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Analysis of Industrial Wastewater Effects on Surface Water Quality of the Kafue River in Zambia

[1] Jacqueline Kabwe, [2] Danny Chisanga Musenge

[1, 2] Department of Agriculture and Environmental Science, Information and Communication University, Zambia Research and Development Centre, Lusaka, Zambia

Corresponding Author: **Jacqueline Kabwe**

Abstract

The Kafue River is a vital socio-economic and ecological resource for Zambia, but faces severe degradation from industrial wastewater discharge. This study aimed to analyze the impact of industrial effluents on the surface water quality of the Kafue River, focusing on spatial and temporal variations and compliance with regulatory standards. A quantitative research design was employed, with water samples collected from upstream, midstream, and downstream zones in both dry and wet seasons. Key physicochemical parameters---including pH, turbidity, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrates, ammonium, phosphorus, and electrical conductivity---were analyzed using standard laboratory methods and statistical tools (SPSS). The findings revealed significant spatial degradation, with downstream zones exhibiting the highest levels of turbidity, nutrients (nitrate, ammonium, phosphorus), organic pollution (BOD, COD), and electrical conductivity, alongside critically low dissolved oxygen. Strong negative correlations were found between DO and pollutants, indicating oxygen depletion from organic and nutrient loading. Seasonal analysis showed significantly worse water quality in the wet season due to amplified runoff. The study concluded that industrial wastewater discharge has a substantial and measurable detrimental effect on the Kafue River's water quality, leading to eutrophication risk and ecological stress. The results underscore systemic non-compliance with ZEMA and WHO standards, highlighting critical gaps in regulatory enforcement and the urgent need for advanced wastewater treatment, integrated catchment management, and robust policy implementation.

Introduction
Background
The Kafue River is one of Zambia's most critical natural assets, essential for agriculture, hydropower, industry, and community livelihoods. Spanning approximately 1,576 km, it supports diverse ecosystems like the Kafue Flats, a vital wetland for biodiversity (Kapambwe *et al*., 2017) [15]. However, rapid industrial development within the Kafue District has led to the discharge of substantial volumes of untreated or partially treated wastewater into the river. Effluents from fertilizer manufacturers (e.g., Nitrogen Chemicals of Zambia) and agro-processors (e.g., Kafue Sugar PLC) introduce nutrients and organic compounds, severely compromising water quality (Ng'ambi & Tembo, 2021; Jones *et al*., 2020) [27, 14]. This pollution threatens aquatic life, ecosystem services, and public health, with communities reporting high incidences of waterborne diseases (Kasonde *et al*., 2020) [16]. Despite existing regulatory frameworks like the Environmental Management Act (2011) enforced by the Zambia Environmental Management Agency (ZEMA), effective pollution control remains a challenge, necessitating detailed assessment to inform mitigation strategies.

Statement of the Problem
The Kafue River, particularly around Kafue Township, is experiencing intense degradation due to concentrated industrial pollution. Industries discharge large volumes of wastewater laden with organic pollutants and nutrients directly into the river. This has led to observable ecological consequences: declines in fish populations, proliferation of aquatic weeds, habitat

destruction, and increased public health risks from waterborne diseases. While the problem is recognized, there is a lack of comprehensive, localized studies that systematically quantify the spatial and temporal impact of these discharges, evaluate compliance with standards, and link pollutant dynamics to specific industrial sources. This study addresses that gap by providing an empirical analysis of how industrial wastewater alters the physicochemical quality of the Kafue River's surface water.

Objectives of the Study
The main objective was to determine the impact of industrial wastewater on the surface water quality of the Kafue River in Zambia.

Specific objectives of the study
1. To analyze the physical and chemical characteristics of surface water in the Kafue River in relation to industrial effluent.
2. To evaluate the spatial and temporal variations in water quality parameters along different sections of the river affected by industrial discharges.
3. To assess the compliance of industrial wastewater effluent with Zambian (ZEMA) and international water quality standards.

Hypothesis
1. H₀ (Null Hypothesis): Industrial wastewater discharge has no significant effect on the physical and chemical quality of surface water in the Kafue River.
2. H₁ (Alternative Hypothesis): Industrial wastewater discharge has a significant effect on the physical and chemical quality of surface water in the Kafue River.

Theoretical Framework
Human Ecology Theory
This study is anchored on Human Ecology Theory, which provides a lens to understand the dynamic interactions between human activities (industrial operations) and the natural environment (aquatic ecosystem) (Bennett & Satterfield, 2018) [6]. The theory emphasizes the interdependence between socio-economic systems and ecological health. In the context of the Kafue River, it explains how industrial subsystems (e.g., manufacturing plants in Kafue Township) disrupt the natural river subsystem through pollutant discharge, leading to altered water chemistry (e.g., oxygen depletion, nutrient loading) and subsequent impacts on aquatic life and dependent human communities. This framework supports the development of sustainable strategies that reconcile industrial growth with environmental stewardship and informed policy-making.

Conceptual Framework of Industrial Wastewater Impact on Surface Water Quality
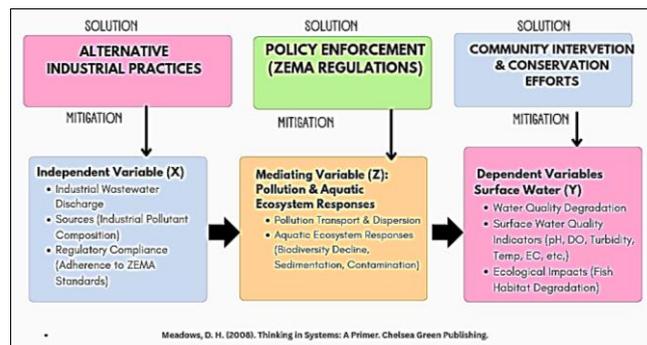

Fig 1: Conceptual Framework

The conceptual framework (Fig. 1) structures the analysis of industrial wastewater impact. The Independent Variable (X) is Industrial Wastewater Discharge, defined by pollutant composition and volume. This influences the Mediating Variable (Z), Pollution & Aquatic Ecosystem Responses, which includes pollutant transport and biological effects like biodiversity decline. These processes lead to the Dependent Variables (Y), Surface Water Quality Degradation, measured through specific physicochemical indicators (pH, DO, Turbidity, etc.) and ecological impacts. The framework integrates Mitigation Strategies—Policy Enforcement, Community Intervention, and Alternative Industrial Practices—as necessary interventions to disrupt the pollution pathway and restore water quality.

Literature Review
Sources and Composition of Industrial Wastewater
Industrial wastewater composition is highly variable, depending on the sector and processes involved. Globally, a significant challenge in developing contexts like Zambia is the informal or indirect use of untreated wastewater, often for agriculture due to water scarcity (Qadir *et al*., 2020) [30]. In the Kafue River catchment, key polluting industries include fertilizer plants, which discharge nitrogen and phosphorus compounds leading to eutrophication (Ng'ambi & Tembo, 2021) [27], and agro-processing operations such as sugar mills, which release organic matter and nutrients (Jones *et al*., 2020) [14]. These pollutants fundamentally alter the chemistry of receiving water bodies. The historical evolution of wastewater management, from primitive disposal to advanced treatment technologies in developed nations, contrasts sharply with the treatment gaps and infrastructural limitations prevalent in many African countries, including Zambia (Mubanga & Kambole, 2019) [25].

The most common pollutants found in industrial wastewater in the Kafue River context include organic compounds (measured as BOD and COD), nutrients (nitrates, ammonium, phosphorus), suspended solids (contributing to turbidity), and microbial contaminants from faecal wastes (Jones *et al*., 2020; Kasonde *et al*., 2020) [14, 16]. Microbiological contamination introduces pathogens capable of causing waterborne diseases. Treatment methodologies are broadly categorized into biological processes, which use microorganisms to break down organic matter, and chemical processes, such as precipitation and adsorption, which are often more efficient but costlier and can generate hazardous sludge (Singh *et al*., 2017; Gangaraju *et al*., 2021) [33, 13].

Impact on Water Quality Parameters and Ecosystems
The discharge of industrial effluents critically alters fundamental water quality parameters. Elevated Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) indicate high organic loading, which depletes dissolved oxygen (DO), creating hypoxic conditions lethal to aquatic fauna (Fredrickson *et al*., 2018) [12]. Nutrient pollution (nitrates, phosphates) drives eutrophication, causing algal blooms, further oxygen depletion, and biodiversity loss (Zimba & Kunda, 2019) [40]. Studies specific to the Kafue River confirm these trends, documenting fish kills and habitat degradation linked to spills and chronic discharges from agro-processing (Jones *et al*., 2020; Banda *et al*., 2020) [14, 41]. These changes degrade ecosystem services---such as fisheries and natural water purification---and pose direct risks to human health through contaminated drinking and irrigation water, with communities reporting high incidences of diseases like diarrhea and gastroenteritis (Kasonde *et al*., 2020) [16].
A comparative analysis of river systems worldwide reveals that successful remediation, as seen in the Thames River (UK) and Rhine River, relies on stringent regulations and advanced treatment (Walsh & Ward, 2022) [38]. In contrast, severely polluted rivers like the Yamuna in India highlight the challenges of management in densely populated, industrial areas despite intervention plans. In Africa, rivers such as the Crocodile and Vaal in South Africa face crises due to failing wastewater treatment infrastructure and enforcement gaps, mirroring the challenges observed in Zambia.

Regulatory Frameworks and Management Challenges
Effective governance is paramount for pollution control. Internationally, frameworks like the EU Water Framework Directive and the US Clean Water Act set stringent standards for pollutant discharge (European Communities, 2001; Walsh & Ward, 2022) [10, 38]. In Zambia, the Environmental Management Act (2011) established the Zambia Environmental Management Agency (ZEMA) as the primary regulatory body (Parliament of Zambia, 2011) [29]. However, literature consistently identifies a significant enforcement gap---limited institutional capacity, financial resources, and technical expertise hinder effective monitoring and compliance (Fernandez & Shaw, 2016; Mubanga & Kambole, 2019) [11, 25]. This gap allows industries to bypass treatment requirements, exacerbating river pollution. The regulatory framework is further supported by acts like the Water Resources Management Act (2011) and the Mines and Minerals Development Act

(2015), which mandate environmental impact assessments and pollution prevention. Despite these laws, systemic non-compliance persists, as evidenced by continued effluent violations in the Kafue River (Moyo & Kachale, 2023) [47].

Wastewater Treatment Technologies and Practices
Conventional wastewater treatment typically involves primary (physical), secondary (biological), and tertiary (advanced) processes. Primary treatment uses coagulation-flocculation to remove suspended solids, while secondary treatment often employs the Activated Sludge Process (ASP) to degrade organic matter (Gangaraju *et al*., 2021) [13]. However, these methods have limitations; they are often inefficient at removing persistent contaminants like endocrine-disrupting chemicals (EDCs) and certain nutrients (Singh *et al*., 2017; Gangaraju *et al*., 2021) [33, 13]. Disinfection via chlorination can form harmful by-products like trihalomethanes (THMs) (Singh *et al*., 2017) [33].
Emerging technologies offer promising solutions. Enzyme-based treatments enhance the biodegradation of toxic pollutants (Singh *et al*., 2017) [33]. Membrane technologies, particularly Nano-filtration (NF) and Membrane Bioreactors (MBRs), have demonstrated high efficiency in removing nutrients and complex organics from industrial streams (Drioli *et al*., 2017; Meschke *et al*., 2018) [9, 22]. Case studies from Kanpur, India, and Hyderabad, India, demonstrate both the challenges of managing industrial tannery waste and the potential of large-scale treatment and informal wastewater reuse in agriculture. The adoption of such advanced, cost-effective technologies is crucial for regions like the Kafue District.

Research Gap
While existing studies acknowledge pollution in the Kafue River, a clear research gap exists. There is a need for localized, systematic analyses that quantitatively assess the spatial gradient of pollution, its seasonal dynamics, and direct compliance with ZEMA and WHO standards (Moyo & Kachale, 2023; Aurélien *et al*., 2022) [47, 48]. Furthermore, many studies focus on a single pollutant type or lack empirical linkage to specific industrial sources in Kafue District. This research fills this gap by providing a holistic physicochemical assessment across multiple zones and seasons, statistically linking degradation to industrial discharge points, and evaluating the effectiveness of the current regulatory approach, thereby offering evidence-based insights for targeted mitigation strategies (Jones *et al*., 2020; Banda *et al*., 2020) [14, 41].

Methods and Procedures
Research Design
This study adopted a quantitative, empirical research design to assess the environmental impact of industrial wastewater on surface water quality in the Kafue River. The design focused on the systematic measurement and statistical analysis of physicochemical parameters to objectively determine pollution levels, spatial trends, and seasonal variations. This approach aligns with data-driven methodologies recommended for assessing pollution in ecologically sensitive riverine systems (Jones *et al*., 2020) [14].

Study Area
The study was conducted on the Kafue River within Kafue

District, Zambia, a region characterized by concentrated industrial activity. The river is a vital resource for agriculture, hydropower, and community livelihoods, making it particularly vulnerable to pollution from adjacent industries (Jones *et al*., 2020; Kasonde *et al*., 2020) [14, 16]. To capture the spatial impact of effluent discharge, three strategic sampling zones were identified along a pollution gradient:

- Upstream: A relatively unpolluted control zone, minimally influenced by Kafue Township industries.
- Midstream: The section of the river that receives direct industrial effluent discharges from major manufacturing and agro-processing facilities located within the Kafue industrial.
- Downstream: A zone reflecting the cumulative impact of pollution from both midstream and additional runoff, affecting water quality for downstream ecosystems and communities.

Sampling was conducted over both the **dry season** (September November 2024) and **wet season** (December-April 2025) to capture critical temporal variations in water quality driven by rainfall and runoff patterns.

Sampling Techniques
A stratified random sampling strategy was employed for water quality assessment. This technique enhances representativeness by segmenting the population---in this case, the river---into distinct subgroups (zones) based on shared characteristics (pollution exposure) before random sampling within each (Palinkas *et al*., 2015) [49]. Water samples were collected from multiple points within each of the three zones (Upstream, Midstream, Downstream) to ensure data diversity and robustness. In addition to environmental sampling, quota sampling was used to engage key stakeholders---including industry representatives, ZEMA officials, and community members---to provide contextual insights into wastewater management practices and challenges.

Data Collection Methods
Primary Data Collection involved field-based water sampling and laboratory analysis. *In-situ* measurements of temperature and pH were taken at each sampling point using calibrated portable meters (Hanna Instruments). Water samples were collected in pre-cleaned polyethylene bottles, preserved according to standard methods (APHA, 2017), and transported on ice to an accredited laboratory for analysis.
The following physicochemical parameters were analyzed using standard methods:
- Turbidity: Nephelometric method (NTU).
- Electrical Conductivity (EC): Conductivity meter (μS/cm).
- Dissolved Oxygen (DO): Winkler titration method (mg/L).
- Biochemical Oxygen Demand (BOD): 5-day BOD test (mg/L).
- Chemical Oxygen Demand (COD): Closed reflux method (mg/L).
- Nutrients: Nitrate (NO_3^-), Ammonium (NH_4^+), and Phosphorus (P) via spectrophotometry (mg/L).

Secondary Data included historical water quality reports from the Zambia Environmental Management Agency (ZEMA), environmental impact assessments, and relevant scientific literature to contextualize findings within existing pollution trends and regulatory frameworks (Parliament of Zambia, 2011; Jones *et al*., 2020) [29, 14].
Photographic Documentation was maintained throughout the process, from on-site sampling to laboratory analysis, to ensure procedural transparency and provide visual evidence of fieldwork conditions (See Appendix, Figures 9-12).

Data Analysis
Data were analyzed using Statistical Package for the Social Sciences (SPSS) version 26. Analytical procedures included:
Descriptive Statistics: Calculation of mean, standard deviation, minimum, and maximum for all parameters to summarize central tendencies and variability.

Inferential Statistics:
One-Way Analysis of Variance (ANOVA): To test for statistically significant differences in water quality parameters across the three river zones (Upstream, Midstream, Downstream).
Independent Samples t-test: To compare mean parameter values between the dry and wet seasons and determine seasonal significance.
Pearson's Correlation Analysis: To examine the strength and direction of relationships between parameters (e.g., DO vs. BOD/COD, nutrients vs. organic pollution).
Compliance Assessment: Measured values for each parameter were compared against the Zambian (ZEMA) and international (WHO) water quality guidelines to evaluate regulatory compliance.

Ethical Considerations
The study adhered to strict ethical guidelines. Informed consent was obtained from all interview and survey participants. Environmental sampling protocols followed safety standards to prevent contamination. The research protocol was reviewed and approved by the Ethics Committee of the Information and Communications University (ICU) and received oversight from the Zambia Resources and Development Center (ZRDC) Committee, ensuring alignment with national and institutional research ethics standards.

Limitations of the Study
Seasonal Variability: While two seasons were covered, intra-seasonal variability (e.g., early vs. late wet season) could influence results.
Access Constraints: Limited access to some industrial discharge points or historical compliance data may have restricted source-specific analysis.
Stakeholder Bias: Responses from industry representatives or community members may have been influenced by social desirability or vested interests.
To mitigate these limitations, the study employed triangulation through multiple data sources, rigorous statistical validation, and transparent reporting of methodological constraints.

Findings the Results
A. Descriptive Statistics and Spatial Variation in Water Quality
The analysis of water samples from the Kafue River revealed significant degradation in water quality, particularly in downstream zones. Table 1 presents the

descriptive statistics for key physicochemical parameters across the three sampling zones.

Table 1: Descriptive Statistics of Water Quality Parameters in the Kafue River

Parameters	Upstream	Mid stream	Down stream	ZEMA WHO
Temperature (°C)	24.1	25.8	26.8	< 30
pH	7.25	7.32	7.38	6.5 – 8.5
Turbidity (NTU)	5.8	9.4	15.2	≤ 5
Electrical Conductivity (µS/cm)	315	380	465	≤ 1500
Dissolved Oxygen (mg/L)	5.8	4.5	3.1	≥ 5
BOD (mg/L)	7.4	10.6	14.2	≤ 10
Nitrate (mg/L)	8.1	12.3	18.5	≤ 45
Ammonium (mg/L)	1.1	1.8	3.2	≤ 1.5
Phosphorus (mg/L)	1.8	3.4	5.9	≤ 2.2

Note: Values are mean concentrations. BOD = Biochemical Oxygen Demand

As shown in Table 1, turbidity, BOD, ammonium, and phosphorus exceeded regulatory limits in midstream and downstream zones. Dissolved oxygen fell below the 5 mg/L threshold in downstream areas, indicating hypoxic conditions harmful to aquatic life.

The spatial degradation trend is visually evident in Figure 1, which shows the significant decline in dissolved oxygen from upstream to downstream.
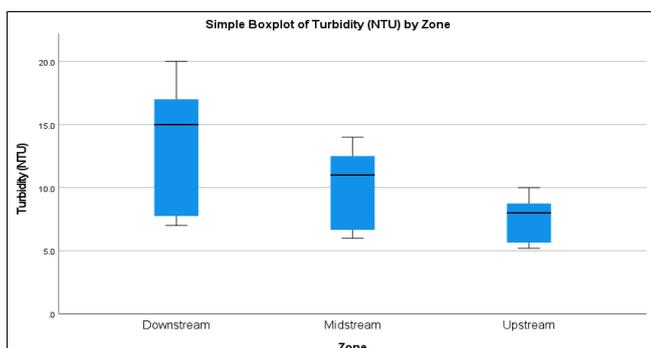
Spatial Variation

Fig 2: Boxplot of Turbidity by Zone

Turbidity increased significantly downstream, with several high outliers, indicating frequent particulate pollution events.
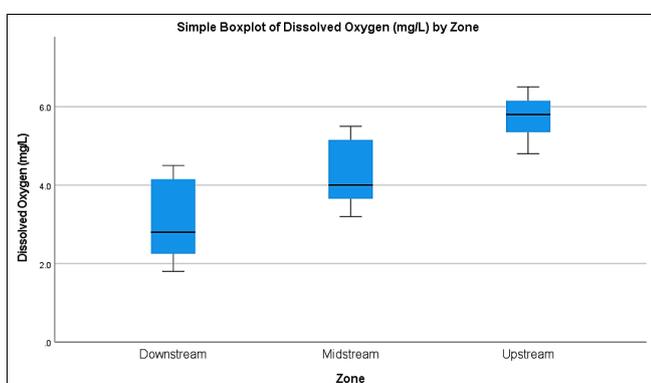

Fig 1: Boxplot of Dissolved Oxygen by Zone

DO levels declined progressively downstream, with median values near hypoxic levels in the downstream zone.

Interpretation: The spatial gradient confirms that industrial discharge points significantly degrade water quality as the river flows through Kafue Township.

Seasonal Variation

Table 2: Seasonal Comparison of Key Parameters

Parameter	Dry Season Mean	Wet Season Mean	p-value
BOD (mg/L)	7.36	14.21	0.005
COD (mg/L)	22	42.08	0.006
DO (mg/L)	5.27	3.74	0.009

Interpretation: Wet season values are significantly worse due to runoff and increased effluent discharge, highlighting seasonal vulnerability.

Correlation Analysis

Strong negative correlations were found between DO and pollutants (BOD, COD, nutrients), indicating that organic and nutrient loading directly depletes oxygen.

Table 3: Correlation Matrix of Key Water Quality Parameters

DO	BOD	COD	Nitrate	Ammonium	Phosphorus	
DO	1	-0.984	-0.985	-0.971	-0.977	-0.954
BOD	-0.984	1	0.999	0.997	0.997	0.99
COD	-0.985	0.999	1	0.995	0.996	0.989
Nitrate	-0.971	0.997	0.995	1	0.996	0.996
Ammonium	-0.977	0.997	0.996	0.996	1	0.995
Phosphorus	-0.954	0.99	0.989	0.996	0.995	1

All correlations significant at $p < 0.01$.

Interpretation: Strong negative correlations between DO and pollutants confirm that organic and nutrient loads drive oxygen depletion.

Table 4: One-Way ANOVA Results Across River Zones

Parameter	Sum of Squares (Between)	F-value	p-value
Turbidity	380.547	19.027	<0.001
Electrical Conductivity	151,873.8	7593.69	<0.001
Dissolved Oxygen	38.57	1.928	<0.001
BOD	695.623	34.781	<0.001
COD	6,181.24	309.062	<0.001
Nitrate	1,140.54	57.027	<0.001

Interpretation: Significant differences across zones confirm spatial pollution gradients.
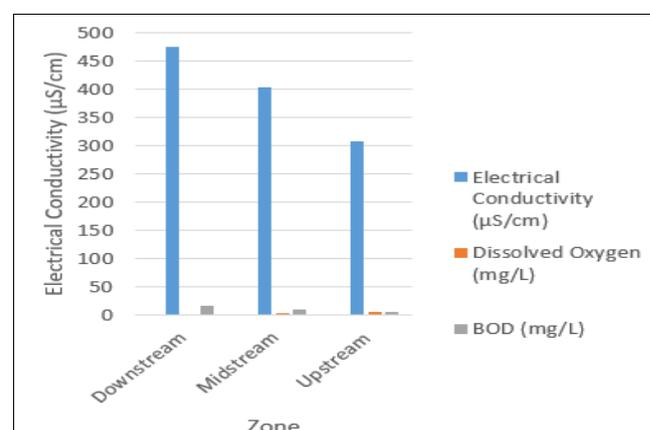
Seasonal Variation

Fig 3: Seasonal Comparison of Water Quality Parameters

Based on the provided chart structure, the data currently shows spatial variation — how water quality parameters (Electrical Conductivity, Dissolved Oxygen, BOD) change from Downstream to Midstream (and potentially other zones) at one point in time.

Conclusions and Recommendations
Conclusions
This study provides empirical evidence that industrial wastewater discharge has a substantial and measurable detrimental effect on the surface water quality of the Kafue River. The analysis robustly supports the alternative hypothesis (H_1), rejecting the null hypothesis that industrial discharge has no significant impact.

Key conclusions are drawn from the spatial, temporal, and statistical analyses:

Significant Spatial Degradation: A pronounced downstream pollution gradient was established. The Downstream zone exhibited the highest levels of turbidity, nutrients (nitrate, ammonium, phosphorus), organic pollution (BOD, COD), and electrical conductivity, alongside critically low dissolved oxygen (DO) concentrations. This pattern confirms the cumulative impact of effluent discharges from industries in Kafue Township, such as the Nitrogen Chemicals of Zambia (NCZ) and Kafue Sugar PLC, validating the study's conceptual framework linking industrial activity (Independent Variable) to water quality degradation (Dependent Variable) (Ng'ambi & Tembo, 2021; Jones et al., 2020) [27, 14].

Pronounced Seasonal Variation: Independent samples t-tests confirmed that water quality deteriorates markedly during the wet season. Significantly higher mean values for BOD, COD, and electrical conductivity, coupled with significantly lower DO, were recorded compared to the dry season. This indicates that wet-season runoff amplifies pollutant loading from non-point sources, overwhelming the river's assimilative capacity and exacerbating ecological stress (Kasonde et al., 2020; Palinkas et al., 2015) [16, 49].

Interconnected Pollution Dynamics: Strong negative correlations between DO and pollutants (BOD, COD, nutrients) demonstrate that organic and nutrient loading directly drives oxygen depletion. Strong positive correlations among the pollutants themselves suggest they originate from common, compounded waste streams. This synergy elevates the risk of eutrophication, algal blooms, and habitat degradation, threatening aquatic biodiversity and ecosystem services (Zimba & Kunda, 2019; Banda et al., 2020) [40, 41].

Systemic Regulatory Non-Compliance: The evaluation against ZEMA and WHO standards revealed widespread non-compliance, particularly in midstream and downstream zones. Parameters such as turbidity, BOD, ammonium, and phosphorus frequently exceeded permissible limits. This highlights a critical gap between policy and practice, underscoring weaknesses in monitoring, enforcement, and institutional capacity as identified in the literature (Fernandez & Shaw, 2016; Mubanga & Kambole, 2019) [11, 25].

In summary, the Kafue River is under severe ecological stress due to untreated or poorly treated industrial wastewater. The degradation poses significant risks to aquatic life, ecosystem health, and the well-being of communities dependent on the river for water and livelihoods.

Recommendations
To mitigate the identified pollution and steer the Kafue River toward recovery, the following multi-level recommendations are proposed:

Strengthen Regulatory Enforcement and Monitoring:
ZEMA should implement a continuous, real-time water quality monitoring network at strategic points, especially downstream of major industrial discharges.
Stricter discharge permits with enforceable limits and substantial penalties for non-compliance must be imposed. Regular, unannounced audits of industrial effluent treatment plants should be conducted.
Enhance ZEMA's institutional capacity through increased funding, technical training, and logistical support for effective enforcement (Parliament of Zambia, 2011; Mubanga & Kambole, 2019) [29, 25].

Mandate Advanced Wastewater Treatment:
Industries, particularly the NCZ plant and Kafue Sugar PLC, must be compelled to invest in and operate advanced on-site treatment technologies. Based on successful case studies, technologies such as Membrane Bioreactors (MBRs) and Nano-filtration (NF) should be adopted to effectively remove nutrients and persistent organic compounds before discharge (Drioli et al., 2017; Meschke et al., 2018) [9, 22].
- Government and development partners should explore incentives (e.g., tax breaks, green financing) to facilitate this technological transition.
- Implement Integrated Catchment Management:
- Develop and enforce riparian buffer zone policies to reduce agricultural runoff and sediment load.
- Promote sustainable agricultural practices within the catchment to minimize fertilizer and pesticide use.

Stormwater management plans for Kafue Township are urgently needed to capture and treat first-flush runoff during the wet season, addressing the seasonal spike in pollution (Palinkas et al., 2015) [49].

Enhance Stakeholder Engagement and Public Awareness:
Launch sustained public awareness campaigns to educate communities on the health risks of using polluted water and the importance of conservation.
Foster multi-stakeholder platforms involving industries, regulators, communities, and NGOs to promote transparency, shared responsibility, and collaborative problem-solving (Parliament of Zambia, 2011; Mubanga & Kambole, 2019) [29, 25].

Prioritize Further Research:
Conduct source apportionment studies using chemical fingerprinting to precisely quantify the contribution of specific industries to the pollutant load.
Initiate long-term ecological impact studies to monitor biodiversity changes, sediment contamination, and the effectiveness of implemented remediation strategies over time.
By adopting these integrated recommendations---combining stringent regulation, technological innovation, catchment management, and community involvement---Zambia can reconcile industrial development with the imperative of environmental sustainability, ensuring the long-term health of the Kafue River.

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