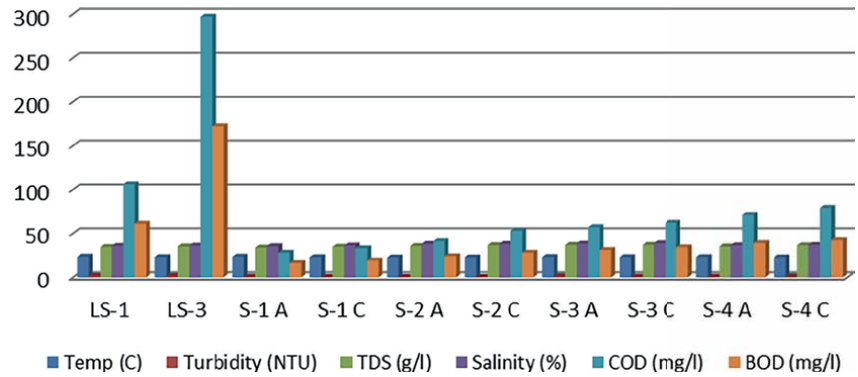


Figure 9.
Physicochemical parameters of seawater 10 feet depth samples (high tide).

3.1.2.2 Cadmium (Cd)

High tide: Cd concentrations ranged from 0.2005–0.8656 mg/l (surface) and 0.0447–0.9709 mg/l (depth) (**Figures 12** and **13**).

Low tide: Cd concentrations ranged from 0.2649–0.9700 mg/l (surface) and 0.4542–0.9764 mg/l (depth) (**Figures 14** and **15**).

3.1.2.3 Nickel (Ni)

High tide: Ni concentrations ranged from 9.9213–15.2370 mg/l (surface) and 9.3925–18.8420 mg/l (depth) (**Figures 12** and **13**).

Low tide: Ni concentrations ranged from 11.0631–16.7673 mg/l (surface) and 10.0284–17.9874 mg/l (depth) (**Figures 14** and **15**).

3.1.2.4 Mercury (Hg)

High tide: Hg concentrations ranged from 0.0011–0.0125 mg/l (surface) and 0.0086–0.0339 mg/l (depth) (**Figures 12** and **13**).

S. No.	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp 0C	Turbidity NTU	TDS (g/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
1	LS-1	32.3	1.70	30.1	31.5	2120	910	0.9024	0.9700	16.7673	0.0493
2	LS-3	32.6	1.35	32.0	33.4	2015	830	0.8798	0.6392	13.9764	0.0219
3	S-1 A	32.5	1.87	32.3	33.7	1150	640	0.7187	0.8957	14.4401	0.0116
4	S-1 C	32.3	1.20	33.2	34.7	1010	510	0.6887	0.6945	11.0631	0.0103
5	S-2 A	32.3	2.05	34.4	35.9	2040	870	0.5045	0.4973	13.4021	0.0325
6	S-2 C	32.0	1.68	33.7	35.1	390	174	0.2122	0.2649	12.4319	0.0107
7	S-3 A	32.1	1.68	30.6	32.5	570	220	0.5267	0.7091	16.9830	0.0126
8	S-3 C	31.8	1.57	34.3	35.8	2036	180	0.3796	0.3879	13.6080	0.0093
9	S-4 A	32.5	1.64	33.8	35.2	2098	215	0.7331	0.8095	14.5392	0.0208
10	S-4 C	32.2	1.40	33.8	35.3	750	340	0.6048	0.6002	11.4907	0.0120

Table 7.
Seawater surface sample data (low tide).

S. No.	Sampling site	Physicochemical parameters						Heavy metals (mg/l)			
		Temp 0C	Turbidity NTU	TDS (g/l)	Salinity (%)	COD (mg/l)	BOD (mg/l)	Pb	Cd	Ni	Hg
1	LS-1	32.4	2.95	30.3	31.6	2240	1030	0.9911	0.9764	17.9874	0.0918
2	LS-3	32.6	1.96	31.7	33.0	1992	970	0.8952	0.7359	15.1397	0.0728
3	S-1 A	32.3	3.32	33.0	33.7	1030	490	0.8602	0.9243	15.3997	0.0562
4	S-1 C	32.4	1.53	33.2	34.6	870	380	0.8001	0.6333	13.4538	0.0494
5	S-2 A	32.2	1.61	34.6	36.1	1740	730	0.6271	0.5561	12.3927	0.0411
6	S-2 C	32.1	1.63	33.5	34.9	210	97	0.4958	0.4542	11.5024	0.0289
7	S-3 A	32.1	1.53	30.9	35.6	447	190	0.8050	0.9021	14.0764	0.0216
8	S-3 C	31.5	1.17	34.2	35.6	513	225	0.4128	0.8416	10.0284	0.0118
9	S-4 A	32.1	6.32	34.0	35.4	950	438	0.8870	0.7997	15.7752	0.0227
10	S-4 C	32.2	1.55	33.9	35.4	271	129	0.8024	0.7002	12.6082	0.0209

Table 8.
Seawater 10 feet depth sample data (low tide).

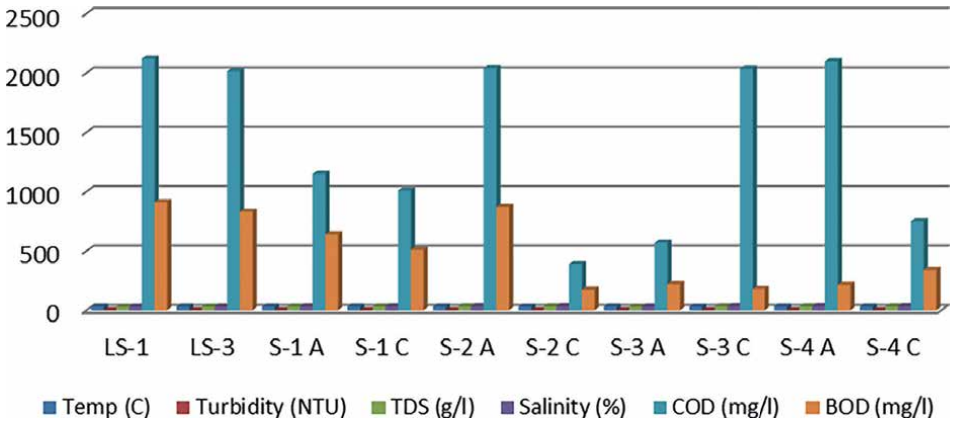


Figure 10.
Physicochemical parameters of seawater surface samples (low tide).

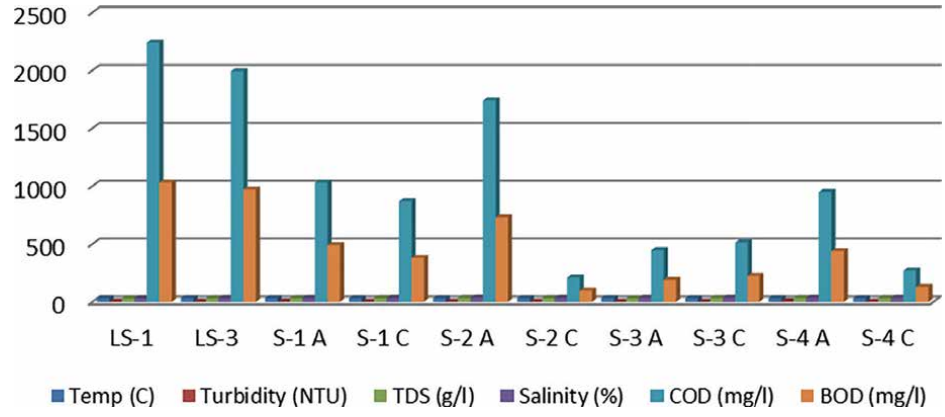


Figure 11.
Physicochemical parameters of seawater 10 feet depth samples (low tide).

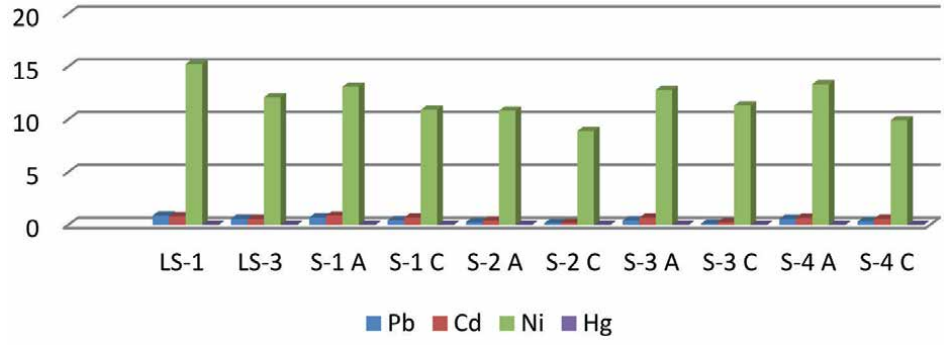


Figure 12.
Heavy metal concentration in seawater surface samples (high tide).

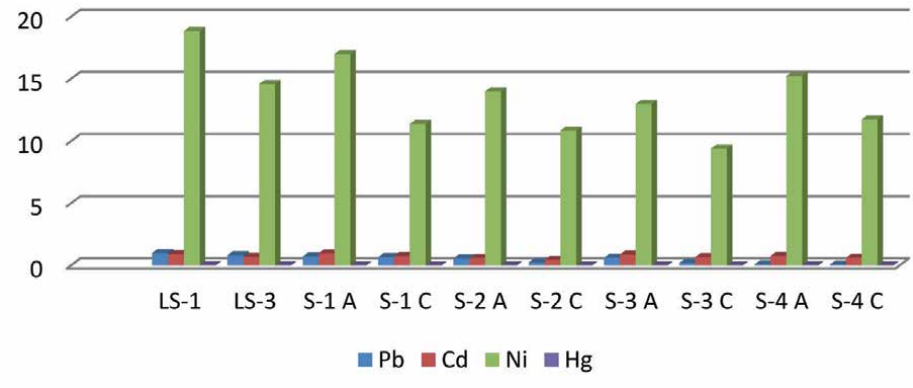


Figure 13.
Heavy metals in seawater 10 feet depth samples (high tide).

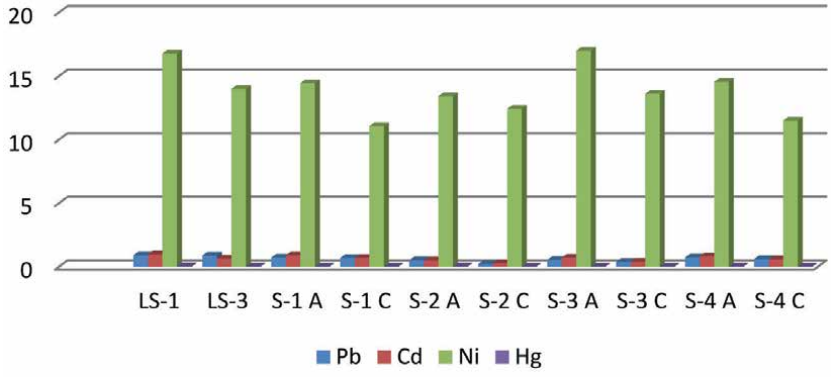


Figure 14.
Heavy metal concentrations in seawater surface samples (low tide).

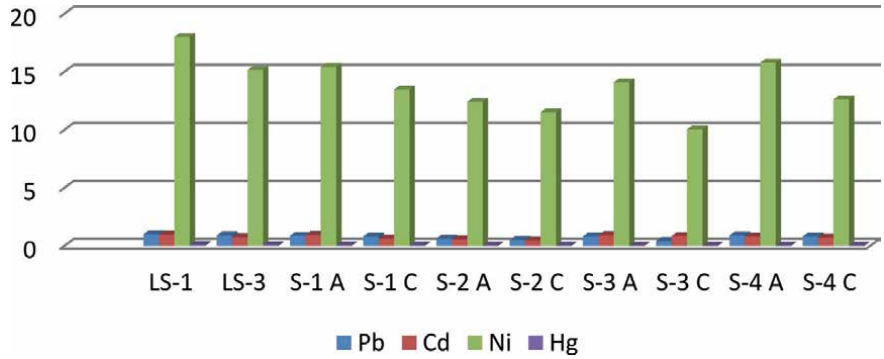


Figure 15.
Heavy metals in seawater 10 feet depth samples (low tide).

Low tide: Hg concentrations ranged from 0.0093–0.0493 mg/l (surface) and 0.0118–0.0918 mg/l (depth) (**Figures 14** and **15**).

3.2 Physicochemical characteristics of Sindh-Pakistan coastline

3.2.1 Analysis of coastal water samples of Sindh-Pakistan coastline

Turbidity: Turbidity levels were found to be within acceptable limits for aquatic life, suggesting that effluent influx may not significantly harm offshore coastal areas.

Salinity: On the other hand according to distance variation salinity levels were higher than the acceptable range for aquatic life, with values recorded at 13–39.4% for 0–20 m, 7.9–27.91% for 20–50 m, and 1.6–13.80% for 50–100 m offshore areas (see **Table 9** or **Figure 16**).

Total Dissolved Solids (TDS): However, the Total Dissolved Solids (TDS) concentrations varied significantly, measuring 1545–36,673 mg/l values at distances of 0–20 m, 1665–36,672 mg/l at 20–50 m, and 2399–37,997 mg/l at 50–100 m respectively.

COD and BOD5: The organic contamination levels in water are typically assessed using Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD). High COD values were recorded, ranging from 9 to 4100 mg/l values away from the distances of 0–20 m, 46–2870 mg/l at 20–50 m, and 3–1465 mg/l at 50–100 m offshore. The Biological Oxygen Demand (BOD, measured over 5 days at 20°C) varied from 66 to 2169 mg/l at 0 to 20 m, 46 to 1518 mg/l at 20 to 50 m, and 23 to 385 mg/l at

S.#	Parameters	Units	Standard for aquatic life	0–20 m	20–50 m	50–100 m
1	Temperature	Co	22	25–25.8	25–25.9	25–26
2	Turbidity	NTU	25	1.05–15.2	0.77–10.64	0.315–5.32
3	TDS	mg/I	35,000	1545–36,673	1665–36,672	2399–37,997
4	Salinity	%	3.5	13–39.4	7.9–27.91	1.6–13.80

Table 9.
Physiochemical assessment range value and offshore distance of marine water [8].

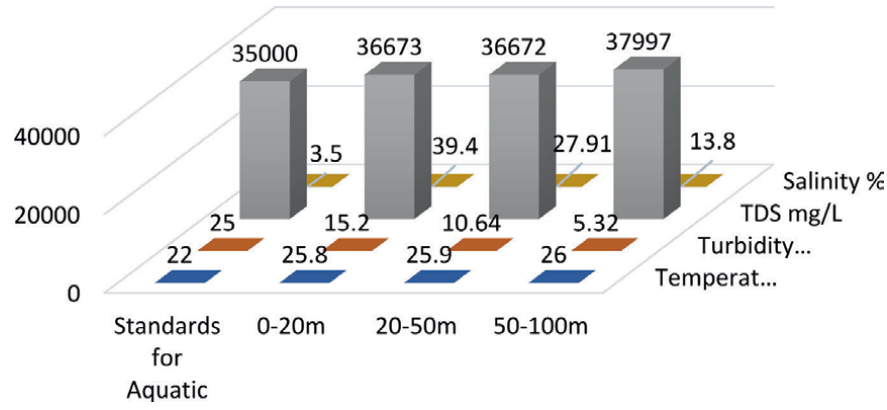


Figure 16.
Physiochemical assessment range value and offshore distance of marine water.

50 to 100 m (see **Table 10**). Both COD and BOD values show a gradual decrease from the coast to offshore areas (refer to **Table 10** and **Figure 17**).

The concentrations of heavy metals (Pb, Cd, Ni, and Hg) were analyzed in thirty (30) marine water samples collected from selected offshore coastal locations.

Lead (Pb): Lead (Pb) levels ranged from 5 to 423 ppb at distances of 0–20 m, 3.7–166.1 ppb at 20–50 m, and 8.9–63.8 ppb at 50–100 m, as detailed in **Table 11** or illustrated in **Figures 18** and **19**.

Cadmium (Cd): Cadmium (Cd) concentrations varied from 3 to 253 ppb at 0 to 20 m, 1 to 74.9 ppb at 20 to 50 m, and 1 to 17.5 ppb at 50 to 100 m (see **Table 11** or **Figures 18** and **19**).

Nickel (Ni): Nickel (Ni) levels were found to be between 7.4 and 359.5 ppb at 0–20 m, 3 and 319 ppb at 20–50 m, and 3.2 and 139 ppb at 50–100 m (refer to **Table 11** or **Figures 18** and **19**).

Mercury (Hg): Mercury (Hg) concentrations ranged from 10.3 to 12.5 ppb at 0–20 m, 1.9 to 8.9 ppb at 20–50 m, and 1.1 to 1.6 ppb at 50–100 m (see **Table 11** or **Figures 18** and **19**).

3.3 Comparison with literature in similar research

This study evaluates the accumulation and bio-magnification of multiple metals, highlighting their potential ecological and environmental impacts. In **Table 12**, the founded metal species are compared with recent literature from the past few years as well as with established standards. The findings indicate a concerning deterioration in the condition of marine waters, with the highest recorded concentrations of heavy metals. These values surpass the acute threshold limits set by the standards.

S.#	Parameters	Units	Standard for aquatic life	0–20 m	20–50 m	50–100 m
1	COD	mg/I or ppm	400	9–4100	46–2870	3–1465
2	BOD (5 days at 20 Co)		250	66–2169	46–1518	23–385

Table 10.
Organic physiochemical assessment range value and offshore distance of marine water [9].

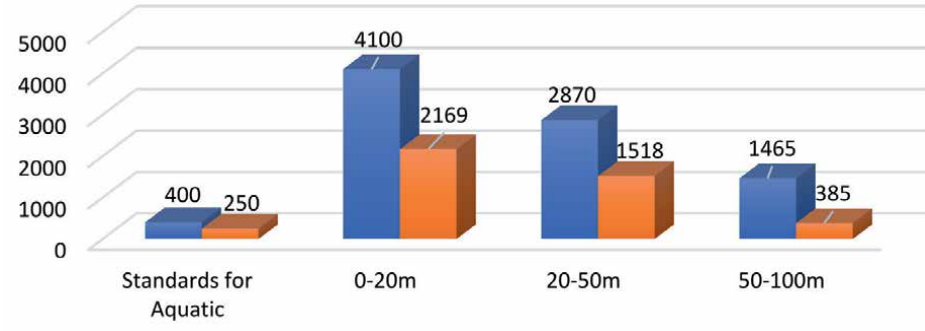


Figure 17.
Organic physiochemical assessment range value and offshore distance of marine water.

S.#	Parameters	Units	Standard for aquatic life	0–20 m	20–50 m	50–100 m
1	Pb	µg/I or ppb	8.1 (chronic) 42 (acute)	5–324	3.7–166.1	8.9–63.8
2	Cd		9.3 (chronic) 42 (acute)	3–253	1–74.9	1–17.5
3	Ni		8.2 (chronic) 74 (acute)	7.4–359.5	3–319	3.2–139.5
4	Hg		0.025 (chronic) 1.8 (acute)	10.3–12.5	1.9–8.9	1.1–1.6

Table 11.
Heavy metal assessment range value and offshore distance of marine water environmental conservation [8].

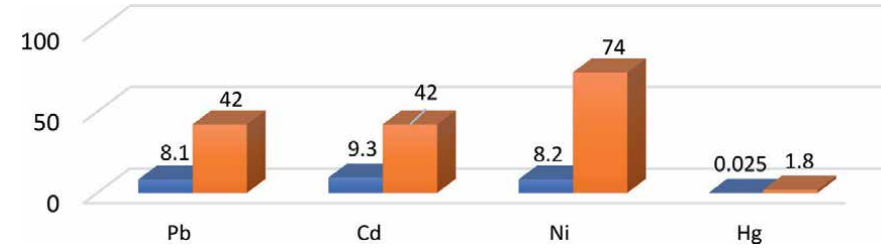


Figure 18.
Standards for aquatic life for heavy metals.

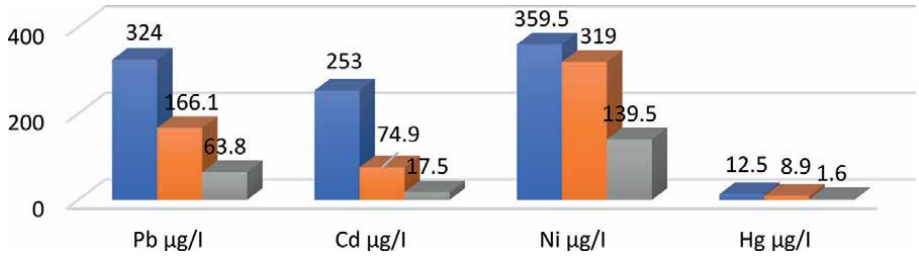


Figure 19.
Heavy metal assessment range value and offshore distance of marine water.

4. Conclusion

Thoughtful and adverse impacts of pollution issues of Pakistan's largest industrial city, Karachi, are highlighted in this study. More than 450 million gallons of wastewater are produced by this city on a regular frequency. However, three treatment plants are placed but not in full working order, just 30% of it. As per results, rivers are mostly fed by the direct and untreated flow of wastewater released from the SITE zone that finally mixes up in the Arabian Sea.

Marine water analysis exposed disturbingly high concentrations of heavy metals, including lead (Pb), cadmium (Cd), nickel (Ni), and mercury (Hg), far beyond the standard limits. The constant release of untreated domestic and industrial wastewater, along with harbor activities, has severely impacted the marine environment, leading to higher organic matter levels, increased salinity, and rising temperatures.

Parameter(s)	Literature [2, 4, 9, 10]						Standard for aquatic life	Locations of current study (Various distances from coastline)		
	Paradise Point	Hawke's Bay	Sandspit	Sea view	Ghizri Creek	Korangi Creek		0–20 m	20–50 m	50–100 m
Pb	0.19 ± 0.09	2 ± 0.1	1.8 ± 0.31	2.7 ± 0.1	2.5 ± 0.4	3.5 ± 0.6	8.1 (chronic) 42 (acute)	5–324	3.7–166.1	8.9–63.8
Ni	0.3 ± 0.09	0.5 ± 0.06	0.55 ± 0.1	0.77 ± 0.056	0.69 ± 0.03	0.3 ± 0.08	9.3 (chronic) 42 (acute)	7.4–359.5	3–319	3.2–139.5
Cd	—	—	—	—	—	—	8.2 (chronic) 74 (acute)	3–253	1–74.9	1–17.5
Hg	—	—	—	—	—	—	0.025 (chronic) 1.8 (acute)	10.3–12.5	1.9–8.9	1.1–1.6

Table 12.
Showing a comparison of the current situation with literature and standards [10].

The environmental and socioeconomic impacts of this pollution are adversely impacted. The degradation of fish habitats, mangrove ecosystems, and marine biodiversity puts livelihoods dependent on the seafood trade and tourism at risk. Moreover, the bioaccumulation of toxic metals in marine life poses a severe health threat to local communities, particularly fishermen and coastal inhabitants.

Immediate and collaborative action is vital to beat the rising marine pollution.

5. Recommendations

In light of the findings and conclusions drawn from this study, the following recommendations are proposed to address the pollution issues faced by Karachi Harbor and its surrounding coastal areas:

- *Establishment of a comprehensive water pollution monitoring system*: A robust water pollution monitoring mechanism should be developed and implemented to regularly assess the quality of seawater in Karachi Harbor. This system should include real-time data collection and analysis for key pollutants, such as heavy metals, organic matter, and other chemical parameters, ensuring that appropriate corrective actions can be taken promptly.

- *Adoption of international remediation standards*: Karachi Harbor's pollution control measures should align with international remediation standards for coastal waters. National regulatory bodies and agencies, in consultation with global environmental organizations, should adopt best practices and set appropriate standards for pollution mitigation and habitat restoration.

- *Collaborative mechanism to reduce pollutant influx*: A collaborative approach should be adopted between provincial regulatory bodies, local authorities, and national agencies to address the influx of pollutants from the river system. Effective coordination and joint efforts will ensure that measures such as waste treatment, industrial effluent management, and proper disposal practices are implemented to prevent further contamination of the harbor.

- *Formation of local, provincial, and national consultative committees*: It is essential to establish consultative committees at the local, provincial, and national levels to generate and implement a comprehensive cleanup strategy for Karachi Harbor. These committees should be tasked with formulating regulations for the use of seawater for various purposes, including fishing, recreation, and industrial activities while ensuring environmental protection.

- *Formulation and implementation of national environmental quality standards*: National Environmental Quality Standards (NEQS) specifically tailored to coastal water pollution should be formulated and enforced to regulate the discharge of contaminants into marine ecosystems. These standards should include specific limits for heavy metals, organic pollutants, and other hazardous substances to protect the health of marine life and coastal communities.

- *Optimization of sewage treatment plants*: The existing sewage treatment plants in Karachi should operate at full capacity to treat domestic and industrial

wastewater effectively. The plants should be upgraded and maintained to ensure they can handle the volume of wastewater generated by the city. Additionally, all untreated wastewater should be diverted to these plants for proper treatment before being discharged into the sea.

- *Strengthening the implementation of the MARPOL 73/78 protocol*: The MARPOL 73/78 protocol, which regulates pollution from ships, should be enforced more effectively by the MPCD (Marine Pollution Control Division) of the Karachi Port Trust (KPT). Strict monitoring and penalties should be imposed on vessels found violating the protocol to reduce marine pollution from shipping activities.

- *Public awareness campaign on Karachi Harbor pollution*: Public awareness regarding the pollution of Karachi Harbor and its adverse effects on both human health and marine life should be raised through various platforms, including social media, public service announcements, and educational outreach programs. Engaging the public will foster a sense of responsibility and encourage more sustainable practices among local communities.

- *Organizing educational programs and media campaigns*: Seminars, talk shows, and webinars should be organized to inform and educate the public about the importance of marine conservation and the challenges facing Karachi Harbor. These platforms should serve as an opportunity for experts to share knowledge on the causes, impacts, and solutions to pollution in the coastal environment.

- *Integration of environmental protection in academic curricula*: Environmental protection, particularly in the marine domain, should be integrated into the curricula of universities and colleges. Lectures, workshops, and hands-on training sessions on the importance of marine conservation, sustainable practices, and pollution control should be delivered to students to equip them with the knowledge and skills to actively contribute to environmental protection.

Through these recommendations, it is expected that concerted efforts from both government agencies and local communities will help mitigate the pollution problem in Karachi Harbor, ensuring the long-term health and sustainability of the coastal environment. The involvement of various stakeholders and the implementation of these recommendations will lead to improved water quality, better public health, and a more sustainable marine ecosystem for Karachi's coastal population.

Key recommendations include:

- *Enforcing environmental regulations*: Strengthening environmental governance and implementing the "polluter pays" principle to hold industries accountable for untreated effluents.

- *Infrastructure development*: Establishing additional wastewater treatment plants and upgrading existing facilities to handle both domestic and industrial effluents.

- *Public awareness campaigns*: Educating communities about the health and environmental impacts of marine pollution to foster better waste management practices.

- *Monitoring and research*: Establishing a comprehensive monitoring system for marine pollution to guide evidence-based policy and intervention strategies.

Protecting Karachi's coastal environment is essential for preserving biodiversity, ensuring public health, and safeguarding the region's economic stability. A concerted effort from government agencies, industries, and local stakeholders is vital to restore and sustainably manage this critical marine ecosystem.

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Notes/thanks/other declarations

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List of acronyms/abbreviations

mg/l	milligram per liter
MGD	million gallon per day
%	percent
NTU	nephelometric turbidity unit
STP	sewerage treatment plant (I, II and III)
SEQS	Sindh environmental quality standards
EPA	environmental protection agency Govt. of Pakistan
COD	chemical oxygen demand
BOD	biochemical oxygen demand 5 days
Pb	lead
Cd	cadmium
Ni	nickel
Hg	mercury
WHO	World Health Organization
°C	centigrade
NoGL	no guideline limits available
ASTM	American society for testing and materials
USEPA	United States environmental protection agency
APHA	American public health association
CDGK	city district government
SEPA	Sindh environmental protection agency
NEQS	national environmental quality standards
ERC	environmental research center
BUKC	Bahria University Karachi Campus
KMC	Karachi municipal corporation

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Chapter 5

Socio-Economic Impacts of Climate Change and Marine Pollution on Fish-Dependent Communities of Southern Africa

Tirivashe Phillip Masere, Albert Gumbo, Albert Shumba, Kizito Kunaka, Cosmas Parwada and Victoria Stella Masere

Abstract

Climate change and marine pollution are significantly impacting the fisheries sector in Southern Africa, posing serious threats to the livelihoods and health of communities dependent on fishing and aquaculture. Utilizing a systematic literature review approach, this chapter explores the socio-economic consequences of marine pollution and climate-driven changes in fish populations and fisheries on these communities. A total of 30 studies were included, revealing that marine pollution and climate change contribute to reduced fish catches, lower incomes, and diminished food security, exacerbating poverty, inequality, and other socio-economic vulnerabilities—especially for women and marginalized groups. The review also identifies key adaptation and mitigation strategies, such as climate-resilient fisheries management, livelihood diversification, and improved climate information systems. The findings underscore the urgent need for targeted actions to enhance the adaptation and resilience of fish-dependent communities in Southern Africa.

Keywords: community economic dynamics, coastal fishing communities, sustainable livelihoods, climate-adaptive fisheries, oceanic pollution

1. Introduction

Fisheries are integral to the economies of Southern Africa, providing vital sources of food, income, and employment, particularly in coastal and inland communities. They are a cornerstone of the region's food security and rural livelihoods. The sector supports millions of people, many of whom rely on artisanal and small-scale fishing for their sustenance and economic stability. These fish-dependent communities are particularly vulnerable to environmental changes that threaten the health of marine and freshwater ecosystems, which are fundamental to their survival. As such, the livelihoods of millions of people in the Southern African region are intricately tied

to the availability and sustainability of fish stocks, making disruptions to fisheries a major threat to both local and national economies.

Fish are a primary source of protein for much of the Southern African population, with the fisheries sector being a key contributor to rural economies. In coastal communities, fishing is not just an economic activity but a way of life, linked to food security, cultural practices, and social well-being. However, the increasing impacts of climate change and marine pollution are creating significant challenges for these communities. Changes in sea temperatures, ocean acidification, and unpredictable weather patterns are affecting the abundance and distribution of fish stocks, reducing catches, and threatening the food security of vulnerable populations. Simultaneously, marine pollution—largely driven by land-based sources such as urban runoff, plastics, and industrial discharge—further exacerbates these environmental stresses, undermining the health of marine ecosystems and jeopardizing the livelihoods of those who depend on them [1].

In recent decades, climate change has emerged as a critical threat to marine ecosystems across Southern Africa. Warming sea temperatures, ocean acidification, and shifts in weather patterns are disrupting the ecological balance of marine and freshwater environments. Rising temperatures are pushing fish stocks into cooler waters, altering migration patterns and breeding cycles, thus affecting the availability of fish in traditional fishing areas [2]. Additionally, ocean acidification, a result of increasing atmospheric carbon dioxide (CO_2), is threatening marine species, particularly those with calcium carbonate shells, such as mollusks and corals, which are vital components of the marine food web [3]. These disruptions in the marine environment are leading to reduced fish stocks, which in turn threaten the food security and income of local fishing communities.

At the same time, marine pollution is intensifying the pressures on these ecosystems. The large-scale accumulation of plastic waste, oil spills, and chemical contaminants is degrading marine habitats and reducing biodiversity. Plastics, which now account for a substantial proportion of oceanic waste, are known to cause physical harm to marine life, including entanglement and ingestion, which can lead to death [4]. In addition, chemical pollutants from industrial and agricultural runoff, such as heavy metals and pesticides, are contaminating aquatic environments and adversely affecting fish health, with significant implications for the safety of seafood consumed by local communities [5, 6]. The combination of these environmental stressors undermines the resilience of marine ecosystems and further threatens the livelihoods of fish-dependent communities [1].

This chapter seeks to assess the socio-economic impacts of climate change and marine pollution on fish-dependent communities in Southern Africa. Specifically, the chapter will explore how environmental changes resulting from climate change—such as shifting fish stocks, changes in breeding and migration patterns, and ocean acidification—are affecting the availability of fish and the income of these communities. It will also examine the additional burden of marine pollution, including plastic waste, industrial contaminants, and runoff, on the health of marine ecosystems and the communities that rely on them. The objective is to provide a comprehensive understanding of the socio-economic vulnerabilities of fish-dependent communities in the face of these environmental threats. Through this analysis, the chapter will underline the importance of implementing targeted interventions and sustainable management practices to mitigate the impacts of climate change and marine pollution, thereby ensuring the long-term resilience of marine ecosystems and the well-being of the communities that depend on them [1, 7].

Item	Inclusion criteria	Exclusion criteria
Geography	Focus on Southern Africa and fish-dependent communities.	Studies outside Southern Africa or non-coastal regions.
Relevance	Impact of climate change (temperature and acidification) and marine pollution (plastics and chemicals) on fish populations and livelihoods.	
Socio-economic Focus	Analysis of food security, income, and community well-being, particularly in small-scale fisheries.	Research without a socio-economic focus.
Adaptation	Focus on adaptive strategies and sustainable practices.	
Publication Type	Peer-reviewed sources only.	Non-peer-reviewed sources.

Table 1.
Inclusion and exclusion criteria employed in the review.

2. Research approach: Systematic literature review methodology

A systematic literature review (SLR) was used to assess studies on the socio-economic impacts of climate change and marine pollution on fish-dependent communities in Southern Africa. The aim was to consolidate findings, identify research gaps, and underscore the urgency of addressing these environmental challenges.

The search was conducted across three academic databases, namely, Scopus, Web of Science and Google Scholar. Keywords included "climate change," "marine pollution," "socio-economic impacts," "Southern Africa," and related terms. Studies from 1997 to 2023, focusing on peer-reviewed articles and government reports, were included. **Table 1** shows the inclusion and exclusion criteria used when selecting studies to be used in the analysis.

Consequently, data from 30 studies were extracted, focusing on climate change impacts on fish population, the impact of marine pollution on ecosystems and fish health, socio-economic consequences on livelihoods, measures for mitigating climate and pollution impacts, and existing policies and institutional responses. The studies were analyzed for common themes, challenges, and gaps, such as the socio-economic resilience of communities and the need for region-specific research.

3. Climate change and marine pollution in southern African region

3.1 Climate change projections for southern Africa's coastal zones

Southern Africa is experiencing a significant rise in temperatures, leading to more frequent and intense heat waves, particularly in coastal zones. As global warming continues, heat waves in both land and oceanic areas are expected to increase in magnitude and duration. The 2015–2017 droughts in Cape Town were three times more likely under current climate change conditions [7]. Projections suggest that some regions will experience wetter conditions, while others will face increased dryness, with heavy rainfall events becoming more frequent and droughts intensifying **Figure 1**. The climate crisis demands urgent adaptation and mitigation actions.

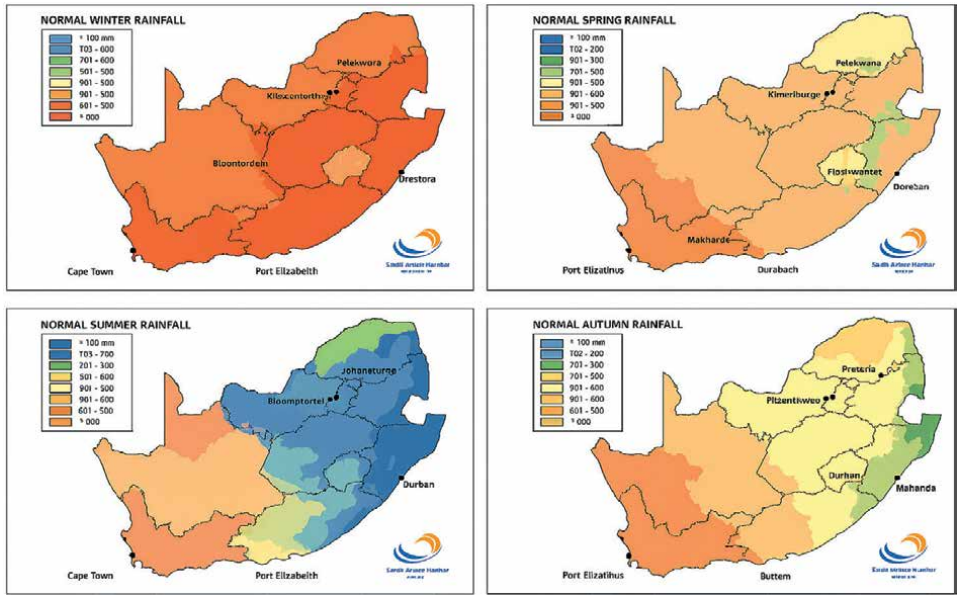


Figure 1.
Projected rainfall pattern in future for Southern Africa [7].

3.1.1 Rising sea temperatures

Sea temperatures around Southern Africa are rising, with the region experiencing a sea level increase of 5 mm per year, exceeding the global average of 3–4 mm. This has led to coastal erosion, affecting up to 56% of Western Africa's coastlines [7]. South Africa's coastal areas are facing heightened heat waves and reduced precipitation, exacerbating the impacts of rising sea temperatures. Fish stocks are migrating to colder waters, leading to a decline in fish sizes and reduced catches, significantly impacting the livelihoods and food security of local fishing communities. By 2050, fish catches could decline by 7.7%, with some regions seeing up to a 60% decrease [2].

3.1.2 Ocean acidification

Ocean acidification is worsening in Southern Africa, especially South Africa, due to increased carbon dioxide absorption, lowering ocean pH. This threatens marine life, particularly species with calcium carbonate shells like corals and shellfish [3]. Acidification is expected to alter fish distribution, making it more difficult for fishing communities to access their traditional fishing grounds and negatively impacting their income [3].

3.1.3 Changing weather patterns

Changing weather patterns in coastal areas of Southern Africa are becoming increasingly alarming. Rising temperatures are altering rainfall patterns, leading to more frequent and severe droughts and floods. This not only affects the environment but also the livelihoods of people living in these areas. Research indicates that minimum and maximum temperatures in Southern Africa's coastal areas have been rising

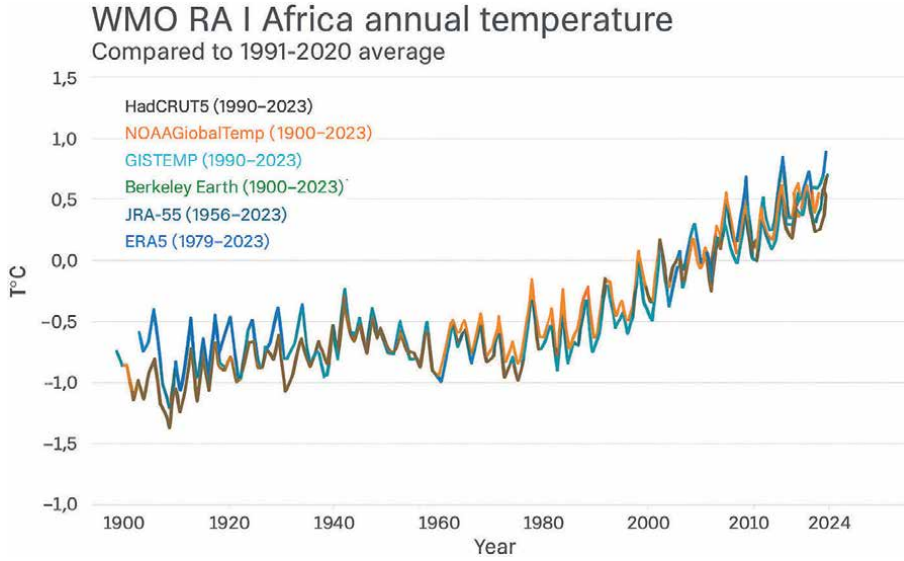


Figure 2.
Temperature difference in °C with respect to the 1991–2020 climatological period for Africa from 1900 to 2023, based on six datasets, including observational datasets [9].

over the years. Projections suggest a warming of 1.5–2.1°C by 2065, with a potential rise of 3–6°C by the century's end [8]. The temperatures have been on an upward trajectory since the 1900s to the 2000 (**Figure 2**).

Long-term records show a decadal increase of 0.2°C, three times the global average for the twentieth century [10]. Regional models suggest an increase of 3.7°C in summer and 4°C in winter by the 2080s [11].

Most projections suggest reduced precipitation across Southern Africa in the next century. By 2050, the region is expected to see significant decreases in rainfall, especially during the growing season [8]. The Southern African monsoon is likely to weaken, with fewer rainy days and less intense rainfall expected by the 2080s [8, 11]. The El Niño-Southern Oscillation (ENSO) will increase variability, making rainfall patterns even more unpredictable [7].

3.2 Marine pollution in southern Africa

Marine pollution, driven largely by land-based sources, is a major concern in Southern Africa. Over 80% of marine pollution comes from industrialization and poor waste management [3]. Key pollutants include plastics, oil spills, and chemical runoff.

3.2.1 Plastic pollution

Plastic pollution has emerged as a growing environmental crisis, rapidly escalating in recent years [12]. The global production of plastic has now surpassed the combined mass of all marine and terrestrial animals, with production doubling between 2003 and 2016. Alarmingly, between 60% and 80% of all plastic produced eventually becomes waste, much of which finds its way into the oceans, contributing to widespread marine pollution [12]. As plastics degrade, they break down into smaller particles known as microplastics, which only worsen the issue by entering the food

chain and polluting marine ecosystems. Projections indicate that, if current trends continue, oceanic plastic pollution could increase substantially by 2050 [4]. This pollution poses a severe threat to marine biodiversity, affecting at least 2141 marine species. The harmful effects include ingestion of plastic debris, entanglement, and smothering, all of which disrupt ecosystems and threaten species survival [13].

3.2.2 Chemical contaminants

Chemical pollutants, particularly from industrial and agricultural activities, are a significant source of contamination in aquatic ecosystems. The release of heavy metals, such as cadmium (Cd), copper (Cu), and lead (Pb), often exceeds safety thresholds, posing serious risks to both aquatic life and human health [14]. In South Africa's Eastern Cape, for instance, elevated concentrations of these metals in fish have raised concerns about potential health impacts for local communities [5]. Similar chemical contaminants have been detected in aquatic life across various regions, highlighting a global issue that threatens the integrity of freshwater and marine ecosystems. These pollutants not only compromise water quality but also disrupt the biological functions of marine and freshwater organisms, further exacerbating the challenges of maintaining healthy ecosystems [13, 15].

3.2.3 Urban pollution

Urban areas are significant contributors to coastal pollution, primarily through runoff from industrial, agricultural, and urban activities. Rainfall often carries toxic substances such as heavy metals, agrochemicals, and sewage into waterways, where they can accumulate and disrupt marine ecosystems [15–17]. This influx of pollutants contributes to eutrophication, a process where nutrient overload leads to oxygen depletion and the degradation of aquatic habitats. The consequences of this pollution are far-reaching, particularly for coastal communities whose livelihoods depend on healthy marine resources. Fish-dependent communities are vulnerable as pollution damages fish populations and reduces the availability of marine resources. As urbanization continues to expand, the challenge of managing and mitigating urban pollution becomes increasingly critical for both environmental and socio-economic sustainability [6].

3.3 Interactions between climate change and coastal pollution

Climate change and coastal pollution are interlinked, exacerbating each other's impacts. Flooding, intensified by climate change, can overwhelm wastewater treatment systems, releasing pollutants into the oceans [1]. As ocean chemistry shifts, pollution becomes more harmful to marine life, reducing ecosystems' ability to sequester carbon and provide other critical services [3, 6]. Coastal pollution weakens ecosystem resilience, making these areas more vulnerable to climate change impacts.

4. Climate change and marine pollution impacts on fisheries and aquatic ecosystems

Climate change in southern Africa, like other sub-Saharan regions, influences fish populations through altered habitat, temperature fluctuations, and the introduction

of non-native species. Rising temperatures, increased rainfall variability, extreme weather events, sea-level rise, and changes in ocean currents significantly affect fish biodiversity and fisheries [18]. Changes in river flow, habitat availability, and extreme weather events disrupt fish populations. While warming has led to both increased and decreased fish catches in the region, the overall risks to biodiversity are significant. Non-native species like the smallmouth bass have further threatened native fish populations, including the endangered Clanwilliam sandfish [19].

Rising temperatures in freshwater rivers and streams reduce oxygen levels and flow rates, impairing fish spawning and survival. Spawning seasons shorten, and in some species, altered metabolic rates and increased toxicity of pollutants further stress populations [20]. Some species may adapt, but rising temperatures are likely to reduce spawning habitats, especially for migratory fish [20]. While coastal warming may occasionally benefit species, migration distances increase, and competition rises as habitats shrink [21]. These changes could be harmful to fish populations globally.

Climate change also alters river flow patterns, increasing droughts and floods, which negatively impact migratory fish reproduction [20]. Higher flow rates can damage spawning grounds and reduce food availability. Increases in cyclones may cause short-term fish population declines, though recovery is possible. Overall, altered river flows threaten many fish species, increasing extinction risks. Migratory fish are at higher extinction risk than non-migratory fish.

Climate change reduces reproductive rates in various fish species, threatening population sustainability [22]. Ocean warming impacts species like blacktail seabream (*Diplodussargus capensis*), with reproductive activity restricted to specific temperature ranges [2, 3]. Coastal development and pollution further degrade breeding habitats, worsening challenges for fish populations.

Rising CO_2 concentrations acidify both saltwater and freshwater, affecting fish physiology and ecosystems [3]. Ocean acidification may reduce zooplankton growth, limiting food availability for fish and hindering migratory responses, especially for species like eels [20]. However, some migratory fish may adapt, and more research is needed to understand the long-term effects.

Climate change-related pollutants impair fish immune systems, increasing disease susceptibility and affecting fish populations. Pollution, particularly in estuaries, can lead to immunosuppression and higher disease transmission, especially for juvenile migratory fish [23]. Noise pollution from boats also disrupts fish breeding, affecting biodiversity and fisheries [24]. Overexploitation of fisheries in southern Africa exacerbates sustainability issues, as resources are harvested unsustainably and under increasing pressure from human activity.

5. Socio-economic consequences for fish-dependent communities

There are a wide range of socio-economic consequences that arise as a result of the impact of marine pollution and climate change on fish-dependent communities. We have categorized these socio-economic consequences under three broad themes, namely, economic impacts, health and social impacts, and environmental and fisheries impacts.

5.1 Economic impacts

Table 2 details the significant economic impacts on fishing communities and related sectors due to environmental challenges (climate change and marine

Category	Impact description	References
Economic Vulnerabilities	Fishers face low income, basic housing vulnerable to climate-related damage, and limited financial resources. Marine pollution affects well-being through food, recreation, and tourism.	[12, 24, 25]
Reduced Income from Fishing	Decline in fish catches reduce income and forces fishers to seek alternative livelihoods. Economic diversification is needed.	[24, 26, 27]
Economic Impact	Fisheries account for 1.3% of Africa's GDP and employ over 12 million people, with a significant multiplier effect on regional economies. Pollution could severely impact this sector.	[28]
Economic Impacts on Cultural Services	Tourism, crucial for SIDS economies, suffers due to marine pollution. High cleanup costs and the COVID-19 crisis exacerbate losses in tourism.	[12, 29]

Table 2.
Economic impacts of climate change and marine pollution.

pollution). Economic vulnerabilities highlight the struggles of fishers, who deal with low incomes, inadequate housing, and limited financial resources, all exacerbated by marine pollution affecting their livelihoods and tourism. The reduced income from fishing is alarming, as declining fish catches push fishers to seek alternative livelihoods, emphasizing the urgent need for economic diversification. The economic impact of fisheries is notable, contributing 1.3% to Africa's GDP and employing over 12 million people, with pollution threatening this vital sector. Additionally, economic impacts on cultural services illustrate how marine pollution adversely affects tourism, particularly in Small Island Developing States (SIDS), where high cleanup costs and the COVID-19 crisis have intensified losses, further undermining local economies.

5.2 Health and social impacts

There are serious health and social impacts resulting from environmental degradation in marine ecosystems (**Table 3**). Food insecurity is a critical issue, with over 79% of fishing communities reporting challenges in accessing food, as declining fish stocks jeopardize their primary source of protein. Human health is compromised by marine pollution, resulting in disease outbreaks like cholera and malaria, while plastics in the environment serve as reservoirs for pathogens.

Health risks also extend to beach users and waste pickers, who face injuries and health threats from marine debris with limited access to healthcare. Additionally, leaching of toxic chemicals from plastics exacerbates environmental and health risks, and microplastics entering the food chain pose potential health hazards for humans consuming affected marine life, particularly shellfish and small fish.

5.3 Environmental and fisheries impacts

Table 4 outlines the significant environmental and fisheries impacts stemming from marine pollution, climate change, and related ecological challenges. Pollution, particularly from plastics and ghost gear, severely depletes fish stocks and disrupts aquaculture, yet data on these effects in Africa remains scarce. Also compromised are ecosystem services, with plastic pollution harming marine organisms like corals and intensifying issues such as ocean acidification.

Category	Impact description	References
Food insecurity	Declining fish stocks threaten food security in fishing communities, with over 79% reporting food access challenges. Fish is vital for animal protein in low-income countries.	[30, 31]
Human health impacts	Marine pollution and climate change contribute to diseases such as cholera and malaria due to poor sanitation and polluted water. Plastics act as reservoirs for harmful pathogens.	[1, 32]
Health risks for beach users & waste pickers	Waste pickers and beach users face injuries from marine debris and exposure to pathogens, with limited healthcare access.	[23, 33]
Leaching of toxic chemicals	Plastics in the ocean leach harmful chemicals into the environment, exacerbating chemical toxicity in marine life and human health.	[1–3, 33, 34]
Microplastic transfer through the food chain	Microplastics ingested by marine organisms enter the food chain, potentially impacting human health, particularly in shellfish and small fish.	[1–3, 33, 34]

Table 3.
Health and social impacts on fish-dependent communities.

Category	Impact description	References
Impacts on fisheries and aquaculture	Pollution, including ghost gear and plastic waste, depletes fish stocks and affects aquaculture, including shellfish farming. Data on these impacts in Africa is limited.	[12, 24]
Impact on ecosystem services	Plastic pollution impacts marine organisms, particularly corals, and exacerbates existing pressures like ocean acidification.	[1, 3]
Environmental challenges	Unstable winds and water currents disrupt fishing practices. Invasive species like crayfish also reduce fish availability. Climate change may exacerbate these challenges.	[27, 35]
Social and economic challenges	Limited access to weather forecasts and fishing equipment makes life harder for marginalized fishing communities. Climate change exacerbates food and income insecurity.	[18, 35]
Fish supply crisis	The decline in fish supply due to overfishing and climate change exacerbates food security issues, with millions dependent on fish for protein.	[12, 24, 30, 31]

Table 4.
Environmental and Fisheries Impacts on fish-dependent communities.

Moreover, environmental challenges like unstable currents and invasive species hinder fishing practices, while social and economic challenges faced by marginalized communities are exacerbated by limited access to resources and climate change, increasing food and income insecurity. Ultimately, the fish supply crisis caused by overfishing and changing climates threatens food security for millions reliant on fish as a primary protein source.

6. Adaptation and mitigation strategies

6.1 Climate-resilient fisheries management

Fishing, a vital source of food and income, is increasingly affected by climate change, impacting fish abundance due to ocean acidification, rising sea temperatures,

decreasing pH, and rising sea levels [18]. To align with international standards, Southern African countries have initiated fisheries management policies. For instance, Malawi's Fisheries Conservation and Management Act (1997) promotes sustainable use of aquatic resources through Participatory Fisheries Management, engaging local communities in decision-making. In Zimbabwe, the Zimbabwe Parks and Wildlife Management Authority oversees fisheries to ensure ecological preservation [18].

6.2 Livelihood diversification

Governments play a crucial role in aiding sectors to adapt to climate change impacts. Fishers, particularly small-scale operators, have embraced various strategies, such as changing fishing techniques, shifting locations, targeting new fish species, and diversifying livelihoods into livestock and crop production [36]. However, challenges like land access, awareness, and funding hinder their ability to sustain these efforts [36].

6.3 Climate information systems and early warning mechanisms

Identifying climate hotspots and managing fisheries data through technologies like Geographic Information Systems (GIS) and Remote sensing (RS) is essential in enhancing adaptation in fisheries [36].

6.4 Policy and institutional responses

Southern African governments must prioritize reducing anthropogenic emissions to curb climate change. Fisheries authorities should collaborate on policies that balance community needs with ecological sustainability [36]. For example, the Benguela Current Convention (BCC) and the FAO project "Enhancing Climate Change Resilience" in Namibia, Angola, and South Africa aim to assess and adapt to climate impacts on fisheries [37].

7. Policy recommendations and future directions

To ensure the resilience and sustainability of fish-dependent communities in Southern Africa, a comprehensive policy approach is needed.

1. Strengthening local capacity and resources: Governments and international organizations should provide financial resources, training, and technical support to small-scale fishers to facilitate livelihood diversification. Policies should improve access to land, capital, and climate-resilient technologies, while integrating tailored support for women to promote gender equality and address their unique vulnerabilities.

2. Enhanced climate data and early warning systems: Developing climate information systems and early warning mechanisms is crucial for effective adaptation. Governments should invest in technologies like GIS and Remote Sensing to monitor climate impacts on fish stocks and enable timely, informed decision-making.

3. Reduction of marine pollution and ecosystem protection: Stronger regulations are needed to combat marine pollution, particularly plastics and chemicals. Policymakers should focus on stricter waste management, expanded recycling, and promoting cleaner industrial practices. Conservation strategies like marine protected areas and regulating overfishing should be prioritized.

4. Promotion of participatory fisheries management (PFM): Community-based approaches such as Participatory Fisheries Management (PFM) should be expanded across the region. Involving local communities in decision-making ensures policies reflect their needs, balancing ecological sustainability with socio-economic realities.

5. Research and sustainable fisheries management: Future research should focus on the socio-economic impacts of climate change and marine pollution on fish-dependent communities, particularly in areas like Seychelles. Integrating local ecological knowledge with modern fisheries management practices is vital for developing region-specific strategies.

6. Regional cooperation and policy coordination: To address the cross-border impacts of climate change and marine pollution, regional cooperation is essential. Governments should align climate resilience efforts, share best practices, and pool resources through platforms like the Benguela Current Convention to strengthen policy coordination and implementation.

8. Conclusion

The fisheries sector in Southern Africa is vital for the food, income, and employment of millions in coastal and inland communities. However, climate change and marine pollution are increasingly threatening the sustainability of these fisheries and the livelihoods of those who depend on them. Rising ocean temperatures, acidification, and unpredictable weather are disrupting fish populations, while pollution from plastics and chemicals further damages marine ecosystems. These environmental changes are severely impacting food security, income, and well-being, particularly in small-scale fishing communities that rely heavily on local fish stocks. The socio-economic impacts are profound, with increased food insecurity and economic instability. Vulnerable groups, such as women and children, are disproportionately affected by these challenges. The decline in fish stocks forces many fishers to seek alternative livelihoods, exacerbating regional economic instability. To mitigate these threats, targeted interventions are crucial, focusing on pollution reduction, marine biodiversity protection, and enhancing resilience to climate change. Effective action is needed to ensure the long-term viability of Southern Africa's fisheries, protecting both ecosystems and the people who depend on them. Additionally, addressing gaps in adaptation and mitigation strategies is essential. Key challenges include inadequate funding, limited access to resources for small-scale fishers, and insufficient climate data. Research is needed to understand the socio-economic impacts and identify sustainable management practices. Policymakers must focus on supporting local communities with adaptive solutions, climate information, and participatory decision-making. Coordinated efforts among governments, international organizations, and local communities are necessary to close these gaps and secure the future of Southern Africa's fisheries.

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Marine Pollution Crisis – Understanding Impacts and Innovating Solutions examines one of the most pressing environmental challenges of our time: the escalating threat of marine pollution and its far-reaching consequences for ecosystems and human societies. Drawing on multidisciplinary perspectives, the book offers a compelling synthesis of the key types of marine pollutants—ranging from microplastics and heavy metals to nutrient runoff—and critically examines their impacts on biodiversity, fisheries, and coastal communities. With a global outlook and regional case studies, the volume highlights the interconnectedness of ocean health and sustainable development. Readers will discover discussions on environmental monitoring, socio-economic vulnerability, pollution governance, and adaptation strategies in response to climate change. The book's strength lies in its integrative approach, combining environmental science, policy analysis, and sustainability thinking to propose practical pathways for mitigating marine pollution. Ideal for researchers, students, policymakers, and practitioners in marine science, environmental studies, and resource management, this edited volume provides valuable insight into marine environmental sustainability, climate-resilient coastal livelihoods, and evidence-based decision-making. It makes a meaningful contribution to the ongoing global discourse on sustainable oceans, making it a timely and essential resource for those committed to protecting marine ecosystems and promoting the health of our planet.

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