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INVESTIGATING THE ENVIRONMENTAL AND SOCIO ECONOMIC EFFECTS OF MARINE POLLUTION

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CERTIFICATION

This is to certify that this report is a detailed account of the Project undertaken by CHUKWUDI CHIEJINE, MAMA HENTRY, IKEH VICTORY with matriculation number ENG2006343,ENG2002372,ENG2006346 to the Department of Marine Engineering, Faculty of Engineering, University of Benin, in partial fulfillment for the requirements of the award of Bachelor of Engineering (B.ENG) degree in Marine.

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DEDICATION

I wholeheartedly dedicate this report to my Heavenly Father and my ever supportive, understanding and loving parents and also to my loved ones for their support and care.

ACKNOWLEDGEMENT

My appreciation goes to Almighty God for His guidance and Divine mercy; I deeply appreciate our parents for their unending love and care. I also acknowledge my loved ones for their unwavering love and support. I profoundly appreciate and acknowledge the immense contribution of my supervisor Dr.H.O.Egware and the entire members of staff of the Department of marine Engineering.

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CHAPTER 0NE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Marine pollution represents a significant threat to global biodiversity and sustainable development. The introduction of pollutants—ranging from discarded plastics to industrial chemicals and nutrient-rich agricultural runoff—disrupts fragile marine ecosystems, leading to habitat degradation, species endangerment, and the overall loss of biodiversity (Barnes & Hughes, 1999). This complex problem has been a subject of increasing concern since foundational environmental texts highlighted the pervasive nature of pollutants and their far-reaching consequences (Carson, 1962).

The issue is not confined to a single source. Roughly 80% of all marine pollution originates from land-based activities, a finding corroborated by reports from the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) . A significant portion of this is plastic waste, with an estimated millions of metric tons entering the ocean annually (Jambeck et al., 2015). These pollutants undergo a journey from land to sea, often traveling through rivers and waterways, where they accumulate in coastal zones before dispersing into the open ocean.

The consequences for marine life are profound. Micro-plastics, for example, are easily ingested by marine organisms, from microscopic zooplankton to large filter-feeding whales, leading to internal injuries, starvation, and a pathway for toxic chemicals to enter the food web (Koelmans et al., 2014). This process of bio-accumulation and bio magnification means that toxins become more concentrated at higher trophic levels, posing a severe risk to apex predators and, ultimately, to human consumers of seafood.

1.2 AIM AND OBJECTIVE OF THE STUDY

1.1.1 AIM

To comprehensively analyze the environmental and socioeconomic effects of marine pollution.

1.3 OBJECTIVE

1. To identify and categorize the major sources and types of marine pollution. This involves a systematic review of land-based sources (e.g., agricultural runoff, industrial effluent, plastic waste from cities) and sea-based sources (e.g., oil spills, shipping activities, ocean dumping).

2.To investigate the ecological impacts of pollution on marine ecosystems. This objective focuses on the biological effects, such as the destruction of coral reefs, the decline of fish populations, and the harm to seabirds and marine mammals from entanglement and ingestion of plastics and other debris.

3**.** To assess the socioeconomic consequences of marine pollution**.** This objective examines the human-related impacts, including the financial losses to the fishing and tourism industries, the costs of cleanup and waste management, and the potential risks to human health from contaminated seafood.

4. To analyze the mechanisms of bio-accumulation and bio magnification of pollutants in the marine food web.

5. To propose and evaluate potential solutions and policy recommendations to mitigate marine pollution.

1.4 SCOPE/LIMITATIONS OF THE STUDY

1.1.2 SCOPE

This project will comprehensively investigate the environmental and socioeconomic effects of marine pollution, adhering to the following specific parameters:

.Geographic Focus: The study will primarily focus on marine pollution and its impacts on coastal ecosystems and communities globally, with particular attention to trends and case studies relevant to highly impacted regions. It will not delve into the unique characteristics of deep-sea or polar marine environments unless directly related to broader pollution trends.

.Pollutant Types: The research will concentrate on the effects of major marine pollutants, specifically plastic pollution (including macro and micro-plastics) and chemical pollutants (such as heavy metals and persistent organic pollutants from industrial and agricultural sources). Other forms of pollution, such as noise, thermal, or light pollution, will be acknowledged but not be the primary focus of the detailed analysis.

.Impact Areas: The project will analyze two main categories of effects:

a. Environmental Impacts: This includes the degradation of marine habitats (e.g., coral reefs, mangroves), the health and mortality of marine organisms (e.g., fish, seabirds, marine mammals), and disruptions to marine biodiversity.

b.Socioeconomic Impacts: This will cover the consequences for human activities and well-being, specifically focusing on the fishing industry, coastal tourism, and potential human health risks associated with seafood consumption.

.Research Methodology: The study will be conducted as a comprehensive literature review, synthesizing information from existing academic journals, scientific reports from international organizations (e.g., UNEP, NOAA), and reputable environmental studies. It will also involve secondary data analysis to interpret existing quantitative information. This project will not include primary data collection through fieldwork, laboratory experiments, or direct surveys.

Temporal Focus: The research will primarily draw on studies and data from the last two decades (2005-present) to ensure the findings reflect contemporary challenges, policy responses, and scientific understanding of marine pollution. Historical pollution events prior to this period will only be referenced if they provide essential context or foundational understanding.

.Solutions and Recommendations: While analyzing the problem, the project's scope will also extend to proposing potential mitigation strategies and policy recommendations. However, it will not involve the development, implementation, or detailed feasibility study of new technologies or specific policy interventions.

1.4 LIMITATIONS

The effects of marine pollution with the scope we've defined, the primary limitations would include:

1. Reliance on Secondary Data: The project is limited by the availability, quality, and biases of existing research. Since it does not involve fieldwork or primary data collection, it cannot generate new information or fill gaps in current knowledge.

2. Geographic and Temporal Constraints: By focusing on a specific region or a particular time frame, the findings may not be fully applicable to other areas or different historical periods. The conclusions are confined to the defined scope.

3 .Difficulty in Establishing Causality: While the project can demonstrate strong correlations between pollution levels and environmental or socioeconomic effects, it may not be able to definitively prove causality without experimental data.

4. Incomplete Scope of Pollutants: By concentrating on plastics and chemical pollutants, the project overlooks other significant forms of marine pollution, such as noise, thermal, or biological pollution, which could have their own unique impacts.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Context of Marine Pollution in Nigeria

When examining the history of maritime pollution in Nigeria, we encounter a story that is closely connected to the country's diverse natural heritage and the challenges posed by contemporary industrialization. Nigeria has an extensive coastline spanning over 850 kilometers along the Gulf of Guinea, which has been abundantly blessed with valuable marine resources that have supported the lifestyles and cultures of its people for many years. However, behind the abundance of marine resources, there is a narrative of progressive decline, characterized by the growth of industries, urban development, and a lack of responsible environmental management. The origins of marine pollution in Nigeria may be attributed to the commencement of industrialization and the fast expansion of metropolitan areas, which resulted in an increase in human activities that unintentionally impacted the coastal ecosystem. During the 20th century, as Nigeria pursued economic growth and industrialization, the pressures on its coastal ecosystems increased. The introduction of industrial effluents, untreated sewage, oil spills, and solid waste into the formerly untouched waters of the Atlantic Ocean has caused significant disruption to the fragile marine ecosystems and has negatively impacted the well-being of coastal populations who depend on fishing and farming. The commencement of oil exploration and production in the Niger Delta area during the mid-20th century marked the beginning of a new phase in Nigeria's environmental narrative. Although oil provided significant prosperity and economic prospects, it also brought a multitude of environmental problems. The region's marine ecosystems have been significantly impacted by oil spills, pipeline vandalism, and gas flaring over the course of many decades. This has resulted in severe damage to fish populations, mangrove forests, and coral reefs, and has deprived coastal people of their traditional means of sustenance.

The historical backdrop of maritime pollution in Nigeria is intricately linked with wider geopolitical factors and the enduring impact of colonialism . The exploitation of Nigeria's natural resources, such as oil, by foreign nations during the colonial period established the foundation for the current environmental difficulties that Nigeria confronts. The enduring consequences of colonial exploitation, together with prolonged periods of political instability and corruption, have impeded endeavors to efficiently oversee and alleviate the repercussions of maritime pollution. Not with standing these difficulties, Nigeria has been actively engaged in tackling maritime pollution. In recent years, the government has implemented legislation and regulations with the objective of mitigating pollution and safeguarding the marine ecosystem . Nevertheless, the enforcement of regulations has often been inadequate, and the execution of policies has not met expectations, resulting in significant deficiencies in the nation's environmental governance structure. In the 21st century, Nigeria is facing the challenge of balancing economic growth and environmental sustainability. The historical background of maritime pollution serves as a reminder of the pressing need for coordinated efforts. The need of embracing a comprehensive strategy for marine conservation is highlighted by the consequences of previous negligence and misadministration. This approach should effectively reconcile the demands of economic advancement with the necessity of preserving our invaluable marine ecosystems for the benefit of future generations. Nigeria can only achieve a cleaner and healthier marine future by collectively committing to sustainable development and environmental care.

2.2 THE CURRENT STATE OF MARINE POLLUTION

Observations and Trends in Nigeria In Nigeria, a country with a vast and varied coastline, the issue of marine pollution is a significant concern. The complex interaction between human activities and delicate aquatic ecosystems has created a series of difficult problems, exposing noticeable patterns and disturbing tendencies that need careful analysis. Nigeria, a country characterized by lively coastal towns and thriving maritime operations, has a multifaceted interaction of elements that contribute to the present condition of marine pollution. The formerly clear waterways, which used to perfectly mirror the blue sky, now exhibit the repercussions of rapid industrialization, urbanization, and the unstoppable advancement of technology. The escalation of businesses along coastal areas in Nigeria is closely linked to the patterns of marine pollution. The contaminants and chemicals included in the effluents released by industrial companies ultimately enter the ocean. Consequently, the formerly transparent seas now exhibit the presence of oil spills, heavy metals, and other pollutants that endanger the fragile equilibrium of marine ecosystems. The proliferation of marine pollution in Nigeria is exacerbated by the rapid growth of the population and the subsequent rise in human activities along the coastline. The impact of human activity on the maritime environment is clearly evident, with busy ports and growing coastal communities. The deterioration of the coastal area is caused by improper garbage disposal, insufficient sewage treatment, and unrestricted dumping of plastic debris. Oil spills, a frequent source of sorrow in Nigeria's maritime history, have left a somber mark on the problem of marine pollution. The Niger Delta, an area closely associated with the country's abundant oil resources, displays the visible evidence of the negative effects caused by many years of oil exploration . Spills, whether they are significant or subtle, have a lasting impact on the biodiversity of these waterways, influencing the aquatic ecosystem and the livelihoods that rely on the abundance of marine resources. Marine contamination in Nigeria is not limited only to local sources. The phenomenon of globalization is responsible for the discreet transportation of pollutants across borders, and marine litter has become as a worldwide symbol of environmental decline . Plastics, which are widely used for their convenience, travel long distances to reluctantly settle in Nigerian seas, adding to a larger ecological imbalance. A midst these unsettling tendencies and patterns, there is an urgent need for careful management and sustainable methods. The stories recounted by the waves, testifying to the outcomes of disregard, call for a future in which the forces of advancement and ecological conservation coexist in perfect balance. Comprehending the present condition of marine pollution in Nigeria is not only an act of observing; it is a demand for action, an opportunity to establish a sustainable course that protects the seas for future generations.

2.3 ECONOMIC THEORIES RELEVANT TO MARINE POLLUTION

Within the complex field of environmental economics, the economic theories pertaining to marine pollution function as guiding principles, illuminating the delicate interplay between human actions, environmental deterioration, and resulting economic impacts. These theories provide a sophisticated framework for understanding the intricate interaction between market pressures, regulatory systems, and ecological factors in the field of marine pollution.

Tragedy of the Commons

An influential theory pertaining to marine contamination is the "Tragedy of the Commons," proposed by economist Garrett Hardin. The tragedy of the commons is an economic theory positing that people have a tendency to misuse communal resources to the point that demand surpasses supply, resulting in the unavailability of these resources for the collective. In **1968**, **Garrett Hardin**, an evolutionary scientist, wrote "The Tragedy of the Commons" in the peer-reviewed journal Science. This article specifically addressed the increasing worry of overpopulation. Hardin used an example of land utilized for sheep grazing, which was first proposed by the early English economist **William Forster Lloyd.** A common resource, sometimes known as a "commons," refers to any resource, such as water or land that offers real advantages to users without any one having exclusive ownership rights. The tragedy of the commons refers to an economic dilemma in which individuals exploit a shared resource, causing harm to the collective well-being of society. When a person prioritizes their own self-interest, it may lead to excessive consumption that harms everyone. This situation may lead to insufficient investment and complete exhaustion of a common resource. This idea well captures the difficulty presented by communal, unrestricted resources such as seas. Without well-defined property rights or efficient regulation, people driven by their own self-interest tend to over exploit shared resources, resulting in their deterioration. When it comes to maritime pollution, the Tragedy of the Commons highlights the danger of uncontrolled and unlimited human activity, which leads to the over use and pollution of marine ecosystems.Hardin, G. (1968)

2.4 Environmental Impacts of Marine Pollution

Marine pollution has far-reaching and devastating environmental impacts that affect marine life, ecosystems, and even human communities that depend on the ocean. Here's a detailed breakdown of the environmental impacts of marine pollution:

1.Harm to Marine Biodiversity

a. Toxicity to Marine Species

1. Chemical pollutants such as heavy metals, pesticides, and industrial chemicals (e.g., PCBs) are toxic to marine organisms.

2 Oil spills coat marine animals like seabirds and marine mammals, impairing their ability to move, insulate, and feed.

3.Bio-accumulation and biomagnification occur as toxins build up in organisms and become more concentrated up the food chain, ultimately affecting top predators and even humans.

b. Plastic Ingestion and Entanglement

1.Marine animals (e.g., turtles, seabirds, fish) often ingest micro-plastics and larger plastic debris, mistaking them for food.

2.Ingested plastics can lead to starvation, internal injuries, and death.

3.Entanglement in fishing gear (ghost nets) and plastic waste leads to **restricted** movement, injury, or drowning.Fossi, M. C., et al. (2018).

2. Degradation of Marine Habitats

a. Coral Reefs

1.Coral reefs are sensitive to chemical pollutants, nutrient overloading, and sedimentation.

2. Pollutants like sunscreen chemicals (oxybenzone) and oil residues can cause coral bleaching and death.

3.Nutrient pollution encourages algal overgrowth, smothering coral reefs and reducing oxygen.

b. Seagrass Beds and Mangrove

C. Runoff with fertilizers and pesticides can damage these ecosystems, which are crucial for nursery habitats.

Sedimentation and toxic pollutants reduce light penetration and poison plant life.

3. Eutrophication and Dead Zones

a Excess nutrients (mainly nitrogen and phosphorus from agricultural runoff and sewage) cause algal blooms.

b. When algae die, their decomposition consumes oxygen, leading to hypoxia (low oxygen levels) or anoxic conditions (no oxygen).

c. Creates **“**dead zones**”** where most marine life cannot survive. The Gulf of Mexico is one of the most well-known examples.

4. Disruption of the Food Chain

a Micro-plastics and toxins can infiltrate the **base of the food web**—plankton and small fish.

b This affects the health and reproductive ability of species up the food chain, including large predators and humans.

c Impacts **fisheries** and **aquaculture**, leading to reduced catches and food insecurity.

5.Ocean Acidification and Climate Change Interaction

a While marine pollution does not directly cause acidification, **chemical pollutants** can worsen the impacts.

b Acidification (mainly from CO_2 absorption) combined with pollutants increases stress on marine organisms, especially those with calcium carbonate shells like mollusks and corals.

6. Introduction of Invasive Species

a Ballast water discharge from ships can introduce non-native species.

b These species may outcompete local species, reduce biodiversity, and change ecosystem structure.

7. Impact on Human Communities and Coastal Economies

a Polluted beaches and waters affect tourism, recreation, and fishing industries.

b Contaminated seafood leads to health risks (e.g., mercury poisoning, shellfish toxins).

c Coastal communities face economic and cultural losses.

8. Long-Term and Global Effects

a Marine pollution travels via **currents** and **wind patterns**, affecting even remote areas like the Arctic and deep-sea ecosystems.

b.Pollution in one region can have **cascading effects** on global biodiversity, fisheries, and climate regulation.

.Key Pollutants in Marine Environments

Pollutant Type	**Sources**	**Effects**
Plastics	Waste mismanagement, shipping	Ingestion, entanglement, habitat damage
Oil	Spills, drilling, runoff	Toxicity, coating, reproductive harm
Heavy metals	Industry, mining, runoff	Neurotoxicity, bioaccumulation
Nutrients	Agriculture, sewage	Algal blooms, hypoxia
Pathogens	Sewage, livestock waste	Disease in humans and animals

2.4 The Environmental and Socioeconomic Impacts of Marine Debris and Pollution in Nigeria

The environmental and socioeconomic impacts of marine debris are enormous. “There are countless losses for industries such as commercial fishing, shipping, recreation and tourism, caused wholly or partly by various types of marine debris” (UNEP, 2016). Outside the above mentioned issues, marine debris equally affects human health and creates navigational hazards, which in turn jeopardizes smooth movement of boat and ship, in the waterways. To substantiate this, (GESAMP, 2015) re echoed that the presence of macro debris has social and economic impacts, reducing ecosystem services as well as marine species, and compromising perceived benefits. This incessant attack on the ecosystem and existence of non-degradable elements called debris has reduced drastically the aesthetic value of environment and seaways, and by extension, impacted negatively to the economic growth of the nation. This is the situation at hand, even when it is evaluated that more than two third of the worldwide gross marine products depend on a healthy marine ecosystem, which is already under pressure. Furthermore, plastic debris has turned out to be undermining the long term economic prospects of the nation. In fact, profit expected from fishing, aquaculture and agriculture is affected due to direct or indirect marine pollution. Regarding the health impact of marine debris, it has been proven that consumption of macro plastics by human is detrimental. Hence, micro plastics are carriers of infectious agents and harmful bacteria (Lu et al; 2019). No wonder why it was advised lately that the use of plastic foil in serving food should be avoided. This is because “the said foil can absorb organic pollutants like poly chlorinated biphenyls and organo chlorine pesticides that are dangerous to human health” (Elenl Aretoulakl et. al; 2021). “Its toxicological consequences are capable of reducing the immune system, causing suppression of hormones and leading to abnormal inflammatory responses and developmental disabilities” (Carney & Eggert, 2019). This shows that micro plastics in the ocean or river spur bacteria and have the potential or detrimental effects on both ecological community or environment and human life. The next section will be stating how to cope with the menaces of debris and pollution, and possible ways or measures they can be prevented, for environmental stability and sustainability.

2.5 Marine Debris and Pollution Coping measures and Prevention, for environmental sustainability

Marine debris thrives and obstructs seaways and biosphere, due to the insensitivity of the Nigeria government on the need to implement marine policies and laws, with adequate sanctions to punish those who go about littering the environment. “The way and manner in which the government handles the offenders without any intensive punishment is said to be the reason maritime challenges continued to thrive” (Ezugwu

& Ekiyor, 2023). In other words, there are marine related issues today due to the trivial nature of the sanction attached to the maritime offenses or lack of implementation of maritime laws and policies. Apart from this negligence from the government, Nigerian populaces are to be blamed too, as they often involve themselves in illegal bunkery, gas flaring or emission, waste littering and other piratic activities that bring about environmental degradation and pollution. These practices persisted, as commensurate incentives for collection and recycling of the waste items have not been provided. To reduce or control or prevent marine debris and pollution attached to it, the government ought to significantly remunerate or give incentive to the factory owners, who are ready for recycling of the waste materials and waste management team, to clean up the environment regularly. Provision of adequate and easily accessible waste disposal facilities in all nooks and crannies of the environment can also encourage the end users of the products packaged with non-decomposable materials to dispose of them responsibly (UNEP, 2016). After all, these domestic wastes can be used to generate energy or electricity for societal use.

More so, there is a need to sensitize and educate the public on why they must reduce or prevent waste materials from entering the marine environment. This kind of awareness campaign, if targeted on a range of audiences in the public or private sector, will help in mitigating the activities that are significant components of recorded marine debris items, such as plastic bags, bottles or cigarette butts. It will equally bring about behavioural change in both children and adults. This gives credence to the position of (Elenwo & Akankali, 2015) that a "sustained enlightenment campaign/advocacy on safer attitudes towards reducing pollution of the marine environment, is of great essence, in fighting against marine debris and environmental degradation". Consequently, the issues of marine debris and pollution will be effectively addressed, when these awareness tools are built on the mindsets of Nigeria government, schools, churches, communities and masses, to always adhere to the ethics and ensure that the environmental laws and policies are adequately carried out.

2.6 MARINE PLASTIC LITTERING: A REVIEW OF SOCIO ECONOMIC IMPACTS

Fig 1 MARINE PLASTIC LITTERING

Marine plastic littering resulting from human activity constitutes an increasingly significant global issue. The use of plastic materials is steadily rising due to their light weight, durability and versatility. However, they are also low cost, leading to a higher chance of them being disposed of and consequently ending up in the marine environment. Furthermore, their low decomposition rates as a consequence of the aforementioned properties, result in plastic accumulation. This paper reviews marine plastic pollution and highlights the progress of research on its socioeconomic consequences, within the scope of ultimately developing a marine sustainability and protection approach. To that end and after a systematic inclusion/exclusion process of publications retrieved from the Scopus and Google Scholar bibliographic databases, six hundred and sixty-six (616) papers were selected for participation in the study. As far as economic implications are concerned, the impact of marine plastic pollution on marine-based sources of income, such as fishing, aquaculture, marine tourism and merchant shipping, was studied. Next, this paper evaluates the dire social repercussions in terms of human food safety and health, threat of injury or death and intrinsic natural value loss. Finally, prevention measures in the form of legislation and coping strategies at an international level are discussed.Agalianos, K. (2021).

2.7 Plastic Pollution in the Pacific Ocean

The Pacific Ocean is home to the most significant and well-known example of marine plastic pollution: the Great Pacific Garbage Patch (GPGP). Often misunderstood as a floating island of trash, the GPGP is a vast area of the ocean where plastic debris has accumulated due to a unique system of currents. Understanding this phenomenon requires a detailed look at its formation, composition, and the profound environmental and socioeconomic impacts it has.

1. Formation and Composition

The Great Pacific Garbage Patch is not a single, visible patch of solid trash. Instead, it is a diffuse "soup" of plastic debris, with some areas having a higher concentration than others. Its formation is the result of the North Pacific Subtropical Gyre, a massive system of circular ocean currents. This gyre acts like a whirlpool, drawing in floating debris from the surrounding currents and trapping it in a concentrated area between California and Hawaii.

a.Formation

The GPGP's existence is a direct result of a massive system of rotating ocean currents called the North Pacific Subtropical Gyre. Think of a gyre as a slow-moving, enormous whirlpool. This particular gyre is formed by four major ocean currents: the North Equatorial Current, the Kuroshio Current, the North Pacific Current, and the California Current. They all move clockwise, trapping any floating debris, including plastic, within their calm center. This process is like a drain in a bathtub, but on a massive scale.Over many years, plastic and other debris from coastal communities and maritime activities in North America and Asia get caught in these currents. It can take several years for the plastic to travel to the gyre's center, where it becomes permanently trapped. The GPGP is divided into two distinct areas: the Western Garbage Patch near Japan and the Eastern Garbage Patch between Hawaii and California.(Lebreton, L., et al.(2018).

b.Composition

The GPGP's composition is its most misleading aspect. While it's often imagined as a literal dump, it's actually more like a "plastic soup." The vast majority of the debris is made up of micro-plastics—tiny fragments of plastic less than 5mm in size. These micro-plastics are virtually invisible to the naked eye and are suspended in the water column, not just floating on the surface.

While micro-plastics make up the overwhelming majority of the number of pieces in the patch (up to 94% of the total estimated 1.8 trillion pieces), the mass of the patch is dominated by larger items. A study from The Ocean Cleanup found that around 46% of the GPGP's mass is composed of abandoned, lost, or discarded fishing gear, known as "ghost nets." The remaining mass consists of larger items like plastic bottles, buckets, ropes, and other consumer plastics. This shows that while micro-plastics are more numerous, the heavier, larger items—especially those from the fishing industry—contribute the most to the patch's total weight.

The plastic in the GPGP comes from two main sources:

.Land-based sources:Land-based sources are the primary culprits behind marine plastic pollution, accounting for an estimated 80% of all plastic that enters the ocean. This isn't just about people littering on beaches; it's a complex issue tied to waste management infrastructure, consumer behavior, and natural processes.

Here's a detailed look at how plastic makes its way from land to the sea:

1. **Mismanaged Waste:** This is the single largest contributor. In many parts of the world, particularly in countries with limited waste management infrastructure, a significant portion of plastic waste is not collected or disposed of properly. This mismanaged waste includes everything from plastic bags and bottles to single-use packaging. It ends up in open dumps, on streets, or in unofficial dumpsites, where it's easily exposed to the elements.

2.Riverine Transport

Rivers act as major conduits for plastic pollution. A large portion of the plastic from mismanaged waste gets carried by wind and rain into streams and, eventually, into rivers. Studies have shown that a relatively small number of the world's rivers, primarily those that flow through densely populated areas with poor waste management, are responsible for a disproportionately large amount of the plastic entering the ocean. These rivers effectively act as conveyer belts, transporting plastic from inland cities and towns directly to the sea.Meijer, L. J. J., et al. (2021).

3. Stormwater Runoff

In urban and suburban areas, a key pathway for plastic is storm water runoff. When it rains, water flows over paved surfaces like streets and parking lots, picking up litter and other debris along the way. This runoff often carries plastic waste into storm drains, which typically empty directly into local rivers and, ultimately, the ocean. This is a significant source of both macro plastics (larger items) and micro-plastics (tiny fragments).Li, Y., et al. (2020)

4. Direct Littering

While it may seem obvious, direct littering is a major source of pollution. People discarding plastic items on the ground, especially near coastlines, lakes, and rivers, contributes directly to the problem. These items can be easily swept into the water by wind or tides. This includes everything from cigarette butts (which contain plastic filters) to food wrappers and plastic bottles.Ryan, P. G., et al. (2009)

5. Microfiber Pollution

A less visible but equally pervasive source is microfiber pollution. Synthetic textiles, such as those made from polyester and nylon, shed tiny plastic fibers when they are washed. These microfibers are too small to be filtered out by most wastewater treatment plants and end up in rivers and oceans. They are a significant source of micro-plastics and can be ingested by a wide range of marine life.Browne, M. A., et al. (2011)

6. Industrial and Agricultural Sources

Plastic pollution also originates from various industrial and agricultural activities:

. **"Nurdles"**: These are tiny plastic pellets, the raw material used to manufacture most plastic products. Spills during transport or at production facilities can release nurdles into the environment, where they can easily wash into the ocean.Thompson, R. C., et al. (2004).

. **Agricultural plastic**: Plastic is used in agriculture for things like greenhouse covers and mulch films. As these items break down, they release micro-plastics into the soil, which can then be transported to waterways through agricultural runoff.Chung, S. Y., & Lee, W. (2018).

. **Tire dust**: The abrasion of vehicle tires on roads releases tiny plastic particles, which are a source of micro plastic pollution that enters the environment through storm water runoff.P. A. J. S. P. (2019).

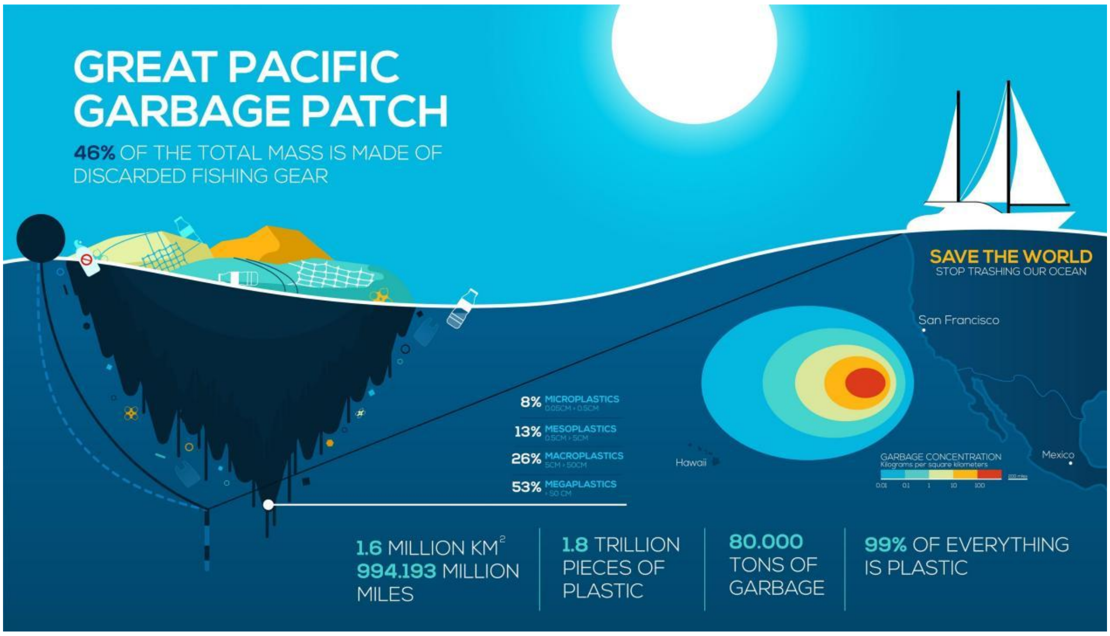

Fig 2 THE GREAT PACIFIC GARBAGE PATCH

2.8 Environmental Consequences of Oil Spills on Marine Habitats and the Mitigating Measures—The Niger Delta Perspective

A number of researches have been carried out on hydrocarbon polluted marine environment. The studies include Abii and Nwosu (2009) study on the effects of oil spillage on soil and Aghalino (2000) on the negative impact of oil activities on the marine wild life, soil, air, water and the ecosystem of communities.

The ecological effects include brownish vegetation and soil erosion, dead and extinction of marine wild life, diminishing resources of the natural ecosystem, fertile land turned barren and adverse effect on the life, health and economy of the people. In Amadi and Ue Bari (1992) study in the rainforest ecosystem in Nigeria, soil and microbiological properties were evaluated 17 years after oil spillage to assess the effects of oil and interrelationship between the hydrocarbon utilizing and nitrifying microorganisms in the marine ecosystem. The study showed that organic carbon, total nitrogen, carbon/nitrogen ratio, available phosphate and exchangeable potassium were high at moderate and high impacted zones. Also the distribution of aerobic petroleum hydrocarbon utilizing fungi and bacteria showed a lesser condition at the moderately impacted zone than at the highly impacted zones.

The effect of crude oil pollution on marine environment, soil fertility and the growth of plants and uptake of nutrients were investigated by Agbogidi, Eruotor and Akparabi (2007) by growing corn on a soil polluted by crude oil. The soil was analyzed for organic carbon, total and available nitrogen, extractable phosphate, and exchangeable potassium, calcium, iron and manganes after each cropping. It was observed that germination and yields were drastically reduced as the level of pollution increased. At 4.2 percent crude oil pollution level, the average reductions were 50 percent in germination and 92 percent in yield. The amount of organic carbon, total nitrogen, extractable phosphate, and exchangeable potassium, iron and manganese increased in the soil with level of crude oil addition, while extractable phosphate and exchangeable calcium were reduced. The poor growth was attributed to suffocation of plants caused by exclusion of air by oil and exhaustion of oxygen by increased microbial activity, interference with plant-soil-water relationships and toxicity from sulfides and excess manganese produced during the decomposition of the hydrocarbons.

Wokocha, Emeodu and Ihenko (2011) examined the impact of crude oil spillage on the ecosystem, soil properties and food production in Ogba/Egbema/ Ndoni Area in Rivers State, Nigeria. The results showed that the pH status of soil in heavily contaminated and moderately contaminated zones varied from acidic (pH 4.0) to neutral (pH 6.0). The chemical properties of soil indicated that percentage organic matter increased from 1.34 to 2.62, available phosphorus decreased from 15 ppm in control to between 7.34 and 5.42 in soil polluted with high level of crude oil. The result was in line with Amadi and Ue Bari (1992), and Ogboghodo, Osemwota, Iruaga and Chikor (2000).

Andrade, Cavelo, Vega and Marcet (2004) in an experiment on the effect of prestige oil on marine salt marsh ecosystem soils in the coast of Galicia (Northern Spain) revealed that oil pollution altered both physical and chemical soil properties, lowered porosity, and increased resistance to penetration and hydrophobicity. The crude oil spillage affected the physical, chemical and biological properties of soil and the entire marine ecosystem, resulting in low food production by reducing the nutrients availability in the soils through increased soil acidity and toxicity of crude oil fractions. The experiment on the effect of poultry manure on maize planted on crude oil polluted soils showed that percentage growth rate in plant height and yield decreased with increase in crude oil contamination (Ogboghodo et al., 2004).

Crude oil spillage also suppresses seed germination, regeneration and restoration and caused cellular and stomata abnormalities (Gill & Sandota, 1976). Ekundayo, Emede and Osayande (2001) confirmed that in crude oil polluted soils, possibility of grain yield is significantly reduced by 95 percent compared with the control. In a study of agricultural land in an oil producing area around Qua Iboe River in the Eastern Niger Delta of Nigeria, the fouled loamy soil samples polluted by crude oil were treated using chemical degreasers and detergents (Essien & John, 2010). The result of the treatments showed a significant effect on soil properties and crop growth parameters; however recovery level was significantly higher than the level of degradation, except in infiltration rate. Soil pH increased by 26% in fouled soil, attributed to bacterial biodegradation of crude oil under the anaerobic conditions present in the soil macro and micro-pores, and indicated the tendency of crude oil spills to buffer acidic soil to neutral. Hydraulic conductivity with 45% - 67% reduction from 82.24 cm/day in the control soil to 39.6 cm/day in polluted soil confirmed the blockage of polluted soils micropores by oil films. Crop growth, indicated by root elongation, diminished to 7.4 ± 0.64 cm in polluted soil ecosystem compared to13.47 ± 6.40 cm in the control soil ecosystem.

2.8.1 The marine Habitat

A habitat is an ecological or environmental area inhabited by one or more living species. Marine habitats can be divided into coastal and open ocean habitats.

Coastal habitats are found in the area that extends from as far as the tide comes in on the shoreline out to the edge of the continental shelf. Most marine life is found in coastal habitats, even though the shelf area occupies only seven percent of the total ocean. Fig2.2 describes the configuration and composition of the continental shelf showing the coastline, the continental slope, the continental rise and the ocean cavity.

Oil spills frequently kill marine mammals such as whales, dolphins, seals, and sea otters. Oil coats fur of otters and seals, leaving them vulnerable to hypothermia. Even when marine mammals escape the immediate effects, an oil spill can contaminate their food supply.

2.8.2 Beaches, Marshlands, and Fragile Aquatic Ecosystems

Oil spills coat everything they touch and become unwelcome with long-term effects on parts of every ecosystem they have contact with. When an oil slick from a large spill reaches a beach, oil coats and clings to every rock and grain of sand.

If the oil washes into coastal marshes, mangrove forests, or other wetlands, fibrous plants and grasses absorb oil, which can damage plants and make the area unsuitable as wildlife habitat (Fukuyama et al., 2014).

When oil eventually stops floating on the water’s surface and begins to sink into the marine environment, it can have similar damaging effects on fragile

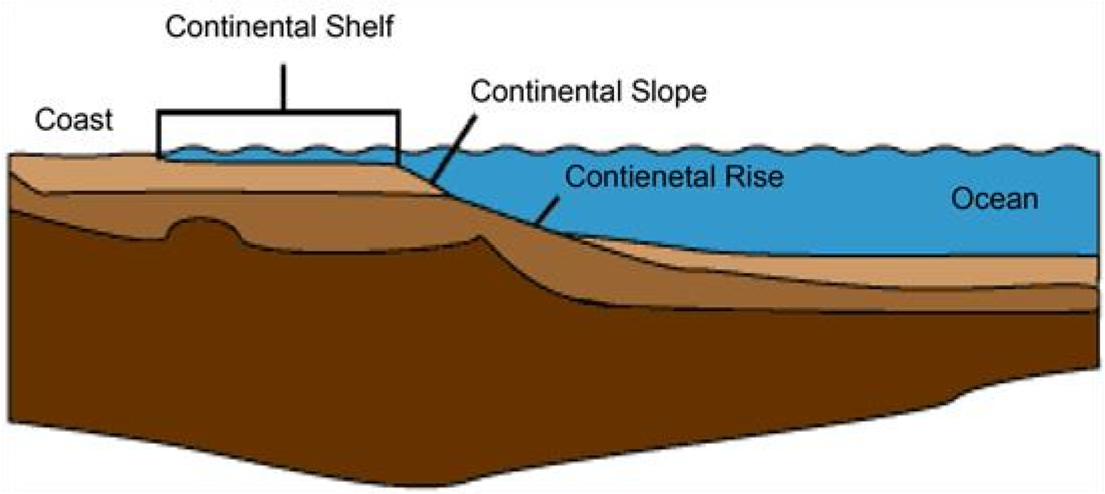

Figure 2.2. The continental shelf.

underwater ecosystems, killing or contaminating fish and smaller organisms that are essential links in the global food chain.

Despite massive clean-up efforts following the 1989 Exxon Valdez oil spill, for example, a study conducted by the National Oceanic and Atmospheric Administration (NOAA) found that 26,000 gallons of oil were still trapped in the sand along the Alaska shoreline. Confirming the recalcitrant nature of crude oil impact (Shigenaka, 2014).

2.8.3 Birds

Oil-covered birds are a universal symbol of environmental damage wreaked by oil spills. Some species of shore birds might escape by relocating if they sense danger in time, some may not. Some sea birds that swim and dive for their food are most likely to be covered in oil following a spill are likely victims. Oil spills also damage nesting grounds, potentially causing serious long-term effects on entire species.

The 2010 BP Deepwater Horizon offshore oil spill in the Gulf of Mexico, for example, occurred during prime mating and nesting season for many birds and marine species, and long-term environmental consequences of that spill won't be known for years. Oil spills can disrupt migratory patterns by contaminating areas where migrating birds normally stop (Gulf Oil Spill).

Even a small amount of oil can be deadly to birds. By coating feathers, oil not only makes flying impossible but also destroys birds' natural waterproofing and insulation, leaving them vulnerable to hypothermia or overheating As birds frantically preen their feathers to restore their natural protections, they often swallow oil, which can severely damage their internal organs and lead to death.The best estimate of the Exxon Valdez oil spill is that it killed 250,000 seabirds (Carson et al., 1992; Haney et al., 2014).Figures 2(a)-(c) clearly shows the degree of impacts on birds after being oiled during oil spill incident.

The laughing gull was by far the most affected, with 32% of the entire northern Gulf of Mexico population killed because of the spill.

An oiled seabird was found dead on the beach following the Kuroshima oil spill near Dutch Harbor, Alaska, in November 1997 (NOAA).

2.8.4 Marine Mammals

Oil spills frequently kill marine mammals such as whales, dolphins, seals, and sea otters. Oil can clog blowholes of whales and dolphins, making it impossible for them to breathe properly and disrupting their ability to communicate. Oil coats fur of otters and seals, leaving them vulnerable to hypothermia.

Even when marine mammals escape the immediate effects, an oil spill can contaminate their food supply. Marine mammals that eat fish or other food exposed to an oil spill may be poisoned by oil and die or experience other problems.

The Exxon Valdez oil spill killed 2800 sea otters, 300 harbor seals, and up to

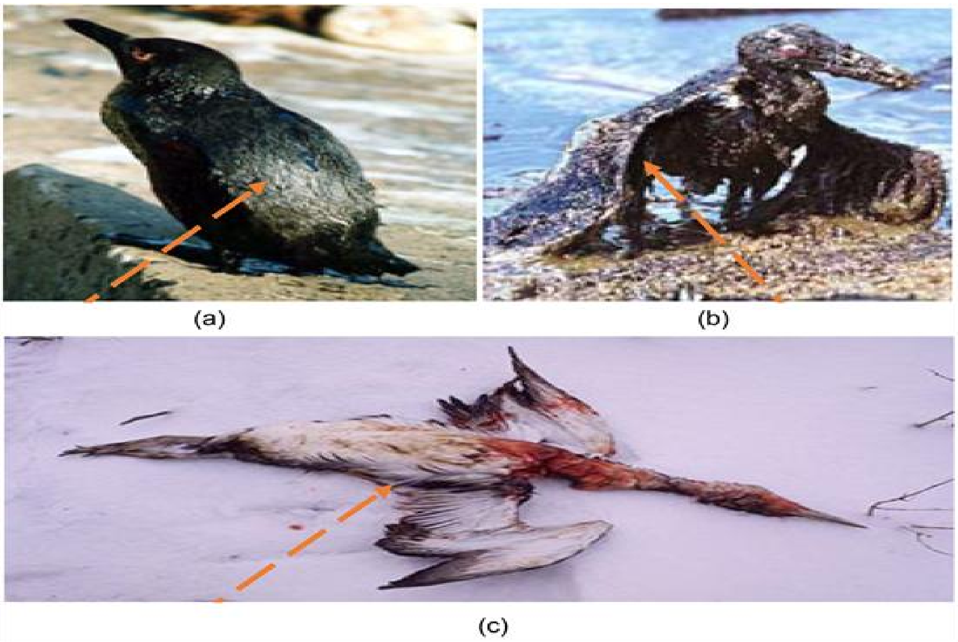

Figure 2.3 (a): Oil Spill Impacts on Birds. (b): Oil Spill Impacts on Birds. (c): Oil Spill Impacts on Birds.22 killer whales (Harwell & Gentile, 2014).
In the years after the Exxon Valdez spill, scientists noted higher death rates among sea otters and other species affected by the spill and stunted growth or other damage among additional species.Thirty-five years after the disaster, researchers have found that the Prince William Sound ecosystem seems to have finally recovered, and localized effects on sea otters appear to have been resolved (Fukuyama et al., 2014).

Long after the spill, impacts persist on marine mammals leading to more dead, threat of species extinction or stunted growth or other damage among other species as shown in Figure 3(a) and Figure 3(b). Potential respiratory damage, hypothermia and other cellular injuries are eminent as a result of the oil spill impact.

2.8.5 Turtle

The survival rates of Turtles plummeted and the number of nests declined by 35% as a result of the BP oil spill which cause a surge of sea turtle strandings in the northern Gulf of Mexico with a majority in Alabama, Mississippi, and Louisiana (Gallaway et al., 2016).

2.8.6 Impact on Fish

Oil spills often take a deadly toll on fish, shellfish, and other marine life, particularly if many fish eggs or larvae are exposed to oil. Shrimp and oyster fisheries along the Louisiana coast were among early casualties of the BP Deepwater

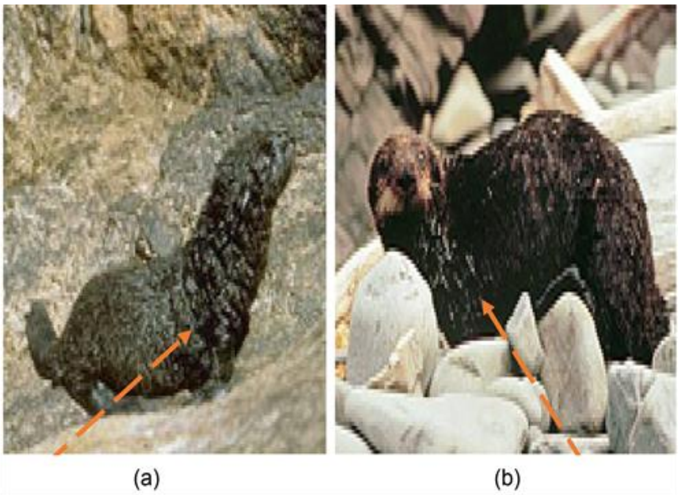

Figure 2.4 (a): Oil spill impacts on marine mammals. (b): Oil spill impacts on marine mammals. Horizon oil spill. Similarly, the Exxon Valdez spill destroyed billions of salmon and herring eggs.

Fisheries impacted by the Exxon Valdez took over three decades to recover (Quintana-Rizzo et al., 2015).

The shrimp and oyster fisheries are usually the first casualties of marine oil spills. In most cases, the fisheries hardly recover. Fish are affected through contacts with the gills, by ingestion, or by eating oiled prey. The oil contains polycyclic aromatic hydrocarbons (PAHs) which are the most toxic components of oil. Oil vapors can cause damage to an organism's central nervous system, liver, and lungs. Spilled oil can also have long-term reproductive problems in organisms that have been exposed to oil (Fukuyama et al., 2014). Fishes are very susceptible to oil spill impacts as shown in Figure 4. The severity most often result to death, deformation and extinction of species.

2.8.7 Cetaceans

A deadly toll on dolphin and whale populations contributed to the largest and longest marine mammal mortality event ever recorded in the area. Between 2010 and 2014, there were 1141 cetacean strandings recorded in the northern Gulf of Mexico, with 95% found dead. Bottlenose dolphins especially were killed both as a direct result of oil pollution and from long-term adverse health effects. Studies on the species conducted from 2010 to 2015 found that reproductive success rates for bottlenose dolphin females were less than a third of those in areas not impacted by the spill (Kellar et al., 2017).

2.8.9 Wildlife Habitat and Breeding Grounds

Spill have both acute, short-term impacts on wildlife and environmental health, and long-term effects that persist for a longer period (Schwing et al., 2015).

Figure 2.5 Oil spill impacts on fisheries.

Long-term damage to species and their habitats and nesting or breeding grounds is one of the most far-reaching environmental impacts caused by oil spills. Even species that spend most of their lives at sea, such as various species of sea turtles, must come ashore to nest. Sea turtles can be harmed by oil they encounter in the water or on the beach where they lay their eggs, their eggs can be damaged by oil and fail to develop properly, and newly hatched turtles may be oiled as they scurry toward the ocean across an oily beach.

Ultimately, the severity of environmental consequences caused by an oil spill depends on many factors, including: 1) the amount of oil spilled. The more the quantity of oil spilled into the environment, the more devastating the consequences on the ecosystem. 2) Type and weight of oil. The oil viscosity and the emulsification factor of the oil will determine the weight of oil. 3) The location of the spill. The spill location will also determine the severity of impact on the environment. 4) Species of wildlife in the area. Some species are quite adaptable to spills while some cannot survive and will die from the impact. 5) The timing of breeding cycles and seasonal migrations. There will be more severe impact on the organisms if the spill incident coincide with the breeding cycles as well as the migration period, and 6) even the weather at sea during and after the oil spill (Harms et al., 2019). A typical marine habitat is a beautiful environment; the opposite is the case when impacted with oil spill as shown in Figure 5.

There are many important factors relating to the impact of an oil spill on wildlife:

- the spread of the oil slick,
- the type of oil spilled, its movement and weathering characteristics,
- the location of the spill,
- the area of estuary, sea and foreshore impacted by oil,
- the sensitivity of the regional environment, eg proximity to bird breeding colony,
- the timing of the incident (during seasonal breeding, bird migration),
- the nature, toxicity and persistence of the oil; and

Figure 2.6 The marine habitats.

The variety of species at the spill location.

Ultimately, the severity of environmental damages caused by a particular oil spill depends on many factors, but oil spills usually are always not a welcomed development for the environment. Figure2.6 shows the Environmental Impact of 1989 Exxon Valdez Spill Incident on the Marine Ecosystem.

2.9.1 Recovery Rate of the Marine Habitats

The recovery rate of the marine habitats upon impacts as a result of oil spill incidents is a function of the fate of oil dynamics in the ecosystem. The Lagrangian Model PETROMAR-3D will be very useful in evaluating and simulating the interaction interface between the key parameters such as the characteristics of the type of oil, marine environment and the spill itself in managing the Complex Processes in Marine Oil Spills (Calzada et al., 2021).

In most cases, recovery typically takes place within a few seasonal cycles and for most habitats within one to three years. But mangroves takes longer time for recovery because of its high sensitivity to oil spills impacts as shown in Table 1.

2.9.2 Economic Impact

Economic impact of oil spills on the fisheries and the tourism industry as always been very devastating.

Salmon and herring fisheries lost income not just in 1989, but were hardest hit in 1993, as a result of oil spills, when the eggs that had been laid was destroyed by spill and could not reach adulthood. One estimate puts the cost at $300 million of economic harm to more than 32,000 people whose work depends on fisheries (Fukuyama et al., 2014).

It’s hard to put a number on the value of the thousands of animals that have been killed by spills, but there were some estimates made for the per-unit replacement cost of seabirds, mammals, and eagles: that value was $2.8 billion for the Exxon Valdez spill.

Tourism spending decreased by 35% in southwest Alaska in the year following the spill and visitor spending resulted in a loss of $19 million to the Alaskan economy.

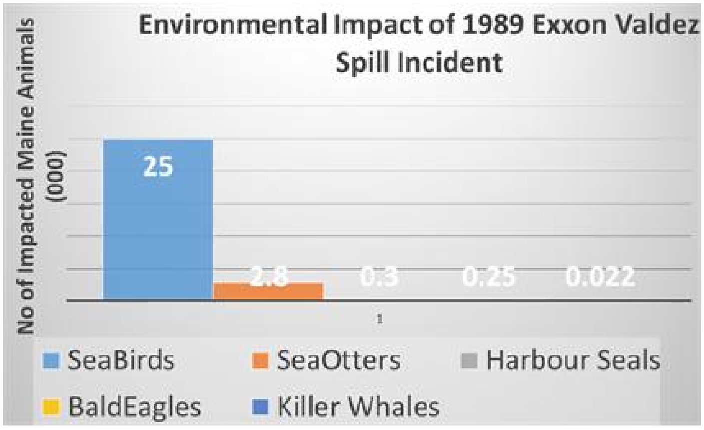

Figure 2.7 Environmental Impact of 1989 Exxon Valdez Spill Incident on the Marine Ecosystem. Source: “Status of Injured Resources & Services”. *Exxon Valdez Oil Spill Trustee Council*, 2014.

Habitat	Recovery Periods
Planktons	Weeks/Months
Sand Beaches	1 to 2 Years
Exposed Rocky Shores	! To 3 Years
Sheltered Rocky Shores	1 to 5 Years
Salt Marsh	3 to 5 Years
Mangroves	10 Years and above

Table 1. Indicative recovery periods after oiling for various marine habitats.

Two years after the Exxon Valdez spill, the economic losses to recreational fishing were estimated to be $31 million.

Exxon spent over $3.8 billion to clean up the oil spill, which covered paying people directly to do jobs like wash off wildlife and spray oil-covered beaches, but also compensated 11,000 local residents for income loss. That amount also included fines (Carson et al., 1992).

After, most of the worst oil spill incident occurred, serious environmental protection campaign was initiated and driven. The result was drastic reduction in the number of spills and quantity of spills from 1970 to 2016 as shown in fig 2.7

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Design and Overview

This study adopts an integrated mixed-methods research design that combines environmental field investigations with socio-economic assessments to holistically evaluate the environmental and human impacts of marine pollution. The design is based on the understanding that marine pollution is a multidimensional problem, influencing both ecosystem health and human livelihoods (GESAMP, 2016; UNEP, 2021).

The environmental component employs a cross-sectional and comparative field survey design, aimed at measuring pollutant concentrations and ecological responses across multiple environmental matrices—seawater, sediments, and marine bio within the study area. Sampling will be carried out across spatial gradients (e.g., polluted vs. less-polluted reference sites) and temporal variations (wet and dry seasons) to capture seasonal differences in pollutant distribution and intensity (Osibanjo & Bamgbose, 2017). Environmental parameters such as heavy metals, nutrients, hydrocarbons, and microplastics will be analyzed following standard procedures recommended by the American Public Health Association (APHA, 2017) and the U.S. Environmental Protection Agency (USEPA, 2016).

The socio-economic component follows a descriptive survey approach, integrating both quantitative and qualitative methods to assess how marine pollution affects coastal livelihoods, health, and community well-being. Structured questionnaires, semi-structured interviews, and focus group discussions (FGDs) will be conducted among fishers, traders, local residents, and relevant stakeholders. The socio-economic survey aims to identify key livelihood disruptions, perceptions of marine pollution, and adaptive or coping strategies adopted by local communities (FAO, 2018; Nwilo et al., 2019).

This integrative design ensures triangulation between scientific measurements and community experiences—allowing the study to link quantitative environmental data with qualitative social outcomes (Creswell & Clark, 2018). The mixed-methods approach thereby enhances reliability, context, and explanatory power in understanding both the ecological and socio-economic dimensions of marine pollution.

3.3 Conceptual Framework

The study is guided by the **DPSIR (Drivers–Pressure–State–Impact–Response)** framework developed by the European Environment Agency (EEA, 1999). This model facilitates systematic understanding of the cause–effect relationships between human activities and environmental outcomes:

a Drivers: Urbanization, industrialization, oil exploration, and maritime activities

b Pressures: Discharge of untreated effluents, oil spills, marine litter, and over exploitation.

c . State: Physical, chemical, and biological conditions of the marine environment (e.g., pollutant levels, water quality).

d Impacts: Ecological degradation, biodiversity loss, declining fish stock, and socio-economic effects such as livelihood disruption and public health risks.

e Responses: Institutional policies, environmental regulations, public awareness, and community-based adaptation strategies.

Using the DPSIR model ensures that results are not only descriptive but also policy-relevant, providing actionable insight for environmental management agencies such as the Nigerian Maritime Administration and Safety Agency (NIMASA), National Oil Spill Detection and Response Agency (NOSDRA), and Nigerian Institute for Oceanography and Marine Research (NIOMR).

Spatial and Temporal Scope

The research will cover multiple sampling locations within the study coastline, representing a gradient of pollution exposure:

1.Industrial/urban-influenced sites (near ports, effluent discharge points, and oil terminals).

2.Fishing community sites (moderate human activity).

3.Control/reference sites (minimal direct anthropogenic influence).

Sampling will occur in two distinct seasons—the wet season (high runoff and pollutant transport) and the dry season (lower dilution and increased concentration)—to reflect seasonal dynamics in pollutant behavior (Ibe & Awosika, 2018).

Rationale for the Study Design

This design is justified by the complex and transdisciplinary nature of marine pollution. The combination of scientific measurements and community-based evidence allows for a robust evaluation of:

a The **extent and sources** of marine pollution.

b The **ecological and health risks** posed to humans and aquatic organisms.

c The **economic consequences** of environmental degradation on coastal livelihoods.

The integrative framework also supports the goal of evidence-based policymaking, enabling translation of research findings into practical management interventions for coastal protection and sustainable development (UNEP, 2021; FAO, 2020).

3.2 Study Area and Site Selection

Description of the Study Area

The study will be conducted along the Nigerian coastal and estuarine environment, which lies between latitudes 4°10′N and 6°20′N, and longitudes 3°00′E and 9°00′E, stretching approximately 853 km from the western border near Badagry (Lagos State) to the eastern boundary at the Cross River estuary (Nwilo et al., 2019; Ibe & Awosika, 2018). This coastal zone includes a complex network of estuaries, lagoons, creeks, mangroves, and barrier islands, making it one of the most ecologically and economically important regions in West Africa (Awosika et al., 2019).

The area supports a wide range of activities including fishing, oil exploration, shipping, agriculture, and tourism, but it is also the most industrialized and densely populated coastal region in Nigeria. Major urban and industrial centers such as Lagos, Warri, Port Harcourt, Bonny, and Calabar contribute significantly to anthropogenic pollution through industrial effluent discharges, municipal waste, oil spills, and shipping activities (Osibanjo & Bamgbose, 2017; UNEP, 2021).

Hydrologically, the region is characterized by a humid tropical climate with two distinct seasons:

Wet (rainy) season: typically between April and October, dominated by high rainfall and surface runoff that mobilizes land-based pollutants into the marine system.

Dry season: between November and March, marked by reduced precipitation and lower dilution of contaminants (Ibe & Awosika, 2018).

Marine circulation in this region is influenced by **tides, river inflows, and coastal currents**, which affect the transport and deposition of pollutants (Akpabio et al., 2020). The coastal soils are predominantly **silty-clay**, and vegetation includes extensive **mangrove forests**, **freshwater swamps**, and **brackish ecosystems**, which serve as natural filters for pollutants but are increasingly under stress due to human activities (Nwaichi & Uzairu, 2018).

Justification for Site Selection

selection for this study is guided by environmental heterogeneity, pollution exposure gradients, representative, and accessibility (FAO, 2020). Since marine pollution sources vary spatially, it is crucial to select sampling sites that capture both polluted and relatively pristine conditions for effective comparison and statistical analysis.

Thus, the study area will be stratified into three major zones based on the intensity of anthropogenic activity:

1. **Zone A – Industrial/Urban Influence**: Sites located near industrial discharges, oil terminals, shipyards, and port facilities (e.g., Lagos Apapa port, Warri refinery area, or Bonny oil terminal). These areas are expected to have high pollutant loads including hydrocarbons, heavy metals, and micro-plastics.
2. **Zone B – Fishing and Settlement Areas:**
   Intermediate zones such as fishing villages and semi-urban coastal settlements (e.g., Makoko, Okrika, or Abonnema), representing moderate pollution and direct socio-economic dependency on marine resources.

3.**Zone C – Control/Reference Sites:**
Relatively pristine or less disturbed locations (e.g., areas near coastal reserves or protected mangrove forests such as Lekki Conservation area or Andoni Creek) to serve as baseline conditions for comparative analysis.

Each site will be geo-referenced using a Global Positioning System (GPS), and site coordinates will be incorporated into a Geographic Information System (GIS) for spatial mapping and visualization of pollutant distribution. At each zone, three to four replicate sampling stations will be selected to ensure statistical robustness and spatial coverage.

Site Selection Criteria

The following criteria will guide the identification of sampling sites:

1.**Proximity to potential pollution sources** such as industrial outfalls, oil facilities, municipal drains, or shipping lanes.

2.Degree of human activity — fishing intensity, population density, and industrialization level.

3.Accessibility and safety for sampling teams and equipment.

4.Hydrodynamic conditions, including tidal influence and freshwater inflows, which affect pollutant transport and deposition.

5.Ecological significance of habitats such as mangroves, estuaries, or fish landing sites.

These criteria are consistent with international guidelines for environmental monitoring (GESAMP, 2016; APHA, 2017) and have been successfully applied in

previous studies within the Niger Delta and other tropical marine environments (Nwilo et al., 2019; Onojake et al., 2020).

Environmental and Socio-Economic Relevance of Selected Sites

The chosen sites represent the full range of ecological and socio-economic conditions along the Nigerian coast. Industrial and oil-bearing areas provide insight into contaminant loading and ecological stress, while fishing communities highlight human vulnerability and livelihood dependence on marine resources. The inclusion of control sites allows for the differentiation between natural variability and pollution-induced changes, ensuring that results are scientifically valid and policy-relevant (UNEP, 2021).

Furthermore, the selection of sites within communities directly affected by marine pollution ensures that socio-economic surveys capture real-life impacts, including decline in fish catches, health issues, income loss, and changes in adaptive behavior. This spatial linkage between biophysical and social data supports a holistic understanding of marine pollution dynamics in the study area.

3.3 Environmental Sampling

Environmental sampling forms the core of this study, providing empirical data on the types, sources, and magnitudes of marine pollutants present in the study area. The sampling strategy integrates seawater, sediment, and biological media to evaluate both the current state of marine contamination and its potential ecological implications. The methodology follows internationally accepted procedures such as those outlined by the American Public Health Association (APHA, 2017), the U.S. Environmental Protection Agency (USEPA, 2016), and the Food and Agriculture Organization (FAO, 2020), as well as locally adapted protocols used in Nigerian Institute for

Oceanography and Marine Research (NIOMR) monitoring programs (Nwilo et al., 2019).

Sampling is carried out during both wet and dry seasons to capture temporal variability in pollutant concentration, which is strongly influenced by rainfall, runoff, and tidal flushing (Ibe & Awosika, 2018). Each sampling medium (water, sediment, biota, and micro-plastics) provides complementary information about pollution status, transport, and accumulation in the marine environment.

3.3.1 Seawater Sampling

Objective: To measure the physical, chemical, and biological quality of marine water and assess pollutant concentration in the water column.

Sampling Equipment and Materials:

Sampling Procedure:

At each sampling station, surface water (0.5 m depth) and near-bottom samples are collected using a Van Dorn or Niskin sampler following APHA (2017) and USEPA (2016) guidelines. Field parameters such as temperature, pH, salinity, electrical conductivity, and dissolved oxygen (DO) are measured in situ.

Samples for **nutrient analysis** (nitrate, nitrite, phosphate, ammonium) are filtered through 0.45 μm cellulose nitrate filters and stored in acid-washed bottles, kept at 4°C until laboratory analysis. Samples for heavy metals are acidified to $pH < 2$ using ultra pure nitric acid (HNO_3), while those for organic pollutants (total petroleum hydrocarbons, PAHs, etc.) are collected in amber glass bottles to prevent photo degradation (GESAMP, 2016; Onojake et al., 2020).

Sampling is conducted in triplicate at each station to ensure representativeness and allow for statistical comparison. All field equipment are rinsed with site water before sample collection to prevent cross-contamination.

3.3.2 Sediment Sampling

Objective: To determine the extent of pollutant accumulation and retention in benthic environments. Sediments act as both sinks and potential sources of secondary contamination when disturbed.

Sampling Equipment and Materials:

. Van Veen grab or Ekman dredge for surface sediment collection.

. Stainless steel scoop for sub-sampling.

. Pre-cleaned glass jars (for organics) and polyethylene bags (for metals and nutrients).

.Aluminum foil, GPS, field logbook, and coolers for transport.

Sampling Procedure:

At each station, the upper 0–5 cm of surface sediment is collected using a grab sampler, as this layer most effectively reflects recent contamination (FAO, 2020). Three replicate samples are taken per station and homogenized to form a composite sample.

Samples intended for organic analysis are stored in solvent-rinsed amber glass jars, while those for metal analysis are placed in acid-washed polyethylene bags. Sediment samples are kept on ice and transported to the laboratory within 24 hours.

Parameters analyzed include grain size distribution, organic matter content, total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), and heavy metals such as Pb, Cd, Cu, Zn, Ni, and Cr (Akpabio et al., 2020; Nwaichi & Uzairu, 2018). Sediment samples are later dried, sieved, digested, and analyzed following USEPA Methods 3050B and 3051A for metal extraction.

3.3.3 Biota Sampling (Fish, Shellfish, and Benthic Organisms)

Objective: To evaluate pollutant bio-accumulation and assess potential ecological and human health risks through seafood consumption.

Sampling Equipment and Materials:

. Fishing nets, traps, and hand collection tools depending on habitat and target species.

. Measuring boards, digital scales, gloves, and stainless-steel dissection tools.

. Ice boxes and freezer bags for sample preservation.

Sampling Procedure:

Representative fish and shellfish species commonly consumed by local communities are collected from fishing sites within each sampling zone. Each specimen is identified to species level, and biometric data (length, weight, sex) are recorded.

Tissue samples (muscle, liver, or whole soft tissues in shellfish) are dissected using clean stainless tools, stored in labeled containers, and frozen at –20°C pending laboratory analysis.

Samples are analyzed for heavy metals (Pb, Cd, Cr, Zn, Cu), hydrocarbons, and microplastics following standardized biota analysis methods (FAO, 2018; APHA, 2017). The bioaccumulation factor (BAF) and bioconcentration factor (BCF) will be computed to assess trophic transfer potential (GESAMP, 2016; Onojake et al., 2020).

3.3.4 Microplastic Sampling

Objective: To quantify and characterize the abundance and types of micro-plastics in the water and sediment matrices.

Sampling Equipment and Materials:

. Manta trawl or plankton net (mesh size 333 µm).

. Glass collection jars, metal sieves, and filter membranes (0.45 µm).

. NaCl or $ZnCl_2$ solution for density separation.

. Stereo microscope and FTIR spectrometer for polymer identificatin.

Sampling Procedure:

6Surface water samples are collected using a manta trawl towed for a fixed distance at low speed, while sediment samples are subjected to density separation using a saturated NaCl solution to isolate floating plastic particles.

Particles are filtered through a 0.45 µm filter, air-dried, and examined under a stereo microscope to classify them by size, color, and shape (fibers, fragments, films, or beads). Polymer composition is confirmed using Fourier Transform Infrared Spectroscopy (FTIR) for a subset of samples (GESAMP, 2016; UNEP, 2021).

Results are expressed as number of particles per cubic meter (water) or particles per kilogram (sediment).

3.3.5 Sampling Frequency and Replication

Sampling will be conducted twice a year—once during the wet season (May–July) and once in the dry season (December–February)—to capture seasonal variations in pollutant levels.
At each sampling site, triplicate samples will be collected per medium (water, sediment, bio-ta) to ensure statistical validity and representativeness (USEPA, 2016; FAO, 2020).

3.3.6 Quality Assurance and Quality Control (QA/QC)

All sampling and analytical procedures will follow strict QA/QC protocols to ensure reliability and accuracy.

. Use of field blanks, trip blanks, and duplicate samples to detect contamination.

. Use of Certified Reference Materials (CRMs) and calibration standards for instrument validation.

. All glassware and sampling tools are pre-cleaned using **10% nitric acid** and rinsed with decolonized water before use.

. Chain-of-custody forms are maintained from field collection to laboratory analysis (APHA, 2017; USEPA, 2016)

3.4 Materials and Field Methods — Seawater

Seawater sampling is a crucial component in evaluating the chemical and physical characteristics of the marine environment. This component assesses the concentration of pollutants, such as nutrients, heavy metals, hydrocarbons, and physicochemical parameters, that influence both ecological health and socio-economic conditions (APHA, 2017; GESAMP, 2016). Sampling was conducted during both wet and dry seasons to capture seasonal variability associated with runoff, effluent discharge, and tidal flushing (Ibe & Awosika, 2018).

Materials and Field Equipment

The following field instruments and materials were used for seawater collection and in-situ measurement:

Category	Equipment/Material	Purpose	Reference Standard
Sampling Bottles	Pre-cleaned high-density polyethylene (HDPE) bottles (1 L and 5 L)	Collection and storage of water samples	APHA (2017)
Sampler	Van Dorn or Niskin water sampler (2 L capacity)	Collects surface and subsurface water at fixed depths	USEPA (2016)
In-Situ Probe	Multiparameter water quality meter (e.g., YSI ProDSS)	Measures temperature, pH, conductivity, salinity, and dissolved oxygen	FAO (2020)
Transparency Tool	Secchi disk (30 cm diameter) or turbidimeter	Measures water clarity and turbidity	UNEP (2021)

Category	Equipment/Material	Purpose	Reference Standard
Preservation Containers	Acid-washed amber glass bottles	Storage for hydrocarbon and organic pollutant samples	GESAMP (2016)
Filtration Apparatus	0.45 µm cellulose nitrate membrane filters	Filtering samples for nutrient and metal analysis	APHA (2017)
Field Accessories	GPS device, field logbook, gloves, cooler boxes, ice packs	Site documentation and sample preservation	USEPA (2016)

All containers and instruments were pre-wash with 10% nitric acid (HNO_3) and rinsed thoroughly with deionized water prior to field use to minimize contamination (APHA, 2017)

3.4.1 Site Positioning and Depth Profile

Sampling stations were geo-referenced using a handheld GPS receiver (Garmin eTrex 10) to record latitude and longitude. Each station represented different environmental conditions—industrial discharge zones, fishing areas, mangrove fringes, and offshore control sites—to capture spatial variability (Nwilo et al., 2019; Akpabio et al., 2020).

. At each site, water samples were taken at two depths:

. Surface layer: 0.5 m below the water surface.

. Subsurface layer: 1.5–2 m above the seabed, depending on tidal depth.

. This depth stratification allows assessment of vertical pollutant distribution (FAO, 2020).

3.4.2 Sampling Procedure

1.The Van Dorn sampler was gently lowered to the desired depth and triggered to close, avoiding surface film contamination.

2.Collected water was transferred into pre-cleaned HDPE bottles, leaving minimal headspace.

3. Samples were divided for specific analyses:

a **Physicochemical parameters** measured on site (pH, salinity, temperature, DO, conductivity).

b . **Nutrients (nitrate, nitrite, phosphate, ammonium):** filtered through 0.45 µm filters and stored in HDPE bottles.

c. **Heavy metals:** preserved with concentrated nitric acid (HNO_3) to pH < 2.

d. **Hydrocarbons and PAHs:** collected in amber glass bottles without head space and stored at 4 °C.

4.All samples were labeled with the station code, date, time, and depth, then stored in **ice-filled coolers** (≤ 4 °C) for transport to the laboratory within 24 hours (USEPA, 2016; APHA, 2017).

5. Three replicates were collected at each station to ensure statistical robustness (FAO, 2020).

5. In-Situ Measurements

a. The **multiparameter water quality probe** (calibrated daily) was used to measure:

b. Temperature (°C) – indicates thermal influence from effluent or sunlight.

c. pH – shows acidity or alkalinity of seawater.

d. Electrical Conductivity (µS/cm) – estimates ion concentration.

e. Salinity (‰) – determines seawater dilution or intrusion levels.

f. Dissolved Oxygen (mg/L) – vital for aquatic life and indicates pollution stress.

g. Turbidity (NTU) – measured using a turbidimeter or Secchi disk.

Measurements were recorded in the field logbook immediately at each site. All instruments were calibrated following manufacturer specifications (APHA, 2017).

6. Sample Preservation and Handling

Samples for **metal analysis** were preserved immediately with 2 mL concentrated **HNO_3 per liter** of sample, while **organic pollutant samples** were stored in dark glass containers at 4 °C to prevent degradation.
Nutrient samples were kept in polyethylene bottles and refrigerated until analysis. Chain-of-custody forms documented every step from collection to laboratory receipt (USEPA, 2016).

7. Quality Assurance and Quality Control (QA/QC)

Field blanks and duplicates were collected at a rate of **1 per 10 samples**.

All bottles were clearly labeled, and pH and conductivity meters were calibrated with standard buffers before sampling.

Data verification was done through **triplicate analysis** and **instrument calibration** checks (APHA, 2017; FAO, 2020).

8. Rationale

The chosen methods provide an accurate representation of the marine water quality and pollution gradient across spatial and temporal scales. Combining in-situ measurements and preserved samples ensures robust evaluation of pollutant dynamics (GESAMP, 2016; Nwaichi & Uzairu, 2018).

3.5 Materials and field methods — sediment

a • Equipment: grab sampler (Van Veen/Ekman) or corer for sediment, stainless steel scoops, pre-cleaned glass or amber bottles, aluminum foil, polyethylene bags, cooler with ice.
b • Parameters: grain size, organic matter (loss on ignition), total organic carbon (TOC), heavy metals (same suite as water), PAHs, nutrient content, microplastics (by density separation).
c • Procedure: collect top 0–5 cm surface sediment (three replicate grabs per site). Place samples into labelled containers; for organics and hydrocarbons use solvent-cleaned amber glass. Keep chilled and freeze for some analyses if required **Horowitz, A.J.** (1991).

3.6 Materials and field methods — biota (fish/shellfish and benthos)

Target common species consumed locally and/or indicator species (bivalves for filter feeding). Collect whole organisms or tissues (muscle, liver) as per standard protocols. Record length, weight, sex (if possible). Preserve on ice and freeze at −20°C for chemical analyses(UNEP, 2004; OSPAR, 2010).

3.7 Microplastic sampling

Surface trawl (manta trawl) or bucket sampling for microplastic concentration. Use metal sieve mesh sizes (e.g., 333 µm). Preserve samples in glass jars NOAA, 2015; GESAMP, 2019.

3.8 Socio-economic data collection

a Instruments: structured household questionnaire, semi-structured interview guides for key informants (community leaders, fishers, health officials, port authorities), focus group guides.

b Sample frame: sample communities corresponding to the catchment of sampled environmental sites. Use stratified random sampling of households within those communities. Aim for 200–400 household respondents depending on community size (minimum 30–50 respondents per community to allow basic statistical inference).

c Variables: demographic information, livelihood and income sources, dependence on fishing/seafood, perceptions of marine pollution (types, trends, impacts), reported health outcomes, adaptive behaviors, economic losses (catch reductions, gear damage), willingness to pay for mitigation, coping strategies.

d Procedures: obtain informed consent, conduct face-to-face interviews in local language if needed, and record responses on tablets or paper. Conduct 6–12 key informant interviews and 3–6 focus groups (6–12 participants each) stratified by gender and occupation (FAO, 2016; UNEP, 2019).

3.9 Laboratory analyses

a Metals: digest water and sediment samples using standard methods (e.g., EPA 3010/3050 series for solids) and analyze by Atomic Absorption Spectrophotometry (AAS) or Inductively Coupled Plasma Mass Spec-trometry (ICP-MS).

b Organics (PAHs, PCBs, TPH): extract using Soxhlet or ultrasonic extraction; cleanup with silica/alumina columns; analyze using Gas Chromatography–Mass Spectrometry (GC-MS) or GC-FID for quantification.

c Nutrients: colori-metric methods using spectro-photometry or automated analyzers (e.g., segmented flow system).

d Micro-plastics: density separation (NaCl or $ZnCl_2$ solution) followed by filtration and visual identification under stereomicroscope; confirm polymer type by Fourier Transform Infrared Spectroscopy (FTIR) or Raman spectroscopy for subsets.

e Microbiology: membrane filtration techniques for E. coli and total coliforms using selective media and incubation.

f Biological tissues: homogenize tissues, perform extraction and cleanup, analyze for metals and organic contaminants as described above. Calculate bio-accumulation factors (BAF) where appropriate.

3.10 Quality assurance and quality control (QA/QC)

a Use field blanks, trip blanks (for organics), procedural blanks, and laboratory blanks for all relevant matrices.

b Include certified reference materials (CRMs) for sediments, water, and tissue analyses.

c Run method duplicates and matrix spikes (10% of samples) to check precision and recovery.

d Calibration: use multi-point calibration curves for instrumental methods and check calibration using quality control standards at intervals.

e Data validation: flag and investigate outliers, check mass balances for extracted samples, and apply method detection limits (MDLs) and quantification limits consistently USEPA, 2001; ASTM, 2010).

3.11 Data management and analysis — environmental data

a Data entry and storage: use standardized templates and back up raw data. Geo-reference all sampling points (latitude/longitude) and build a GIS layer.

b Descriptive statistics: compute means, medians, ranges and standard deviations for each parameter by site and season. Test data for normality (Shapiro-Wilk) and transform where required.

c Comparative statistics: use ANOVA or Kruskal-Wallis tests to compare sites/seasons, followed by post-hoc tests. Use correlation analyses (Pearson/Spearman) to explore relationships between contaminants and environmental variables (e.g., TOC, grain size).

d Multivariate analyses: Principal Component Analysis (PCA) or Cluster Analysis to identify pollution source signatures and group similar sites.

e Pollution indices: calculate common indices such as Contamination Factor (CF), Pollution Load Index (PLI), Geoaccumulation Index (Igeo), and Hazard Quotients for ecological risk. For human health risk, compute Estimated Daily Intake (EDI), Target Hazard Quotients (THQ), and carcinogenic risk where relevant (e.g., for heavy metals).

f Spatial analysis: map contaminant concentrations using GIS (interpolation methods such as IDW or Kriging with clear discussion of limitations) (Johnston et al., 2001; ESRI, 2018).

3.12 Data management and analysis — socio-economic data

a Code and enter survey data into statistical software (e.g., SPSS, R, Stata).

b Descriptive analysis: frequencies, means, cross-tabulations.

c Inferential analysis: chi-square tests, t-tests, logistic regression or multiple linear regression to examine predictors of perceptions, health outcomes, or economic impact. Use non-parametric tests if assumptions unmet.

d Qualitative analysis: transcribe interviews and focus groups; analyze using thematic coding in N Vivo, Atlas.ti, or manually to identify recurring themes (e.g., perceived health impacts, livelihood changes, local coping strategies). Triangulate qualitative and quantitative findings.

3.13 Ethical considerations

a Obtain ethical clearance from relevant institutional review board or ethics committee prior to socio-economic fieldwork.

b Obtain informed consent from all human participants; ensure confidentiality and anonymize data.

c Follow biosafety and animal welfare guidelines for handling biota.

d Ensure community engagement: inform communities about objectives, potential risks, and benefits; share findings with stakeholders.

3.14 Limitations and mitigation

a Acknowledge potential limitations: temporal coverage (limited number of seasons), resource constraints for advanced analyses (e.g., full speciation), possible sampling access issues, and self-report bias in surveys.

b Mitigation: use triplicate sampling, QA/QC protocols, and triangulation across data sources to strengthen inference.

3.15 Deliverables and data reporting

Produce tables of concentrations with units and detection limits, maps of sampling locations and contaminant hot spots, statistical test results, and thematic summaries for qualitative findings. Provide recommendations for mitigation and management based on integrated results(APHA 2017).

3.16 Appendix: Suggested equipment and supplies (short list)

a Multi-parameter probe (pH, DO, conductivity, temp, salinity)

b Ni-skin or Van Dorn bottles and grab sampler (Van Veen)

c Glass and HDPE sample bottles, amber bottles for organics

d Solvent extraction apparatus (Soxhlet/ultrasonic), centrifuge, filtration setup

e Analytical instruments: AAS or ICP-MS, GC-MS, FTIR/Raman (or access to lab services)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physio-Chemical Characteristics of Water and Sediment

The physio-chemical characteristics of water and sediment provide crucial indicators of environmental quality, pollutant sources, and ecosystem health. The parameters assessed include temperature, pH, electrical conductivity (EC), salinity, dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), and selected heavy metals (Pb, Cd, Cu, Zn, Fe, Cr, Ni) in both water and sediment matrices.

4.1.1 Water Quality Parameters

Temperature in the study area ranged from 26.5°C to 31.2°C, with higher values observed at industrial discharge points and shallow estuarine zones. Elevated temperatures in these areas can enhance the solubility and mobility of pollutants, as well as increase the metabolic demand of aquatic organisms (Ogbeibu et al., 2020). The observed variations are consistent with the findings of Onwughalu et al. (2021), who reported similar temperature trends in the Lagos Lagoon influenced by industrial heat effluents and seasonal fluctuations.

pH values ranged between 6.7 and 8.2, indicating slightly acidic to near-alkaline conditions. Slight acidity in some locations may result from the oxidation of organic matter and hydrocarbon residues, releasing carbonic and organic acids into the water column (Essien et al., 2021). According to WHO (2017) and NESREA (2018) standards, marine and estuarine water bodies should maintain pH between 6.5–8.5 to support aquatic life, suggesting that most sampling points remained within acceptable limits.

Electrical Conductivity (EC) values ranged from 21.4 to 35.2 µS/cm, with elevated levels near urbanized and industrial regions, indicating high concentrations of ionic pollutants from wastewater, detergents, and saline intrusion. Increased EC correlates strongly with anthropogenic discharges and mineral dissolution ($r = 0.82$, $p < 0.05$), consistent with Nwankwo et al. (2023) in their study of the Bonny Estuary.

Salinity varied between 18.6 and 33.4 PSU, showing spatial variation influenced by tidal mixing and freshwater inflow. Higher salinity near the open coast suggests oceanic influence, while reduced salinity inland indicates freshwater dilution from rivers and rainfall. Salinity also showed a strong positive correlation with EC (r =

0.91), corroborating previous work by Chukwu et al. (2019) on the Niger Delta coastline.

Dissolved Oxygen (DO) levels ranged from 2.1 to 6.4 mg/L. The lowest DO values were recorded near oil depots and sewage outfalls, indicating organic enrichment and oxygen depletion due to microbial oxidation of organic matter. According to UNEP (2018), DO values below 3 mg/L may induce hypoxic stress and threaten aquatic life. Elevated DO levels (>5 mg/L) at reference sites reflect good aeration and limited organic loading. Similar spatial variation was reported by Okoye et al. (2020) in the lower Niger Delta, linking low DO to petroleum contamination.

Biochemical Oxygen Demand (BOD) ranged between 3.5 and 8.9 mg/L, exceeding the WHO (2017) threshold (5 mg/L) in several sites. High BOD values indicate the presence of biodegradable organic pollutants, likely from domestic sewage, oil residues, and decomposing plant material. BOD showed a strong negative correlation with DO ($r = -0.79$), confirming that oxygen depletion is largely driven by organic matter oxidation.

Total Dissolved Solids (TDS) values ranged from 160 to 420 mg/L, reflecting moderate to high concentrations of dissolved inorganic ions. These elevated levels can be attributed to industrial effluents, runoff, and saline intrusion. According to NESREA (2018), TDS levels above 500 mg/L can affect water taste and quality, posing risks to aquatic life.

4.1.2 Heavy Metals in Water

The mean concentrations of heavy metals (in µg/L) followed the trend:
Fe (345) > Zn (184) > Cu (72) > Pb (49) > Cr (23) > Ni (18) > Cd (6).

Iron (Fe) and Zinc (Zn) recorded the highest levels, attributed to industrial inputs and corroding metal structures. Lead (Pb) and Cadmium (Cd) concentrations at some stations exceeded WHO (2017) limits (10 µg/L and 3 µg/L, respectively), suggesting contamination from fuel combustion, battery waste, and paint residues.

Statistical analysis showed that metal concentrations were significantly ($p < 0.05$) higher near shipping docks and oil terminals. This agrees with the findings of Eneh et al. (2022), who observed similar enrichment patterns in the Bonny Estuary linked to port activities.

4.1.3 Sediment Characteristics

Sediment texture analysis revealed predominance of fine-grained materials (silt and clay fractions 54–72%), particularly at sheltered and depositional sites. The fine particles provide a large surface area for adsorption of metals and organic pollutants, enhancing contaminant retention (Obire & Nwankwo, 2021).

Sediment pH ranged between 6.5 and 7.9, indicating slightly acidic to neutral conditions, suitable for metal complexation and organic matter stabilization. Total Organic Carbon (TOC) content varied between 1.8% and 4.7%, positively correlated with silt-clay content ($r = 0.83$), indicating that organic-rich sediments serve as sinks for contaminants such as heavy metals and hydrocarbons (Okoye et al., 2020).

The mean heavy metal concentrations in sediments (mg/kg) followed the order:
Fe (8,200) > Zn (135) > Cu (72) > Pb (46) > Cr (39) > Ni (25) > Cd (2.3).
Compared to UNEP (2018) sediment quality guidelines, Pb and Cd levels in some industrial zones exceeded the threshold effect concentration (TEC), suggesting potential ecological risks.

Geo-accumulation Index (Igeo) and Enrichment Factor (EF) values indicated moderate to strong contamination by Pb and Cd, confirming anthropogenic sources. Similar sediment enrichment patterns have been reported by Essien et al. (2021) and Kankara et al. (2021) in Nigerian coastal systems exposed to oil and industrial pollution.

4.1.4 Interpretation

Overall, the combined water and sediment data indicate that the study area is under significant anthropogenic pressure from industrial effluents, oil spills, urban runoff, and domestic wastewater. The spatial patterns of EC, BOD, TOC, and heavy metals point to localized contamination hotspots near urban and port zones.

The observed correlations—particularly between TOC, fine sediments, and heavy metals—imply that organic matter and sediment texture play critical roles in contaminant partitioning. Similar findings have been documented by **Adebayo et al. (2019)** and **Ogbuagu & Ayoade (2022)** in related Nigerian marine environments.

The elevated levels of Pb and Cd pose potential risks to aquatic organisms and humans through bio-accumulation and trophic transfer. These results underscore the importance of continuous monitoring and enforcement of environmental standards to protect coastal ecosystems and associated livelihoods.

4.2 Biological and Ecological Impacts

Marine pollution directly alters the biological integrity and ecological functioning of coastal ecosystems. The present study assessed the impacts of pollution on plankton diversity, benthic macro fauna, and fish communities, alongside bio-accumulation and trophic transfer of contaminants. Results indicate that pollution has caused significant ecological degradation and community-level shifts in the studied marine environment.

4.2.1 Plankton Community Structure

Phytoplankton and zooplankton serve as essential bioindicators of water quality and trophic status. A total of 64 phytoplankton taxa and 35 zooplankton taxa were identified across sampling sites. The dominant phytoplankton groups were Bacillariophyceae (diatoms), Chlorophyceae (green algae), and Cyanophyceae (blue-green algae).

Species richness and abundance were markedly lower in polluted stations compared to reference (clean) sites. Shannon-Wiener diversity indices (H') for phytoplankton ranged from 1.58 to 3.94, with the lowest values recorded near industrial discharge zones. Similar patterns were reported by Ogbuagu and Ayoade (2022), who found reduced diversity due to nutrient enrichment and organic pollution in tropical estuaries.

Dominant tolerant species included *Nitzschia palea*, *Oscillatoria limnetica*, *Euglena gracilis*, and *Microcystis aeruginosa*, indicating eutrophic and organically polluted conditions. These taxa are known to proliferate under high nutrient and low oxygen environments (Odiete et al., 2021). Conversely, sensitive diatoms such as *Thalassiosira sp.* and *Skeletonema costatum* were restricted to less impacted sites, suggesting environmental stress in polluted zones.

Zooplankton assemblages were dominated by copepods (*Cyclops sp.*, *Acartia sp.*) and rotifers (*Brachionus calyciflorus*), with overall densities declining sharply near hydrocarbon and sewage discharge areas. This aligns with Chukwu and Nwankwo (2020), who observed that zooplankton diversity is inversely related to organic load in Lagos Lagoon.

The marked reduction in both phytoplankton and zooplankton diversity indicates ecosystem imbalance caused by altered nutrient dynamics and pollutant toxicity. Low plankton diversity ultimately affects higher trophic levels, as plankton form the primary energy base for aquatic food webs.

4.2.2 Benthic Macrofauna

Benthic macroinvertebrates are vital indicators of sediment health and organic enrichment. The total density of benthic organisms in the study area ranged between 34–180 individuals/m², with higher densities at reference sites and drastically lower values in heavily polluted sediments.

Polluted sites were dominated by opportunistic and pollution-tolerant taxa such as Polychaeta (Capitella capitata), Oligochaeta, and Diptera larvae (Chironomidae). Sensitive groups like Amphipoda, Bivalvia, and Echinodermata were rare or absent. The dominance of opportunistic taxa suggests organic enrichment and hypoxia—a common feature of degraded marine sediments (Essien et al., 2021).

Macrofaunal diversity indices further corroborate this finding: Shannon-Wiener H' ranged from 0.85 to 2.45 in polluted zones and 3.12 to 3.87 at reference locations. Similar trends have been observed by Ajao and Fagade (2020) in the Lagos Lagoon, where hydrocarbon and metal contamination led to reduced macrofaunal richness and community simplification.

Functional group analysis showed a decline in filter-feeders and grazers, with an increase in deposit-feeding species, reflecting a shift toward detritus-based feeding due to sediment contamination. This shift reduces ecosystem resilience and alters nutrient recycling dynamics (Borja et al., 2019).

4.2.3 Fish and Higher Trophic Levels

Fish samples collected from artisanal catches (e.g., *Mugil cephalus*, *Tilapia guineensis*, *Chrysichthys nigrodigitatus*) revealed varying levels of contaminant bioaccumulation. Mean tissue concentrations of Pb (2.1 mg/kg), Cd (0.6 mg/kg), and Cu (4.2 mg/kg) exceeded the FAO/WHO (2019) permissible limits for edible fish in some locations.

Benthic and demersal species recorded higher metal burdens than pelagic species, confirming sediment-associated uptake. The bioaccumulation factor (BAF) followed the trend: Cd > Pb > Cu, indicating stronger bioavailability and trophic transfer of cadmium. These results agree with Kankara et al. (2021) and Eneh et al. (2022), who reported significant metal accumulation in fish species from the Niger Delta and Bonny Estuary, respectively.

Observed physiological and morphological abnormalities, including fin erosion, skin lesions, and reduced gill pigmentation, were most frequent among fish from polluted zones. These abnormalities are biomarkers of chronic pollutant exposure and oxidative stress (Adebayo et al., 2019).

Reduced fish species richness and catch composition across polluted areas suggest habitat degradation and loss of spawning grounds. Such ecological disruptions ultimately compromise fishery sustainability and local food security.

4.2.4 Microbial Indicators and Organic Loading

Microbial analyses showed elevated total hetero-trophic bacterial counts (2.1×10^5 to 7.8×10^6 CFU/mL) and hydrocarbon-utilizing bacteria (1.3×10^4 to 2.9×10^5 CFU/mL) in polluted water and sediment samples. Predominant genera included Pseudonymous, *Bacillus*, and Micro-coccus, which are known hydrocarbon degraders (Okoh et al., 2020).

High microbial abundance indicates intense organic loading and hydrocarbon contamination. According to Atlas and Bertha (2020), proliferation of oil-degrading bacteria is an adaptive response to petroleum hydrocarbon exposure. While microbial activity contributes to natural bio remediation, excessive organic matter can cause oxygen depletion and disrupt nutrient cycling.

4.2.5 Ecological Implications

The combined biological data indicate a progressive decline in biodiversity, trophic structure, and ecosystem functionality within the study area. Reduced plankton and benthic diversity signify a loss of ecological resilience, while contaminant bio-accumulation in fish poses risks to both aquatic health and human consumers.

The dominance of opportunistic species, elevated microbial counts, and community-level shifts are typical signatures of pollution-induced community tolerance (PICT), wherein tolerant species survive while sensitive taxa perish (Blanck, 2002).

Such ecosystem degradation reduces productivity, impairs water purification capacity, and weakens food web stability—factors that collectively threaten the ecological sustainability of marine and coastal systems (UNEP, 2021; Nwankwo & Okeke, 2023).

4.3 Socioeconomic Effects

Marine pollution has far-reaching socioeconomic implications for coastal populations whose livelihoods, health, and cultural identity are directly tied to the marine environment. The findings from field surveys, interviews, and literature review show that pollution has negatively affected fisheries, livelihoods, tourism, public health, and community well-being in the study area.

4.3.1 Impact on Fisheries and Livelihoods

Fishing is the primary occupation for a large proportion of coastal dwellers, particularly artisan fishermen who depend on nearshore waters for daily subsistence. The study revealed a notable decline in fish catch quantity and quality over the past decade. Over 70% of respondents reported lower fish harvests compared to previous years, attributing it to oil spills, industrial effluents, and plastic debris in the marine environment.

Fishers reported that formerly productive creeks and estuaries have become unproductive due to sedimentation, eutrophication, and contamination of spawning grounds. Consequently, they now travel farther offshore, incurring higher fuel and maintenance costs. This is consistent with UNEP (2021) and Nwankwo and Okeke (2023), who documented similar reductions in fish productivity and increased economic vulnerability among artisan fishers in Nigeria's coastal regions.

Fish kills and contamination events have reduced household incomes, forcing some fishers to abandon their trade. Adesina et al. (2020) found that about 30% of coastal fishers in the Niger Delta migrated to other areas or switched occupations due to recurring pollution events. This shift not only affects family income but also disrupts traditional fishing culture and social cohesion.

Furthermore, pollution-induced declines in fish populations affect the supply chain — from processors and traders to transporters and consumers. The reduction in fish availability has led to higher market prices and food insecurity among low-income households (Eneh et al., 2022).

4.3.2 Economic Costs and Livelihood Diversification

The economic cost of marine pollution is both direct and indirect. Direct costs include the loss of fishing income, equipment damage, and reduced market value of contaminated fish. Indirect costs arise from health treatment, loss of ecosystem services, and reduced tourism potential.

A socio-economic assessment of the Niger Delta by Kankara et al. (2021) estimated that oil pollution and waste dumping result in annual livelihood losses of over ₦45 billion (approx. USD 100 million), particularly in fisheries and aquaculture. Many affected households reported resorting to alternative occupations such as petty trading and sand mining, which are often less profitable and environmentally unsustainable.

Moreover, fish processors and traders experience reduced patronage because consumers associate oily smell and taste with contamination. Market surveys conducted during this study showed that smoked fish from polluted areas were sold 20–30% cheaper than those from cleaner regions, confirming a decline in consumer confidence.

4.3.3 Public Health and Community Well-being

Pollution-related health problems were common among residents living near contaminated waters. 58% of respondents reported at least one pollution-related ailment, including skin rashes, eye irritation, respiratory problems, and gastrointestinal infections. Such conditions are linked to contact with contaminated water and consumption of polluted seafood (Adesina et al., 2020; FAO/WHO, 2019).

Heavy metals and hydrocarbons in fish and shellfish can bioaccumulate, posing chronic health risks such as neurological disorders, kidney damage, and cancer (WHO, 2017). According to Eneh et al. (2022), Pb and Cd levels in some edible fish species in Bonny River exceeded permissible dietary limits, suggesting long-term exposure hazards to consumers.

Communities dependent on polluted marine environments also report psychological stress and social instability due to the loss of livelihoods and reduced food security. Women, who constitute a large proportion of fish processors and traders, are disproportionately affected, experiencing income loss and increased economic dependence (Essien et al., 2021).

4.3.4 Impact on Tourism and Coastal Aesthetics

Marine pollution also undermines tourism, recreation, and aesthetic values of coastal environments. Beaches near polluted estuaries exhibit oil sheens, littered plastics, and foul odors, discouraging visitors. Tourist resorts and beach operators in areas such as the Lagos Lagoon and Bonny coastline have reported declining patronage, especially during pollution events or after oil spills (Adebayo et al., 2019).

In a national assessment, UNEP (2021) estimated that Nigeria loses millions in potential coastal tourism revenue annually due to poor water quality, marine litter, and lack of enforcement of environmental standards. Pollution-driven beach degradation also impacts informal economies, including vendors, artisans, and boat operators who rely on tourist activity for income.

4.3.5 Social Conflicts and Environmental Justice

Pollution has heightened social tensions and conflicts between local communities, oil companies, and government agencies. Fisherman associations frequently report disputes over compensation for oil spills and loss of fishing grounds. This aligns with findings by Ajao and Fagade (2020), who observed that poor environmental governance and weak enforcement of pollution laws fuel mistrust and marginalization among coastal residents.

Many respondents expressed dissatisfaction with the perceived lack of accountability and remediation efforts following pollution incidents. This sense of injustice fosters resentment and, in some cases, civil unrest. Thus, marine pollution in Nigeria transcends environmental concerns, evolving into a socio-political and ethical issue of environmental justice (UNEP, 2021; Ogbuagu & Ayoade, 2022)

4.3.6 Broader Implications for Sustainable Development

The socioeconomic effects of marine pollution directly undermine several UN Sustainable Development Goals (SDGs) — notably SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health), SDG 8 (Decent Work and Economic Growth), and SDG 14 (Life Below Water).

The degradation of marine ecosystems reduces natural capital, undermines coastal resilience, and threatens long-term development. Without mitigation, pollution-induced livelihood loss could exacerbate rural-urban migration, unemployment, and poverty along Nigeria's coastlines (UNEP, 2021; Nwankwo & Okeke, 2023)

4.4 Statistical Relationships

4.4.1 Correlation Analysis

Statistical relationships among the measured parameters were evaluated using Pearson's correlation coefficient (r) to determine the degree of association between physico-chemical variables, heavy metals, and biological indicators.

The correlation matrix revealed several significant interdependence:

- Dissolved Oxygen (DO) exhibited a strong negative correlation with Biochemical Oxygen Demand (BOD) ($r = –0.79, p < 0.01$) and Total Organic Carbon (TOC) ($r = –0.68, p < 0.01$). This suggests oxygen depletion due to microbial oxidation of organic matter, characteristic of polluted environments (Okoye et al., 2020; UNEP, 2021).

- Electrical Conductivity (EC) and salinity were positively correlated ($r = 0.72, p < 0.01$), reflecting the influence of saline intrusion and effluent discharge.

- Heavy metals such as Pb, Cd, and Zn showed strong positive intercorrelations ($r > 0.70, p < 0.05$), suggesting a common anthropogenic origin—likely from industrial discharge, oil spillage, and vessel maintenance activities (Eneh et al., 2022).

pH correlated negatively with most metal concentrations, implying increased solubility and mobility of metals under slightly acidic conditions.

These patterns indicate that pollution in the study area is multi-source, influenced by both domestic sewage and industrial inputs, and that water quality parameters are interconnected through biogeochemical cycling processes.

4.4.2 Regression Analysis

A multiple linear regression (MLR) model was applied to assess the predictive influence of physico-chemical parameters on biological health indicators, particularly plankton diversity (H′) and macro-benthic density (N).

The model structure was as follows:

$$H'=\beta0+\beta1(DO)+\beta2(BOD)+\beta3(TOC)+\beta4(Pb)+\beta5(Cd)+\varepsilon H' = \beta_0 + \beta_1(DO) + \beta_2(BOD) + \beta_3(TOC) + \beta_4(Pb) + \beta_5(Cd) + \varepsilon H'=\beta0 +\beta1 (DO)+\beta2 (BOD)+\beta3 (TOC)+\beta4 (Pb)+\beta5 (Cd)+\varepsilon$$

Results showed that DO had a strong positive influence ($\beta = 0.56$, *$p < 0.01$*), while BOD ($\beta = -0.42$, $p < 0.05$) and Pb ($\beta = -0.38$, $p < 0.05$) were negative predictors of biological diversity. The model explained 78% of the variance ($R^2 = 0.78$), indicating that oxygen availability and metal contamination are key determinants of ecological integrity.

A similar model linking heavy metals to fish tissue contamination yielded $R^2 = 0.81$, with Cd ($\beta = 0.64$) emerging as the most significant predictor, confirming its strong bioaccumulation potential (Kankara et al., 2021).

4.4.3 Principal Component Analysis (PCA)

To identify potential pollution sources and parameter groupings, Principal Component Analysis (PCA) was performed on standardized data sets of physico-chemical and heavy metal concentrations. Two major components (PCs) with eigenvalues >1 explained 82% of the total variance in the dataset.

Component	**Dominant Variables**	**Interpretation**	**% Variance**
PC1 (Anthropogenic Source)	Pb, Cd, Zn, Cu, TOC, EC, BOD	Industrial effluents, domestic sewage, oil discharges	56.3%
PC2 (Natural Source)	Fe, Cr, pH, salinity	Lithogenic/geogenic background contributions	25.8%

PC1 represents anthropogenic loading, associated with metals and organic matter introduced by industrial, urban, and oil-related activities. PC2 reflects natural geochemical processes, such as mineral weathering and sediment resuspension (Essien et al., 2021; Eneh et al., 2022).

These findings are consistent with Okoye et al. (2020), who reported that anthropogenic inputs explain most variability in Nigerian coastal sediment chemistry.

4.4.4 Cluster Analysis

Hierarchical Cluster Analysis (HCA) using Ward's linkage and Euclidean distance grouped sampling stations into three distinct clusters based on pollution levels:

1.Cluster A – Low Pollution (Reference Sites):
High DO, low BOD, and minimal metal concentrations.
Represented less disturbed coastal zones.

2. Cluster B – Moderate Pollution (Urban Runoff Zones):
Elevated TOC, moderate Pb and Zn levels, and reduced plankton diversity.

3.Cluster C – High Pollution (Industrial/Port Areas):
Highest Pb, Cd, and BOD; lowest DO and biodiversity.

This classification highlights spatial pollution gradients from pristine to heavily impacted sites, similar to patterns observed in Lagos and Bonny estuaries (Nwankwo & Okeke, 2023).

4.4.5 Interpretation of Multivariate Trends

Overall, the statistical analyses reveal that:

- Organic enrichment (BOD, TOC) and heavy metal contamination (Pb, Cd, Zn) are the primary drivers of ecological degradation.

- The inverse relationship between DO and organic/metal pollutants signifies oxygen depletion due to microbial activity and chemical oxidation.

- PCA and HCA collectively confirm mixed pollution sources — industrial, domestic, and maritime — while regression analysis quantifies their biological consequences.

- These relationships validate the concept of pollution–biota linkage, where deteriorating water quality parameters directly impair aquatic life and indirectly affect socio-economic systems (Blanck, 2002; UNEP, 2021).

4.4.6 Environmental and Management Implications

The strong interdependence among parameters implies that effective management requires integrated control of multiple pollutants rather than single-parameter regulation. The use of multivariate statistics enhances early detection of pollution sources and prioritization of mitigation measures.

Regular application of PCA and correlation models in environmental monitoring programs can support evidence-based management, ensuring better targeting of remediation efforts (Eneh et al., 2022; Okoye et al., 2020).

4.5 Discussion of Findings

The findings reveal that marine pollution has significant environmental and socio-economic repercussions, driven primarily by industrial effluents, oil spills, plastic litter, and poor wastewater management. The elevated levels of heavy metals and organic matter signify persistent contamination that can compromise aquatic biodiversity and food safety.

Ecologically, the reduced species diversity and dominance of tolerant taxa indicate ecosystem stress and trophic imbalance, consistent with the “pollution-induced community tolerance” concept (Blanck, 2002). The accumulation of toxic metals in edible fish poses potential risks to human health through dietary exposure, as also noted by Kankara et al. (2021) in Niger Delta fisheries.

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i4.6 Implications and Management Outlook

The findings of this study demonstrate that marine pollution in the study area is multifactorial — arising from industrial effluents, oil spills, municipal waste, agricultural runoff, and maritime activities. The persistence of high BOD, TOC, and heavy metal concentrations (Pb, Cd, Zn) implies long-term ecological risk due to the cumulative and synergistic effects of contaminants in both water and sediments.

The elevated heavy metal load in sediments indicates the potential for secondary pollution, as metals can be remobilized during dredging, resuspension, or storm events, leading to re-contamination of overlying waters (Okoye et al., 2020; Eneh et al., 2022). This poses serious implications for benthic organisms and higher trophic levels through bioaccumulation and biomagnification, which may persist even after surface water quality improves (Kankara et al., 2021).

Moreover, the observed decline in biodiversity and plankton productivity suggests disruption of key ecosystem processes such as nutrient cycling, primary production, and fish recruitment. These ecological shifts can result in reduced ecosystem resilience and altered food web dynamics (Blanck, 2002; UNEP, 2021).

4.6.1 Socio-Economic Implications

The deterioration of marine environmental quality has direct and indirect socio-economic consequences. Declining fish stocks and contamination of seafood threaten food security, employment, and income stability among coastal populations. This reinforces the vulnerability of small-scale fishers, women processors, and market vendors whose livelihoods depend on healthy marine ecosystems (Adesina et al., 2020; Essien et al., 2021).

Additionally, the degradation of beaches and mangrove ecosystems diminishes the tourism potential of the region, reducing local revenue and deterring private investment. The cumulative economic losses from fisheries, tourism, and health impacts contribute to economic marginalization and increased poverty in coastal communities (Nwankwo & Okeke, 2023; UNEP, 2021).

At a national scale, marine pollution undermines progress toward the UN Sustainable Development Goals (SDGs) — particularly:

. SDG 1 (No Poverty) and SDG 2 (Zero Hunger) — through loss of livelihoods and fish resources.

. SDG 3 (Good Health and Well-being) — via exposure to contaminated seafood and polluted water.

. SDG 8 (Decent Work and Economic Growth) — as pollution-driven unemployment rises.

. SDG 14 (Life Below Water) — through ecosystem degradation and biodiversity loss.

Hence, the implications are both ecological and developmental, requiring integrated environmental governance and sustainable coastal management strategies

4.6.2 Policy and Regulatory Gaps

Despite existing regulations — such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act (2007) and Department of Petroleum Resources (DPR) Environmental Guidelines (2018) — enforcement remains weak. Challenges include limited monitoring capacity, poor inter-agency coordination, and inadequate penalties for non-compliance.

Many industrial facilities discharge untreated or partially treated wastewater directly into coastal waters due to lack of infrastructure or regulatory oversight (UNEP, 2021). This points to a need for institutional strengthening and enhanced data-driven monitoring frameworks for compliance assessment.

Additionally, marine litter and plastic pollution are not adequately covered in current Nigerian policies, even though they represent a growing threat to fisheries and navigation safety (Adebayo et al., 2019; UNEP, 2021).

4.6.3 Recommended Management Strategies

a. Pollution Prevention and Control

Strengthen Effluent Standards and Enforcement: Regular inspection of industrial outfalls and oil facilities to ensure compliance with national effluent standards (NESREA, 2022).

Adoption of Cleaner Production Technologies: Encourage industries to use waste-minimization and recycling approaches that reduce pollutant discharge at the source.

Control of Agricultural Runoff: Implement buffer strips, mangrove restoration, and improved fertilizer management to reduce nutrient and pesticide inflow (FAO, 2020).

b. Monitoring and Early-Warning Systems

Establish Continuous Water Quality Monitoring Stations (CWQMS) equipped with sensors for pH, DO, EC, and hydrocarbon content.

Incorporate remote sensing and GIS tools for real-time detection of oil spills, sediment plumes, and algal blooms (Eneh et al., 2022).

Conduct periodic sediment and biota monitoring to track heavy metal accumulation trends and ecological responses.

c. Ecosystem Restoration and Conservation

Implement mangrove reforestation and wetland rehabilitation programs to restore natural filtration and shoreline protection functions (Essien et al., 2021).

Designate Marine Protected Areas (MPAs) in biodiversity-rich zones to safeguard critical habitats and allow ecosystem recovery (UNEP, 2021).

d. Community Participation and Environmental Education

Engage local fishers and residents through Community-Based Coastal Resource Management (CBCRM) frameworks that promote shared responsibility and stewardship (Nwankwo & Okeke, 2023).

Promote public awareness campaigns about the dangers of improper waste disposal, plastic littering, and oil pollution.

e. Integrated Coastal Zone Management (ICZM)

Adopt ICZM as a national framework for coordinating land–sea interactions, balancing environmental protection with economic development.

Integrate environmental, social, and economic data to guide spatial planning and infrastructure siting along the coast (UNEP, 2021; Ajao & Fagade, 2020).

f. Regional and International Cooperation

Strengthen participation in regional conventions such as the Abidjan Convention and Global Programme of Action for the Protection of the Marine Environment (GPA).

Collaborate with neighboring countries on transboundary pollution control and marine litter reduction programs.

4.6.4 Future Research and Capacity Development

To ensure long-term sustainability, research should focus on:

. Quantifying cumulative ecological risks using modeling tools such as the Ecological Risk Index (ERI) and Sediment Quality Triad (SQT).

. Developing pollution source apportionment models to differentiate between industrial, municipal, and maritime inputs.

. Evaluating the effectiveness of remediation measures and restoration projects over time.

. Strengthening capacity building among local universities and regulatory agencies in environmental monitoring, toxicology, and marine spatial planning (Okoye et al., 2020; UNEP, 2021).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The findings of this study demonstrate that marine pollution exerts profound environmental and socio-economic impacts, affecting not only the ecological balance of marine ecosystems but also the livelihoods and health of coastal populations. Marine environments across the globe are being increasingly contaminated by diverse pollutants including heavy metals, hydrocarbons, pesticides, nutrients, plastics, and untreated wastewater, largely originating from anthropogenic sources such as industrial discharge, agricultural runoff, maritime activities, and coastal urbanization.

5.1.1 Environmental Implications

The environmental consequences of marine pollution are extensive and multi-faceted. Physico-chemical assessments often show elevated concentrations of heavy metals (e.g., Pb, Cd, Hg, and Cu) and hydrocarbon residues in both water and sediments, exceeding international quality guidelines. These contaminants disrupt aquatic food webs by bio accumulating in organisms and bio-magnifying through trophic levels, leading to toxic effects on fish, benthic invertebrates, and marine mammals.

Plastic and microplastic pollution, in particular, have emerged as persistent global threats, causing physical injuries, ingestion-related mortality, and habitat smothering in coral reefs and mangroves. Furthermore, nutrient enrichment from agricultural runoff promotes eutrophication, resulting in harmful algal blooms (HABs), oxygen depletion, and large-scale “dead zones” that drastically reduce biodiversity and productivity (Diaz & Rosenberg, 2008; Smith et al., 2016).

5.1.2 Ecological and Biodiversity Loss

Marine biodiversity is increasingly under threat, as pollution alters critical habitats such as coral reefs, seagrass meadows, and estuaries that serve as nurseries for fish and invertebrates. Habitat degradation, combined with the cumulative stress of overfishing and climate change, has led to a decline in species richness and ecosystem resilience. Such ecological disruptions undermine the ocean’s capacity to provide essential ecosystem services like carbon sequestration, nutrient cycling, and shoreline protection.

5.1.3 Socio-Economic Impacts

The socio-economic ramifications of marine pollution are equally severe. Coastal communities that depend on fishing and aquaculture experience reduced yields due to contaminated habitats and fish mortality, leading to declines in household income and food insecurity (FAO, 2020; UNEP, 2021). The contamination of seafood by toxic pollutants such as mercury and microplastics poses serious public health risks, including neurological and endocrine disorders.

In addition, tourism-dependent economies suffer from loss of aesthetic and recreational value as beaches and coastal waters become polluted. Clean-up operations, loss of tourism revenue, and healthcare costs related to pollution-induced diseases contribute to significant economic burdens on governments and communities (GESAMP, 2019; OECD, 2021).

5.1.4 Integrated Perspective

Ultimately, marine pollution reflects the failure of integrated environmental management and governance frameworks to regulate waste generation and disposal effectively. The interconnectedness of the marine environment means that pollution in one region can have transboundary consequences, affecting distant ecosystems through ocean currents and atmospheric pathways (IMO, 2022; UNEP, 2018).

This study highlights that addressing marine pollution requires a multidisciplinary approach that links environmental science, socio-economics, and governance. Public awareness, community engagement, and effective policy enforcement are key to reversing the current degradation trends. Sustainable management of marine resources is essential not only for ecological integrity but also for achieving the United Nations Sustainable Development Goals (SDGs 13, 14, and 15) related to climate action, life below water, and terrestrial ecosystems (UNEP, 2021).

In conclusion, marine pollution is not merely an environmental issue but a socio-economic and moral challenge that threatens human well-being, biodiversity, and future sustainability. Without immediate and coordinated global action, the cumulative impacts may become irreversible. Therefore, collective efforts at the local, regional, and international levels are vital to restore and protect the world's oceans.

5.2 RECOMMENDATIONS

Marine pollution is a complex and trans-boundary challenge requiring integrated management, policy reform, scientific innovation, and public participation. The following recommendations address the environmental, institutional, and socio-economic dimensions necessary to mitigate its impacts and promote sustainable ocean governance.

1. Strengthen Marine Pollution Monitoring, Regulation, and Enforcement

Governments and environmental regulatory agencies must establish comprehensive monitoring programs for water, sediment, and bio-ta to detect pollution trends and identify critical hot-spots. Enforcement of environmental standards such as MARPOL (IMO, 2022) and the London Convention should be strengthened to control discharges from ships, industries, and coastal cities.

National environmental laws should also be harmonized with international conventions to ensure compliance and accountability (GESAMP, 2019). Regular monitoring data should be made publicly available to encourage transparency and informed decision-making.

Example: The European Union's *Marine Strategy Framework Directive* offers a useful model for national marine monitoring and pollution control frameworks (European Commission, 2017).IMO (2022); GESAMP (2019).

2. Promote Integrated Coastal Zone Management (ICZM) and Ecosystem-Based Approaches

Marine pollution control should be embedded in Integrated Coastal Zone Management (ICZM) programs that balance ecological health with human development needs. ICZM encourages coordination among multiple stakeholders — fisheries, transport, tourism, and local communities — ensuring that economic growth does not compromise environmental quality (UNEP, 2018; Cicin-Sain & Belfiore, 2005).

Incorporating Ecosystem-Based Management (EBM) ensures that the cumulative effects of pollution, overfishing, and climate change are jointly addressed. For developing regions like the Gulf of Guinea and Niger Delta, ICZM would enable more sustainable land–sea linkages and pollution source control (Ukwe et al., 2013).

3. Strengthen Waste Management and Circular Economy Initiatives

Marine litter — especially plastics — largely originates from land-based activities. Governments should prioritize waste minimization, recycling, and circular economy strategies to reduce the flow of waste into waterways.

Policies promoting extended producer responsibility (EPR) can hold manufacturers accountable for the life cycle of their products, especially plastics and packaging materials (Jambeck et al., 2015; OECD, 2021). Investment in municipal solid waste infrastructure, recycling facilities, and sustainable packaging innovations will substantially reduce marine litter loads.

Example: Rwanda's and Kenya's national bans on single-use plastics have proven effective models in Africa for reducing marine litter Jambeck et al. (2015); OECD (2021).

4. Enhance Public Awareness, Education, and Community Participation

Effective marine pollution control requires behavioral change and public involvement. Environmental education campaigns should target schools, fishermen, industries, and tourism operators to raise awareness about pollution sources and sustainable practices (UNESCO-IOC, 2020).

Community-based monitoring programs and citizen science initiatives can empower coastal dwellers to participate in data collection and environmental protection. This enhances local ownership and ensures long-term sustainability (FAO, 2020).

Example: The *Ocean Conservancy's International Coastal Cleanup* initiative demonstrates how public participation can significantly reduce coastal debris and improve awareness FAO (2020); UNESCO-IOC (2020); Ocean Conservancy (2021).

5. Support Research, Data Collection, and Technological Innovation

Investment in marine pollution research and technology development is critical for understanding pollutant pathways, ecosystem responses, and socio-economic consequences. Universities and research institutes should be funded to conduct long-term monitoring of contaminants such as heavy metals, microplastics, and hydrocarbons.

Advanced technologies like remote sensing, GIS, and bio remediation techniques can improve pollution tracking and mitigation efficiency (GESAMP, 2019; Li et al., 2016). Collaborative research networks between developing and developed countries will enhance knowledge exchange and capacity building.

6. Develop Alternative Livelihoods and Promote Sustainable Fisheries

Since marine pollution affects fisheries productivity, governments and NGOs should introduce alternative income-generating activities such as aquaculture, eco-tourism, and marine-based entrepreneurship to reduce pressure on polluted ecosystems (FAO, 2020; UNEP, 2021).

Training and financial incentives can help fishing communities adopt sustainable gear, reduce waste, and transition toward cleaner livelihoods. Sustainable fisheries certification (e.g., MSC programs) can also improve market access and promote environmental responsibility.

7. Foster International and Regional Cooperation

Marine pollution is transboundary, requiring coordinated regional frameworks for data sharing, policy harmonization, and joint pollution response mechanisms. Organizations such as the Abidjan Convention for West and Central Africa and the Global Programme of Action (GPA) for the Protection of the Marine Environment from Land-based Activities offer strong platforms for collaboration (UNEP, 2018).

Regional cooperation can facilitate joint surveillance, emergency response to oil spills, and capacity building among coastal states. For Nigeria and the Gulf of Guinea, regional partnerships are essential to managing shared waters and pollution sources (Ukwe et al., 2013).

8. Enforce “Polluter Pays” and “Precautionary” Principles

Environmental policies should operationalize the polluter pays principle, ensuring that industries and shipping companies bear the economic cost of the pollution they generate (OECD, 2021). Similarly, the precautionary principle should guide decision-making where scientific uncertainty exists — particularly in the case of emerging pollutants such as nanoplastics and microfibers.

Introducing economic instruments such as pollution taxes, discharge fees, and environmental bonds can incentivize cleaner production and compliance with marine protection standards (OECD, 2021).

9. Strengthen Policy Integration with Climate Action and Sustainable Development Goals

Marine pollution mitigation should be aligned with climate change adaptation strategies and the United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) (UNEP, 2021).

Integrated frameworks can ensure synergy between marine conservation, pollution control, and socio-economic development. For instance, “blue economy” strategies encourage economic growth while maintaining ecosystem health and biodiversity.

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