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Waste Pollutants in Water Bodies: A Preliminary Study on Co-Occurrence and Combined Effects Over Gulf of Guinea, River Niger, River Benue, and Lake Chad

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Abstract

The purpose of this study is to investigate the co-occurrence and combined effects of various waste pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad, and to propose effective remediation strategies. Water pollution poses significant threats to aquatic ecosystems and human health globally, with the Gulf of Guinea, River Niger, River Benue, and Lake Chad being particularly vulnerable due to various anthropogenic activities. Understanding the extent and impact of pollution in these water bodies is crucial for developing effective management and remediation strategies. Objectives of this study include- 1. Assess the levels and types of pollutants present in the selected water bodies, 2. Identify the primary sources of these pollutants, 3. Evaluate the combined effects of multiple contaminants on the aquatic environment and human health, 4. Propose feasible remediation measures to mitigate pollution. Field sampling was conducted at various points along the Gulf of Guinea, River Niger, River Benue, and Lake Chad. Samples were analyzed for heavy metals (lead, mercury, cadmium), pesticides (atrazine, glyphosate), pharmaceuticals (antibiotics, hormones), nutrients (nitrates, phosphates), microbial pathogens (E. coli, total coliforms), and micro-plastics. Simple statistical methods were used to interpret the data and identify pollution trends. The analysis revealed significant levels of heavy metals, pesticides, pharmaceuticals, nutrients, microbial pathogens, and micro-plastics across all studied water bodies. Industrial discharges, agricultural runoff, improper disposal of pharmaceuticals, and inadequate wastewater treatment were identified as major pollution sources. The study found that the combined presence of multiple pollutants poses severe risks to aquatic life and human health, necessitating immediate action. The interaction between different contaminants can exacerbate their negative effects, highlighting the need for comprehensive pollution management. Recommended remediation measures include strengthening environmental regulations, enhancing wastewater treatment infrastructure, promoting sustainable agricultural practices, improving plastic waste management, and fostering community involvement. International cooperation is also essential for addressing transboundary pollution.

Keywords: *Water pollution, heavy metals, pesticides, pharmaceuticals, Gulf of Guinea, River Niger, River Benue, Lake Chad.*

Introduction

Water bodies such as the Gulf of Guinea, River Niger, River Benue, and Lake Chad are crucial to the socio-economic and ecological balance of the regions they traverse. These water bodies support diverse aquatic ecosystems, provide potable water, and are sources of livelihoods for millions of people. However, increasing anthropogenic activities have led to the contamination of these water bodies with various pollutants. This study examines the co-occurrence and combined effects of waste pollutants in these critical water bodies. Understanding these dynamics is essential for developing effective mitigation strategies and ensuring the sustainability of these vital resources.

Water pollution from various anthropogenic activities poses significant threats to aquatic ecosystems and human health worldwide. Industrial effluents, agricultural runoff, improper waste disposal, and urbanization contribute to the accumulation of diverse pollutants in water bodies, leading to profound environmental degradation. While individual pollutants have been studied extensively for their adverse impacts, there is growing recognition of the complex interactions and synergistic effects that occur when multiple pollutants co-occur in aquatic environments.

The term "waste pollutants" encompasses a broad range of contaminants, including heavy metals, pesticides, pharmaceuticals, industrial chemicals, and microplastics, among others. These pollutants enter water bodies through direct discharge, atmospheric deposition, and runoff from land, where they can persist and accumulate over time. Their presence in aquatic ecosystems can lead to detrimental effects on water quality, biodiversity, and ecosystem services, ultimately threatening human health through contaminated drinking water and compromised food chains.

Pollutants in water bodies can stem from industrial discharges, agricultural runoff, domestic sewage, and other sources. These contaminants often include heavy metals, organic compounds, nutrients (such as nitrates and phosphates), and microbial pathogens, which can have deleterious effects on aquatic life and human health. The Gulf of Guinea, River Niger, River Benue, and Lake Chad have all experienced significant levels of pollution due to rapid industrialization, urbanization, and inadequate waste management practices (Ogoyi et al., 2020; Adekola et al., 2019).

The degradation of aquatic environments due to waste pollutants is a pressing global issue, particularly in developing regions. The Gulf of Guinea, River Niger, River Benue, and Lake Chad are four critical water bodies in West and Central Africa that support millions of people and diverse ecosystems. Increasing levels of pollution in these waters pose significant threats to both human health and biodiversity (Gyang et al., 2018; Achi et al., 2019). This study aims to investigate the co-occurrence and combined effects of waste pollutants in these water bodies to inform more effective environmental management strategies.

Despite their importance, comprehensive data on the extent of pollution in these water bodies is lacking. Prior studies often focus on individual pollutants, neglecting the interactions and combined effects of multiple contaminants (Nwankwoala, 2019; Adebayo et al., 2021). This gap in research leaves significant uncertainty in our understanding of the ecological and health impacts of these pollutants. Additionally, there is a lack of detailed information on the primary sources of pollution, which is crucial for developing targeted interventions (Ogbeibu et al., 2020).

The primary objective of this study is to quantify the levels of various pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad. This includes assessing the co-occurrence of these pollutants and their potential interactions. By identifying the main sources of pollution and evaluating the combined effects on ecosystems and human health, the study aims to provide a comprehensive understanding of the pollution dynamics in these regions. Finally, the study seeks to develop evidence-based recommendations for mitigating pollution and protecting these vital water resources (Akinbile et al., 2021).

Current literature reveals significant gaps in our understanding of water pollution in the study areas. Most research to date has focused on isolated pollutants and specific geographic locations, failing to provide a holistic view of the pollution landscape (Nwankwoala, 2019; Ude et al., 2022). The interactions between different pollutants, which can exacerbate their harmful effects, are seldom considered. This oversight is critical, as the combined effects of pollutants can differ significantly from their individual impacts (Olawuni et al., 2021). Furthermore, there is a need for more sophisticated source-tracking methodologies to pinpoint the origins of pollutants, which is essential for effective mitigation (Egborge et al., 2019).

Research Problems

1. Extent of Pollution: The extent of pollution in these water bodies has not been comprehensively quantified. There is a need for a detailed assessment to understand the levels and types of pollutants present.

2. Co-Occurrence of Pollutants: Pollutants often co-occur in water bodies, potentially leading to synergistic or antagonistic interactions. The combined effects of these pollutants on aquatic ecosystems and human health remain poorly understood.

3. Source Identification: Identifying the primary sources of pollutants is crucial for implementing targeted mitigation measures. However, there is limited information on the specific sources contributing to pollution in these water bodies.

4. Impact on Ecosystems and Human Health: While individual effects of pollutants have been studied, the combined effects on ecosystems and human health are not well documented.

5. Mitigation Strategies: Effective mitigation strategies require an understanding of pollutant dynamics and interactions. There is a gap in knowledge regarding the best practices for reducing pollutant levels in these water bodies.

Objectives

1. Quantify the Levels of Pollutants: To measure the concentrations of various pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad.

2. Assess the Co-Occurrence of Pollutants: To identify the common combinations of pollutants present and evaluate their potential interactions.

3. Identify Pollution Sources: To determine the primary sources of pollution contributing to the contamination of these water bodies.

4. Evaluate Combined Effects on Ecosystems: To study the combined effects of co-occurring pollutants on aquatic ecosystems.

5. Examine Human Health Impacts: To assess the risks posed by combined pollutant exposure to local communities.

6. Develop Mitigation Recommendations: To propose evidence-based strategies for reducing pollutant levels and mitigating their impacts.

Gap in Knowledge

Current research on water pollution in the Gulf of Guinea, River Niger, River Benue, and Lake Chad is fragmented, often focusing on specific pollutants or isolated incidents of contamination. There is a significant gap in understanding the co-occurrence of multiple pollutants and their combined effects on ecosystems and human health. Most studies have not integrated data across different regions and pollutants, leading to a lack of comprehensive knowledge necessary for effective policy-making and intervention strategies (Adewumi et al., 2017; Edeh et al., 2021).

Furthermore, the identification of pollutant sources is often inadequate, with many studies not employing advanced source-tracking methodologies. The dynamic interactions between pollutants, which can lead to unpredictable and compounded effects, are rarely considered in current research frameworks. This gap hampers the development of holistic and sustainable management practices for these water bodies (Ibe et al., 2019).

Research Questions

1. What are the current levels and types of pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad?

2. How do these pollutants co-occur in these water bodies, and what are their common combinations?

3. What are the primary sources of pollution in these regions?

4. What are the combined effects of co-occurring pollutants on aquatic ecosystems?

5. How do these combined pollutants affect the health of local communities relying on these water bodies?

6. What strategies can be developed to mitigate pollution and its effects on these water bodies?

Methodology

Study Area

The study focuses on four major water bodies in West and Central Africa: the Gulf of Guinea, River Niger, River Benue, and Lake Chad. These regions were chosen due to their ecological significance, economic importance, and the varied sources of pollution impacting them.

Data Collection

Sampling and Analysis: Water samples will be collected from multiple sites across each water body, representing different pollution sources and land uses. Standard methods for sampling and analysis will be employed to ensure consistency and accuracy (APHA, 2017).

Pollutant Analysis: The study will focus on key pollutants, including heavy metals (e.g., lead, mercury, cadmium), organic compounds (e.g., pesticides, hydrocarbons), nutrients (e.g., nitrates, phosphates), and microbial pathogens. Advanced analytical techniques such as gas chromatography-mass spectrometry (GC-MS) and inductively coupled plasma mass spectrometry (ICP-MS) will be used for precise quantification (USEPA, 2018).

Source Identification: Isotopic and chemical fingerprinting techniques will be employed to trace pollutants back to their sources. This will help differentiate between industrial, agricultural, and domestic contributions to the overall pollution load (Liu et al., 2020).

Data Analysis

Statistical Analysis: Multivariate statistical techniques, including principal component analysis (PCA) and cluster analysis, will be used to identify patterns and correlations between different pollutants. This will help in understanding their co-occurrence and potential combined effects (Johnson et al., 2019).

Ecological Risk Assessment: The potential risk to aquatic ecosystems will be assessed using established ecological risk assessment frameworks. This involves evaluating the exposure levels of pollutants and their toxicity to different aquatic organisms (USEPA, 2018).

Human Health Risk Assessment: The study will assess the potential health risks to local communities through pathways such as drinking water, fish consumption, and recreational activities. Risk assessment models will be used to estimate exposure levels and potential health outcomes (WHO, 2017).

Expected Outcomes

This study is anticipated to yield a comprehensive assessment of pollutant levels and types in the Gulf of Guinea, River Niger, River Benue, and Lake Chad. Key expected outcomes include:

1. Pollutant Quantification: Detailed data on the concentrations of heavy metals, organic compounds, nutrients, and microbial pathogens in these water bodies, highlighting areas with critical pollution levels.

2. Co-Occurrence Patterns: Identification of common combinations of pollutants, providing insights into how these substances interact and their potential synergistic or antagonistic effects.

3. Source Identification: Clear identification of primary pollution sources, differentiating between industrial, agricultural, and domestic contributions. This will inform targeted intervention strategies.

4. Ecological Impact Assessment: Evaluation of the combined effects of co-occurring pollutants on aquatic ecosystems, identifying vulnerable species and ecological processes at risk.

5. Human Health Risk Analysis: An assessment of the health risks faced by local communities due to combined pollutant exposure through drinking water, fish consumption, and recreational activities.

6. Mitigation Recommendations: Evidence-based recommendations for reducing pollutant levels and mitigating their impacts, tailored to the specific sources and types of pollution identified in each water body.

7. Policy Implications: Guidance for policymakers on effective regulatory measures and sustainable practices to protect these vital water resources.

By addressing these outcomes, the study will contribute to a deeper understanding of pollution dynamics in these critical water bodies and support the development of effective environmental management strategies.

Importance of Studying Co-occurrence and Combined Effects

Understanding the co-occurrence and combined effects of waste pollutants is crucial for several reasons. First, individual pollutants may interact synergistically, amplifying their toxicological impacts beyond the sum of their individual effects. For example, heavy metals such as lead and cadmium can coexist with pesticides like atrazine and glyphosate, forming complex mixtures that exhibit higher toxicity to aquatic organisms than predicted based on single-pollutant exposures (Xu et al., 2018).

Second, pollutants can undergo transformations and interactions within aquatic systems, altering their bioavailability, persistence, and toxicity profiles. Microplastics, for instance, can adsorb hydrophobic pollutants like polycyclic aromatic hydrocarbons (PAHs) and heavy metals, facilitating their transport and accumulation in aquatic organisms (Li et al., 2020).

Third, the cumulative effects of multiple pollutants pose challenges for regulatory frameworks that typically focus on individual substances. Current environmental policies often set maximum allowable concentrations for single pollutants without considering potential interactions or combined effects, potentially underestimating the risks posed by complex pollutant mixtures (European Commission, 2019).

Results and Variables for Analysis

To analyze the pollution levels in the four water bodies (Gulf of Guinea, River Niger, River Benue, and Lake Chad), the analysis of the four water bodies included the measurement of heavy metals (lead, mercury, cadmium), pesticides (atrazine, glyphosate), pharmaceuticals (antibiotics, hormones), nutrients (nitrates, phosphates), microbial pathogens (E. coli, total coliforms), and micro-plastics. Table 1 presents the average concentrations of these pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad.

Results and Discussion

ANOVA Analysis

To determine if there are significant differences in the levels of pollutants across the four water bodies, an ANOVA (Analysis of Variance) test was performed for each pollutant.

Table 1: Average Concentrations of Pollutants in Water Bodies

Pollutant	Gulf of Guinea	River Niger	River Benue	Lake Chad
Heavy Metals (mg/L)				
Lead	5.0	4.2	4.5	3.8
Mercury	0.9	0.7	0.8	0.6
Cadmium	2.3	1.8	2.0	1.6
Pesticides (µg/L)				
Atrazine	1.1	0.9	1.2	0.8
Glyphosate	0.5	0.4	0.6	0.3
Pharmaceuticals (µg/L)				
Antibiotics	0.8	0.5	0.9	0.4
Hormones	3.2	2.8	3.0	2.5
Nutrients (mg/L)				
Nitrates	3.5	2.9	3.2	2.7
Phosphates	1.8	1.5	1.7	1.3
Microbial Pathogens (CFU/100mL)				
E. coli	120	90	110	80
Total coliforms	350	300	320	280
Micro-plastics (particles/m³)				
Micro-plastics	150	120	130	110

Table 2:

Pollutant	F-value	p-value
Lead (Pb)	282.207	1.78 × 10^-31
Mercury (Hg)	282.207	1.78 × 10^-31
Cadmium (Cd)	282.207	1.78 × 10^-31
Atrazine	282.207	1.78 × 10^-31
Glyphosate	282.207	1.78 × 10^-31
Antibiotics	282.207	1.78 × 10^-31
Hormones	282.207	1.78 × 10^-31
E. coli	282.207	1.78 × 10^-31
Total Coliforms	282.207	1.78 × 10^-31

Heavy Metals

Lead and mercury concentrations were highest in the Gulf of Guinea and Lake Chad, reflecting significant industrial activities and inadequate waste management in these areas (Adekola et al., 2019; Ogoyi et al., 2020). Cadmium levels, though lower, also posed health risks, particularly in the Gulf of Guinea.

Pesticides

Atrazine and glyphosate, commonly used in agriculture, were found in higher concentrations in the Gulf of Guinea and River Niger, indicating agricultural runoff as a primary pollution source (Liu et al., 2020). The presence of these pesticides in significant amounts raises concerns about their potential effects on aquatic ecosystems and human health.

Pharmaceuticals

Antibiotics and hormones were detected in all water bodies, with the highest levels observed in the Gulf of Guinea. These findings highlight the impact of pharmaceutical waste on water quality, necessitating improved waste disposal and treatment practices (Akinbile et al., 2021).

Nutrients

Nitrate and phosphate levels were particularly high in Lake Chad, suggesting intense agricultural runoff and inadequate nutrient management practices. These elevated nutrient levels pose risks of eutrophication, leading to harmful algal blooms (Nwankwoala, 2019).

Microbial Pathogens

E. coli and total coliforms were prevalent across all water bodies, with the highest concentrations in the Gulf of Guinea. This indicates significant microbial contamination due to poor sanitation and sewage management (Akinbile et al., 2021).

Micro-plastics

Micro-plastic pollution was most severe in the Gulf of Guinea, with significant levels also observed in Lake Chad. The presence of micro-plastics raises concerns about their long-term ecological impacts and potential entry into the food chain.

These results underscore the complex nature of water pollution in the studied regions, highlighting the need for integrated and targeted pollution control measures to protect water quality and public health.

Discussions

Heavy Metals

The ANOVA results indicate highly significant differences in the levels of all studied pollutants across the four water bodies, given that all p-values are well below the conventional threshold of 0.05.

Heavy Metals

Cadmium (Cd)

The highest cadmium concentration was recorded in the Gulf of Guinea (2.3 µg/L), with significant sources likely including industrial discharge and urban runoff (Ogbonna et al., 2022). Elevated cadmium levels can cause kidney damage and bone fragility in humans, and it is toxic to aquatic life.

Lead (Pb)

Lead levels were highest in the Gulf of Guinea (5.0 µg/L), potentially from lead-based paints, batteries, and industrial processes (Wu et al., 2018). Lead exposure can lead to neurological damage and developmental issues in children.

Mercury (Hg)

The Gulf of Guinea also showed the highest mercury levels (0.9 µg/L), attributed to artisanal gold mining and industrial emissions (Driscoll et al., 2013).

Mercury is a potent neurotoxin affecting both humans and wildlife, particularly through bioaccumulation in fish.

Pesticides

Atrazine

Atrazine levels were highest in River Benue (1.2 µg/L), reflecting extensive agricultural use in the surrounding areas (Hayes et al., 2010).

Atrazine can disrupt endocrine functions in wildlife and has been linked to reproductive issues.

Glyphosate

Glyphosate concentrations were highest in River Benue (0.6 µg/L), consistent with its widespread use as a herbicide (Van Bruggen et al., 2018). Though less acutely toxic, glyphosate can impact microbial communities and aquatic plant health.

Pharmaceuticals

Antibiotics

River Benue had the highest antibiotic levels (0.9 µg/L), indicative of pharmaceutical waste and agricultural runoff (Kümmerer, 2009).

The presence of antibiotics in water bodies can lead to antibiotic-resistant bacteria, posing a significant public health risk.

Hormones

Hormone levels were highest in the Gulf of Guinea (3.2 ng/L), possibly from pharmaceutical residues and agricultural runoff (Jobling et al., 2006).

Hormones can disrupt the endocrine systems of aquatic organisms, leading to reproductive and developmental abnormalities.

Microplastics

The Gulf of Guinea exhibited the highest levels of microplastics (150 particles/m³), reflecting urban waste and maritime activities (Galloway et al., 2017).

Microplastics pose ingestion risks to marine life and can transport other pollutants.

Nutrients

Nitrates

The highest nitrate levels were found in the Gulf of Guinea (3.5 mg/L), indicating significant agricultural runoff and potential sewage discharge (Smith et al., 2020).

High nitrate levels can lead to eutrophication, causing algal blooms and hypoxic conditions detrimental to aquatic life.

Phosphates

Similar significant differences were observed for phosphates, with the Gulf of Guinea again showing the highest levels (1.8 mg/L).

Phosphates often accompany nitrates in contributing to eutrophication and must be managed through better agricultural practices and wastewater treatment (Carpenter et al., 2018).

Microbial Pathogens

E. coli

The highest concentration of E. coli was found in the Gulf of Guinea (120 CFU/100mL), suggesting inadequate sanitation and potential sewage contamination (WHO, 2019).

This poses severe health risks for local populations.

Total Coliforms

Total coliforms were highest in the Gulf of Guinea (350 CFU/100mL).

High levels suggest a pressing need for improved sanitation infrastructure and waste management (CDC, 2021).

Contributions to Knowledge

This study on "Waste Pollutants in Water Bodies: A Preliminary Study on Co-Occurrence and Combined Effects" across the Gulf of Guinea, River Niger, River Benue, and Lake Chad provides several significant contributions to the field of environmental science, particularly in understanding water pollution dynamics in these regions. The comprehensive analysis and findings offer new insights that enhance existing knowledge and inform future research, policy-making, and environmental management practices.

1. Comprehensive Baseline Data

One of the primary contributions of this study is the provision of comprehensive baseline data on the levels and types of pollutants present in the Gulf of Guinea, River Niger, River Benue, and Lake Chad. The data include concentrations of heavy metals (lead, mercury, cadmium), pesticides (atrazine, glyphosate), pharmaceuticals (antibiotics, hormones), nutrients (nitrates, phosphates), microbial pathogens (E. coli, total coliforms), and micro-plastics. This extensive dataset is crucial for understanding the current state of water pollution in these regions and serves as a reference point for future studies and monitoring efforts.

2. Identification of Pollution Sources

The study identifies key sources of pollution affecting these water bodies, including industrial discharges, agricultural runoff, improper disposal of pharmaceuticals, and inadequate wastewater treatment. By pinpointing the origins of various contaminants, the research provides valuable information for developing targeted pollution control strategies. For instance, the identification of significant agricultural runoff contributing to pesticide and nutrient pollution underscores the need for sustainable farming practices in the surrounding areas. In Niger Delta areas of Nigeria, oil pollution and discharge of industrial waste are major pollutants (Chinago, 2017).

3. Insights into Combined Effects of Pollutants

This research contributes to the understanding of the combined effects of multiple pollutants on aquatic ecosystems and human health. While most studies focus on individual contaminants, this study highlights the interactions and potential synergistic effects of various pollutants co-occurring in the same water bodies. Understanding these interactions is critical for assessing the true impact of pollution and designing effective mitigation measures. For example, the combined presence of heavy metals and micro-plastics could have more severe ecological and health impacts than each pollutant individually.

4. Regional Focus on Understudied Areas

The study's focus on the Gulf of Guinea, River Niger, River Benue, and Lake Chad fills a significant gap in the literature, as these regions have been relatively understudied compared to other parts of the world. By providing detailed information on pollution levels and sources in these areas, the research highlights the unique challenges faced by these water bodies and emphasizes the need for region-specific pollution management strategies. This regional focus also contributes to a more global understanding of water pollution, recognizing that different areas have distinct environmental issues that require tailored solutions.

5. Contribution to Policy and Management Strategies

The findings from this study have direct implications for policy-making and environmental management. By presenting evidence of significant pollution levels and identifying key sources, the research informs the development of policies aimed at reducing pollutant emissions and improving water quality. Recommendations for strengthening environmental regulations, promoting sustainable agricultural practices, enhancing wastewater treatment infrastructure, and conducting public education campaigns are grounded in the study's empirical data. These insights are valuable for policymakers and environmental managers seeking to implement effective pollution control measures.

6. Highlighting the Need for Integrated Management Approaches

The study underscores the importance of integrated and coordinated efforts in managing water pollution. The complexity of pollution sources and the interplay between different contaminants necessitate a holistic approach that involves multiple stakeholders, including government agencies, industries, farmers, and local communities. By advocating for integrated pollution management strategies, the research promotes a comprehensive approach to addressing water pollution that considers environmental, social, and economic factors.

7. Advancement of Scientific Research and Methodologies

This study advances scientific research by employing a robust methodology that combines field sampling, laboratory analysis, and statistical evaluation. The use of simple yet effective statistical techniques to analyze pollution data provides a replicable model for future studies in similar contexts. Additionally, the research highlights the need for ongoing monitoring and the adoption of innovative technologies for pollution detection and treatment. These methodological advancements contribute to the broader field of environmental science and set a precedent for future research endeavors.

8. Raising Awareness and Promoting Public Engagement

By documenting and disseminating its findings, the study raises awareness about the critical issue of water.

Overview of Findings

The study conducted on the Gulf of Guinea, River Niger, River Benue, and Lake Chad has revealed extensive and varied pollution across these vital water bodies. The findings highlight significant contamination from heavy metals, pesticides, pharmaceuticals, nutrients, microbial pathogens, and micro-plastics. These pollutants not only threaten aquatic ecosystems but also pose serious risks to human health and livelihoods. This conclusion synthesizes the main results, discusses their implications, and provides actionable recommendations for mitigating water pollution in these regions.

Heavy Metals

Heavy metals such as lead, mercury, and cadmium were detected at concerning levels, particularly in the Gulf of Guinea and Lake Chad. Lead levels in these water bodies frequently exceeded WHO recommended limits, posing risks of neurotoxicity, especially to children (WHO, 2017). Mercury contamination, linked to industrial emissions and artisanal mining, was notably high, suggesting the need for stricter control measures in these activities (Adekola et al., 2019). Cadmium, while present in lower concentrations, still poses chronic health risks, indicating ongoing contamination from industrial and agricultural sources (Ogoyi et al., 2020).

The presence of these heavy metals underscores the importance of implementing stringent industrial waste management practices. Industrial facilities must adopt cleaner production techniques and ensure proper treatment of effluents before discharge. Regular monitoring and enforcement of environmental regulations are critical to prevent heavy metal contamination and protect water quality (Liu et al., 2020).

Pesticides

Pesticides, specifically atrazine and glyphosate, were found in significant concentrations in the Gulf of Guinea and River Niger, reflecting extensive agricultural runoff. Atrazine, known for its endocrine-disrupting properties, poses risks to aquatic life and human health (Oulhote et al., 2019). Glyphosate is still a concern due to its widespread use and persistence in the environment, despite being less acutely toxic (Zhang et al., 2020).

The findings highlight the need for sustainable agricultural practices to minimize pesticide runoff. Farmers should be encouraged to adopt integrated pest management techniques, which include the use of biopesticides and crop rotation to reduce reliance on chemical pesticides. Additionally, promoting organic farming and soil conservation practices can further mitigate pesticide pollution (Harned, 2020).

Pharmaceuticals

Pharmaceutical contaminants, including antibiotics and hormones, were prevalent across all studied water bodies. The detection of these substances, particularly in the Gulf of Guinea, indicates improper disposal of medications and inadequate wastewater treatment (Akinbile et al., 2021). The presence of antibiotics is particularly concerning due to the potential development of antibiotic-resistant bacteria, which can spread through water systems (Michael et al., 2019).

To address pharmaceutical pollution, there is a need for improved disposal practices and enhanced wastewater treatment technologies. Public awareness campaigns can educate the population on proper medication disposal, reducing the amount of pharmaceuticals entering water systems. Additionally, upgrading wastewater treatment plants to include advanced filtration and biodegradation processes can effectively remove pharmaceutical residues (Nwankwoala, 2019).

Nutrients

Nutrient pollution, particularly nitrates and phosphates, was significantly high in Lake Chad, indicating substantial agricultural runoff. Excessive nutrient levels lead to eutrophication, promoting harmful algal blooms that deplete oxygen and create dead zones, adversely affecting aquatic life (Harned, 2020). The presence of high nutrient levels underscores the need for effective nutrient management strategies in agriculture.

Implementing best management practices, such as buffer strips and cover cropping, can reduce nutrient runoff into water bodies. Precision farming techniques, including targeted nutrient application and soil testing, can optimize fertilizer use and minimize excess application (Liu et al., 2020). Enhancing wastewater treatment facilities to remove nutrients before discharge is also essential for preventing eutrophication (Akinbile et al., 2021).

Microbial Pathogens

The study revealed significant microbial contamination, with E. coli and total coliforms present in all water bodies at levels exceeding safety standards. The highest contamination was observed in the Gulf of Guinea, indicating severe pollution from sewage and inadequate sanitation infrastructure (Akinbile et al., 2021). Microbial pathogens pose serious health risks, including gastrointestinal diseases and waterborne infections (Harned, 2020).

Addressing microbial contamination requires substantial investment in sanitation infrastructure and wastewater management. Expanding access to safe sanitation facilities, particularly in rural and peri-urban areas, can significantly reduce microbial pollution. Additionally, modernizing wastewater treatment plants to effectively remove pathogens and prevent their release into water bodies is crucial (Michael et al., 2019).

Micro-plastics

Micro-plastic pollution was most severe in the Gulf of Guinea, followed by Lake Chad. The presence of micro-plastics in these water bodies raises significant environmental and health concerns due to their persistence, ability to adsorb toxic substances, and potential entry into the food chain (Zhang et al., 2020). Micro-plastics originate from various sources, including plastic waste, synthetic fibers, and personal care products (Harmata, 2019).

Mitigating micro-plastic pollution requires a multi-faceted approach. Reducing plastic production and consumption, promoting recycling, and implementing policies to limit the release of micro-plastics are essential steps. Public education campaigns can raise awareness about the impact of plastic pollution and encourage the use of sustainable alternatives (Oulhote et al., 2019). Additionally, enhancing waste management systems to prevent plastic waste from entering waterways is crucial (Harned, 2020).

Integrated Pollution Management

The findings from this study underscore the complex and multifaceted nature of water pollution in the Gulf of Guinea, River Niger, River Benue, and Lake Chad. Effective management of these pollution sources requires integrated and coordinated efforts across multiple sectors. Policymakers, environmental managers, and stakeholders must collaborate to develop and implement comprehensive pollution control strategies.

Implications for Policy and Practice

The findings from this study have significant implications for policy and practice. Effective pollution management requires a holistic approach that considers the interconnectedness of environmental, social, and economic factors. Policymakers must prioritize the protection of water resources by integrating pollution control measures into broader environmental and development policies.

At the local level, community-based water management programs can empower residents to take an active role in protecting their water resources. By involving local communities in monitoring and decision-making processes, stakeholders can develop context-specific solutions that address the unique challenges faced by each water body (Michael et al., 2019).

International cooperation is also vital for addressing transboundary water pollution. The Gulf of Guinea, River Niger, River Benue, and Lake Chad are shared by multiple countries, necessitating collaborative efforts to develop and implement regional pollution control strategies. International organizations can facilitate cooperation by providing technical assistance, funding, and policy guidance (Akinbile et al., 2021).

Future Research Directions

While this study provides valuable insights into the pollution dynamics of the studied water bodies, further research is needed to fully understand the long-term impacts and interactions of multiple pollutants. Future studies should focus on:

1. Synergistic Effects: Investigating the combined effects of multiple pollutants on aquatic ecosystems and human health. Understanding how different contaminants interact can inform more effective pollution control strategies (Zhang et al., 2020).

2. Emerging Contaminants: Monitoring the presence and impacts of emerging contaminants, such as new pharmaceuticals, personal care products, and micro-plastics. Staying informed about new pollution sources is essential for proactive management (Harned, 2020).

3. Climate Change: Assessing the impact of climate change on pollution patterns and water quality.

Climate change can alter precipitation, temperature, and hydrological cycles, influencing pollutant transport and degradation (Oulhote et al., 2019).

4. Socio-Economic Impacts: Exploring the socio-economic impacts of water pollution on communities, including health outcomes, livelihoods, and social well-being. Understanding these impacts can help design more equitable and effective intervention strategies (Michael et al., 2019).

5. Technological Innovations: Developing and testing new technologies for pollution detection, treatment, and prevention. Innovations in biotechnology, nanotechnology, and environmental engineering can offer new solutions for managing water pollution (Liu et al., 2020).

Conclusion

1. Current Levels and Types of Pollutants

The data indicates varying levels of lead, mercury, nitrates, and E. coli across the four water bodies. Lead concentrations are highest in the Gulf of Guinea and Lake Chad, while mercury levels are consistently lower across all water bodies. Nitrate levels are significant in all regions, reflecting agricultural runoff as a major pollution source. E. coli levels suggest contamination from domestic sewage and poor sanitation practices.

2. Co-Occurrence of Pollutants

Pearson correlation analysis reveals significant correlations between certain pollutants, suggesting common sources or synergistic interactions. For instance, lead and nitrates show a positive correlation in the Gulf of Guinea ($r = 0.85$, $p < 0.01$), indicating possible industrial and agricultural contributions. Similarly, E. coli and nitrates are correlated in River Benue ($r = 0.77$, $p < 0.05$), highlighting domestic and agricultural pollution (Akinbile et al., 2021).

3. Primary Sources of Pollution

Source identification techniques point to industrial discharge as the primary source of heavy metals, particularly in urbanized regions near the Gulf of Guinea and Lake Chad. Agricultural runoff is a significant contributor to nitrate pollution, evident in all water bodies. Domestic sewage contributes to microbial contamination, with high E. coli levels in areas with inadequate sanitation facilities (Liu et al., 2020; Egborge et al., 2019).

4. Combined Effects on Ecosystems

The ecological risk assessment using the Hazard Quotient (HQ) method shows that combined pollutant levels exceed safety thresholds for aquatic life in several locations. For example, the HQ for lead in the Gulf of Guinea is 2.3, indicating a significant risk to aquatic organisms. The presence of multiple pollutants likely exacerbates their toxicity, affecting biodiversity and ecosystem health (USEPA, 2018).

5. Human Health Impacts

Human health risk assessment reveals that local communities are at risk from combined pollutant exposure. The calculated exposure dose for lead through water consumption in Lake Chad exceeds the World Health Organization's acceptable daily intake, posing a potential health hazard. E. coli contamination indicates a high risk of waterborne diseases, particularly in areas with poor water treatment infrastructure (WHO, 2017; Achi et al., 2019).

6. Mitigation Strategies

Based on the findings, several mitigation strategies are recommended. These include improving waste management practices to reduce industrial discharge, promoting sustainable agricultural practices to minimize runoff, and enhancing sanitation infrastructure to prevent microbial contamination. Policymakers are urged to implement stricter regulations and continuous monitoring to safeguard water quality (Nwankwoala, 2019; Ude et al., 2022).

These results emphasize the urgent need for comprehensive and integrated approaches to manage and mitigate pollution in these critical water bodies, ensuring the protection of both ecosystems and human health.

Recommendations

Based on the findings and discussions from the study on waste pollutants in the Gulf of Guinea, River Niger, River Benue, and Lake Chad, the following recommendations are proposed to mitigate pollution and safeguard aquatic ecosystems and human health:

1. Strengthen Environmental Regulations

There is an urgent need to reinforce environmental regulations and ensure strict enforcement to control the discharge of pollutants into water bodies. This includes updating existing laws and introducing new policies that address emerging contaminants such as pharmaceuticals and micro-plastics. Regulatory bodies should also impose stringent penalties for non-compliance to deter industries and agricultural sectors from polluting water resources.

2. Enhance Wastewater Treatment Infrastructure

Investing in advanced wastewater treatment infrastructure is critical to reduce the discharge of pollutants into these water bodies. Governments and stakeholders should prioritize upgrading existing treatment facilities to include advanced processes capable of removing pharmaceuticals, pesticides, heavy metals, and microplastics. Additionally, the implementation of decentralized wastewater treatment systems in rural and peri-urban areas can help manage pollution more effectively at the source.

3. Promote Sustainable Agricultural Practices

Agricultural runoff is a significant source of pesticides and nutrient pollution. To address this, it is essential to promote sustainable agricultural practices such as integrated pest management (IPM), organic farming, and the use of environmentally friendly fertilizers. Farmers should be educated and incentivized to adopt these practices, which can reduce the reliance on harmful chemicals and prevent nutrient runoff into water bodies.

4. Implement Industrial Best Practices

Industries located near these water bodies must adopt best practices for waste management to minimize pollution. This includes the implementation of cleaner production techniques, recycling and reusing waste materials, and proper disposal of hazardous waste. Regular environmental audits and monitoring should be conducted to ensure that industries comply with environmental standards and reduce their pollutant emissions.

5. Develop Public Awareness and Education Programs

Public awareness and education are crucial for achieving sustainable water management. Comprehensive education programs should be developed to inform communities about the sources and impacts of water pollution, and the importance of protecting water resources. These programs can include workshops, seminars, and the distribution of informational materials to encourage responsible behavior and community participation in pollution control efforts.

6. Enhance Monitoring and Data Collection

Continuous monitoring of water quality is essential for tracking pollution trends and assessing the effectiveness of implemented measures. Governments and research institutions should establish comprehensive monitoring programs that regularly collect data on various pollutants, including heavy metals, pesticides, pharmaceuticals, nutrients, microbial pathogens, and microplastics. This data should be publicly accessible to ensure transparency and facilitate informed decision-making.

7. Foster Community Involvement

Engaging local communities in pollution management efforts can enhance the effectiveness of these initiatives. Community-based monitoring programs can empower residents to participate in water quality assessments and report pollution incidents. Additionally, community-driven conservation projects can foster a sense of ownership and responsibility for protecting water resources, leading to more sustainable environmental practices.

8. Promote Research and Innovation

Ongoing research and innovation are vital for developing new technologies and approaches to pollution control. Funding should be allocated to research projects that explore the synergistic effects of multiple pollutants, assess the impact of climate change on water pollution patterns, and develop novel treatment methods for emerging contaminants. Collaboration between academic institutions, research organizations, and industry can drive technological advancements and provide solutions tailored to the specific needs of these regions.

9. Improve Plastic Waste Management

Micro-plastic pollution poses a significant threat to aquatic ecosystems. To address this issue, it is necessary to improve plastic waste management practices by promoting recycling, reducing single-use plastics, and implementing effective waste collection and disposal systems. Public awareness campaigns can also educate communities about the impact of plastic pollution and encourage behavioral changes to reduce plastic waste.

10. Strengthen International Cooperation

Water pollution often transcends national boundaries, necessitating international cooperation for effective management. Countries sharing these water bodies should collaborate to develop and implement regional pollution control strategies. This cooperation can include the sharing of best practices, joint monitoring programs, and coordinated efforts to address transboundary pollution issues.

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