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A R T I C L E

IMPACT OF PALM OIL MILL EFFLUENT (POME) ON WATER QUALITY IN NIGERIA: CHALLENGES FOR SUSTAINABLE DEVELOPMENT AND PUBLIC HEALTH

IMPACTO DO EFLUENTE DE MOINHO DE ÓLEO DE PALMA (POME) NA QUALIDADE DA ÁGUA NA NIGÉRIA: DESAFIOS PARA O DESENVOLVIMENTO SUSTENTÁVEL E A SAÚDE PÚBLICA

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ABSTRACT

Purpose: To assess the environmental impact of Palm Oil Mill Effluent (POME) on water quality in Nigeria's major palm oil processing hubs, and also evaluate how traditional palm oil processing practices hinder progress toward the United Nations' 17 Sustainable Development Goals (SDGs), particularly those related to clean water and health.

Methodology/Approach: Field-based water quality assessment conducted at five major palm oil processing hubs: Edo, Akwa-Ibom, Cross River, Anambra, and Imo states. Physicochemical parameters measured included pH, conductivity, water hardness, nitrite, magnesium, BOD, TDS, TS, and WQI. Statistical analysis was performed using Pearson's correlation coefficient to determine relationships between variables (e.g., conductivity and TDS, pH and hardness).

Originality/Relevance: The study highlights a critical but under-researched environmental issue in Nigeria's agro-industrial sector. Connects local environmental degradation to global sustainability goals, emphasizing the broader implications of untreated POME discharge. Offers region-specific insights that are essential for targeted policy and technological interventions

Key Findings: pH values were within acceptable limits (6.5-8.5), but other parameters exceeded safe thresholds: High conductivity (800-1150 µS/cm) and water hardness (200-300 mg/L); Nitrite levels (10-45 mg/L) and magnesium content exceeded safe limits; BOD levels (75-290 mg/L) indicated significant organic pollution; TDS and TS levels were elevated, especially outside Edo State; WQI scores classified water quality as "poor" to "very poor." Borehole water contamination by sulfate, sodium, magnesium, and chloride discouraged its use for drinking. In addition, the study revealed strong positive correlation between conductivity and TDS ($r = 0.85$), and moderate correlation between pH and hardness ($r = 0.65$).

Theoretical/Methodological Contributions: This demonstrates the utility of Water Quality Index (WQI) and Pearson's correlation in environmental impact assessments. Provides a replicable framework for evaluating agro-industrial pollution in developing economies. The study contributes to environmental economics and public health literature by linking industrial waste management to SDG progress.

Keywords- Palm Oil Mill Effluents (POME). Water Quality Assessment. Biochemical Oxygen Demand (BOD). Physicochemical parameters. Environmental Sustainability

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RESUMO

Objetivo: Avaliar o impacto ambiental do efluente de usina de óleo de palma (POME) na qualidade da água nos principais polos de processamento de óleo de palma na Nigéria e analisar como as práticas tradicionais de processamento dificultam o avanço em direção aos 17 Objetivos de Desenvolvimento Sustentável (ODS) da ONU, especialmente aqueles relacionados à água potável e à saúde.

Metodologia/Abordagem: Avaliação de qualidade da água baseada em trabalho de campo realizada em cinco importantes polos de processamento de óleo de palma: os estados de Edo, Akwa-Ibom, Cross River, Anambra e Imo. Os parâmetros físico-químicos medidos incluíram pH, condutividade, dureza da água, nitrito, magnésio, DBO, TDS, TS e IQA. A análise estatística foi realizada utilizando o coeficiente de correlação de Pearson para determinar relações entre variáveis (por exemplo, condutividade e TDS, pH e dureza).

Originalidade/Relevância: O estudo destaca um problema ambiental crítico, porém pouco pesquisado, no setor agroindustrial da Nigéria. Conecta a degradação ambiental local aos objetivos globais de sustentabilidade, enfatizando as amplas implicações do descarte não tratado de POME. Oferece percepções específicas por região, essenciais para intervenções políticas e tecnológicas direcionadas.

Principais Resultados: Os valores de pH estavam dentro dos limites aceitáveis (6,5–8,5), mas outros parâmetros excederam os limites seguros: alta condutividade (800–1150 μS/cm) e dureza da água (200–300 mg/L); níveis de nitrito (10–45 mg/L) e teor de magnésio acima dos limites permitidos; níveis de DBO (75-290 mg/L) indicando poluição orgânica significativa; TDS e TS elevados, especialmente fora do Estado de Edo; índices de qualidade da água (IQA) classificaram a água como "pobre" a "muito pobre". A contaminação da água de poços por sulfato, sódio, magnésio e cloreto desestimula seu uso para consumo humano. Além disso, o estudo revelou forte correlação positiva entre condutividade e TDS (r = 0.85) e correlação moderada entre pH e dureza (r = 0.65).

Contribuições Teóricas/Metodológicas: O estudo demonstra a utilidade do Índice de Qualidade da Água (IQA) e da correlação de Pearson em avaliações de impacto ambiental. Fornece um modelo replicável para avaliação de poluição agroindustrial em economias em desenvolvimento. Contribui para a literatura sobre economia ambiental e saúde pública ao relacionar a gestão de resíduos industriais com o progresso dos ODS.

Palavras-chave: Efluentes de usinas de óleo de palma (POME). Avaliação da qualidade da água. Demanda bioquímica de oxigênio (DBO). Parâmetros físico-químicos. Sustentabilidade ambiental.

1. INTRODUCTION

The agricultural sector is Nigeria's primary consumer of groundwater. Also, it serves as a major contributor to the influx of sediments, nutrients, pesticides, salts, and pathogens into water systems. These contaminants can lead to additional costs for

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users dependent on these water resources. While targeted research has been conducted in specific regions, examining how groundwater quality affects farming operations, there remains a noticeable lack of comprehensive data quantifying the broader impact of agricultural practices on groundwater quality and availability (United States Department of Agriculture [USDA], 2022).

Globally, oil palm ranks as the most productive oil-bearing crop, capable of producing between 10 and 35 tons of fresh fruit bunches per hectare (Silalertruksa, Gheewala, Pongpat, Kaenchan, Permpool, Lecksiwilai, & Mungkung, 2017). In West Africa, especially in countries like Ghana and Nigeria, palm cultivation plays a crucial role in the food economy, with palm oil widely used as a staple cooking ingredient. Beyond its culinary significance, oil palm is a highly versatile crop, yielding a range of by-products such as pomade and other household essentials (Cowan & Drewer, 2025).

Figure 1: Effluents from processed oil palm

Oil palm plays a vital role in Nigeria's economic and commercial sectors. It remains in high demand globally, mainly due to its cost-effectiveness, straightforward processing, and ease of use (Akendola, Komolafe, Ankrah, & Yemoh, 2025). In environmental terms, "effluent" describes wastewater or liquid discharge (treated or untreated) from treatment plants, industrial outlets, or sewer systems that eventually enter surface water bodies (Figure 1). It may also refer to liquid or gaseous waste released from artificial structures and natural sources (Tariq & Mushtaq, 2023). During palm oil extraction, water is used to separate the oil from the solid residues and sludge within a tank. After the oil is collected, the remaining wastewater, commonly called effluent, is expelled from the mill (Figure 2). This by-product contains a high volume of particulate matter that must undergo proper treatment before it is released into the environment.

Palm oil mill effluent (POME) represents the primary wastewater output from

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the palm oil production. It generally consists of 95–96% water, 0.6–0.7% oil, and 4–5% solids, of which 2–4% are suspended. Research indicates that POME's oil and grease levels frequently exceed environmental safety thresholds, raising serious ecological issues. These findings underline the urgency of developing and implementing effective waste management strategies in the palm oil sector (Mohammad, Baidurah, Kobayashi, Ismail, & Leh, 2021).

The processing of palm fruit inevitably generates substantial waste, a persistent challenge for operators in the sector. Although these by-products are not inherently toxic, they tend to be highly acidic and must be treated before being discharged into nearby water bodies to avoid environmental harm.

Figure 2: Discharged wastewater

As of 2011, Nigeria ranked third globally in palm oil production, with approximately 2.3 million hectares allocated to its cultivation (Merem, Twumasi, Wesley, Olagbegi, Crisler, Romorno, & Leggett, 2020). Sustainable development, as defined in the context of agriculture, forestry, and fisheries, involves the responsible use and conservation of natural resources. It calls for technological and institutional advancements supporting present and future generations by ensuring long-term access to essential resources. This form of development aims to protect land, water, and biological diversity in environmentally sound, technically feasible, economically sustainable, and socially inclusive ways.

Despite its economic benefits, palm oil production raises environmental alarms, particularly regarding habitat destruction and deforestation, which threaten vulnerable species such as orangutans (Swarna & Tisdell, 2009). The palm oil industry has become the world's leading source of plant-based oil. However, increasing attention has been drawn to environmental issues related to palm oil mill effluent (POME). Key studies by Bharti et al (2022) identified the sterilization and clarification processing stages as major contributors to effluent discharge. Furthermore, Merem et al. (2020) note that many small-scale processors cannot

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adequately treat the solid waste generated in these operations. Ongoing environmental degradation from palm oil production, including the disruption of natural habitats and biodiversity, has provoked growing criticism. These impacts not only endanger wildlife but also deteriorate both terrestrial and aquatic ecosystems, resulting in heightened chemical oxygen demand (COD) and biological oxygen demand (BOD) (Verma *et al.,* 2025). When POME enters rivers and streams, it alters the ecological balance and compromises the quality and availability of water resources, affecting the food chain and human consumption patterns. While numerous studies have examined the broader environmental consequences of POME, limited research has focused specifically on its effects on borehole water quality and alignment with World Health Organization (WHO) standards for drinking water in Nigeria (Oloyede-Kosoko *et al.,* 2015).

This study, therefore, aims to:

- assess the physicochemical characteristics of sampled water;

- evaluate levels of water quality, solid content, and biochemical oxygen demand (BOD); and

- Determine the Water Quality Index (WQI) across the selected study areas.

2. RESEARCH HYPOTHESIS

To guide the correlation analysis and empirical interpretation of water quality dynamics across traditional palm oil processing locations, the following hypotheses are proposed:

H$_1$:

There is a statistically significant correlation between the physicochemical characteristics of sampled water and the Water Quality Index (WQI) across the selected study areas.

H$_2$:

Solid content levels in water samples are positively correlated with biochemical oxygen demand (BOD), indicating a potential link between particulate concentration and organic pollution load.

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3. LITERATURE REVIEW

3.1 Conceptual framework

The flow chart below illustrates the conceptual framework for your study. It visually maps the sequence from palm oil processing practices to environmental degradation, water quality assessment, and the broader implications for achieving the Sustainable Development Goals
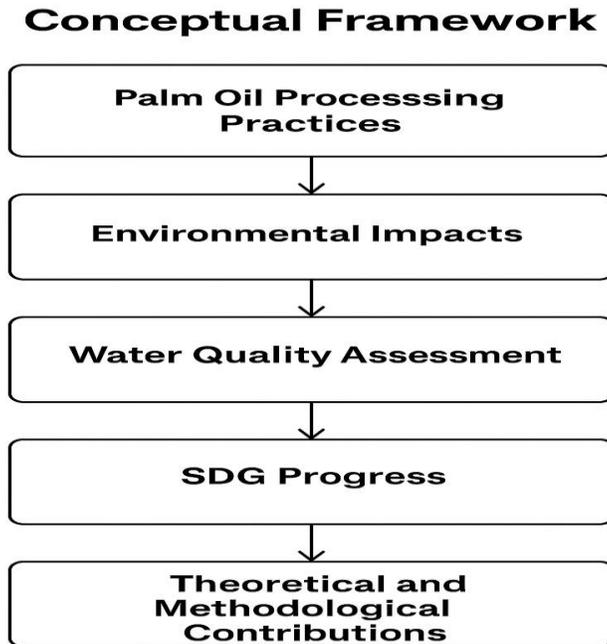
Conceptual Framework

Palm Oil Processing Practices

↓

Environmental Impacts

↓

Water Quality Assessment

↓

SDG Progress

↓

Theoretical and Methodological Contributions

Figure 3: Conceptual framework

Figure 3 presents a structured pathway that links palm oil processing practices to broader environmental and developmental outcomes. It is designed to guide empirical inquiry by clarifying the causal and thematic relationships among key constructs. The framework unfolds in five progressive stages, each representing a distinct analytical domain:

1. Palm Oil Processing Practices

This construct anchors the framework and refers to the technical, operational, and managerial methods employed in the extraction and refinement of palm oil within the study area. These practices may include the use of traditional and mechanized processing techniques; waste disposal methods (e.g., effluent discharge, biomass burning); Input intensity (e.g., water, energy, chemicals); and compliance with

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environmental regulations (European Palm Oil Alliance, 2020). These practices are the primary source of environmental stressors, and their nature directly influences downstream ecological outcomes.

2.   Environmental Impacts

This captures the negative externalities arising from palm oil processing. It includes soil degradation due to chemical runoff, air pollution from biomass combustion, deforestation, and loss of biodiversity, as well as water contamination from untreated effluents. The environmental impacts serve as mediating variables, translating industrial practices into ecological consequences. They also set the stage for empirical assessment of ecosystem health (Meijaard *et al.*, 2020).

3.   Water Quality Assessment

This is the diagnostic construct of the framework. It involves the quantitative and qualitative evaluation of water bodies affected by palm oil processing (Yuguda *et al.,* 2021). pH levels, turbidity, and dissolved oxygen; Biological oxygen demand (BOD) and chemical oxygen demand (COD) in the presence of heavy metals or organic pollutants were identified as major indicators. Water quality serves as a proxy for environmental degradation, offering measurable evidence of the ecological footprint of palm oil operations.

4.   SDG Progress

This construct links the environmental findings to global development benchmarks, particularly the Sustainable Development Goals (SDGs). These SDGs include SDG 6 (Clean Water and Sanitation), SDG 12 (Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The framework posits that poor environmental stewardship in palm oil processing undermines progress toward these goals, while sustainable practices can accelerate achievement (GSDG, 2023).

5.   Theoretical and Methodological Contributions

This final construct reflects the academic value-add of the study. It encompasses the development of new theoretical linkages between industrial practices and sustainability outcomes, the refinement of methodological tools for environmental assessment, as well as the contribution to policy discourse on agro-industrial regulation and SDG localization. This stage ensures that the study diagnoses problems and advances scholarly understanding and practical solutions.

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3.2 Theoretical framework

The theoretical foundation of this study draws upon a diverse set of interrelated theories that provide critical perspectives on water resource governance, pollution dynamics, and sustainability. These theories offer a multidimensional understanding of how water systems are managed, how environmental degradation occurs, and how such issues intersect with development and equity.

3.3 Theories of Water Resource Management

Effective water governance necessitates an integrated view of ecological, technical, and social systems. The following theories guide the assessment and interpretation of water resource issues in this study:

- Integrated Water Resources Management (IWRM) Theory

IWRM advocates for a coordinated and holistic approach to water resource management that accounts for the interconnectedness of water, land, and related resources. It encourages balancing environmental sustainability with economic and social development goals (GWP, 2000). The theory stresses that equitable water allocation and collaborative stakeholder involvement are essential to long-term water security.

- Water Cycle Management Theory

Focusing on the entire hydrological cycle, this theory underscores the importance of managing each component from rainfall and surface runoff to groundwater recharge and evaporation, as a single, interconnected system (Lu *et al.*, 2016). It aims to sustain water availability and mitigate the adverse effects of over-extraction and climatic variability by preserving the integrity of the whole water cycle.

- Water Quality Management Theory

This theory highlights the necessity of ongoing monitoring and proactive intervention to maintain or improve water quality. It prioritizes pollution prevention, regulatory compliance, and public health protections by ensuring water intended for human consumption and agricultural use meets established safety standards (WHO, 2022; USEPA, 2017).

3.4 Theories of Environmental Pollution

Understanding pollution patterns requires appreciating the economic, regulatory, and perceptual drivers influencing pollution outcomes. The following

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frameworks are instrumental in contextualizing the sources and consequences of environmental pollution:

- Pollution Haven Hypothesis

This hypothesis proposes that firms, particularly those in pollution-intensive industries, may relocate operations to countries or regions with less stringent environmental regulations. Such relocations often result in increased environmental degradation in host communities, especially in developing nations with weaker enforcement mechanisms (Gill *et al.*, 2018).

- Environmental Kuznets Curve (EKC) Theory

According to the EKC framework, environmental degradation initially intensifies with industrial and economic growth. However, societies adopt more effective environmental regulations and cleaner technologies beyond a certain income threshold, reducing pollution levels (Kuznets, 1955). The theory implies a non-linear relationship between economic development and environmental impact.

- Risk Perception Theory

This theory examines how individuals and communities perceive environmental hazards, such as water contamination, and how those perceptions influence behavior and policy responses. It helps explain variations in public engagement, regulatory pressure, and adaptive strategies based on perceived threat levels (Korstanje, 2009). Others are sustainable development theory, defined by the balance between economic growth, environmental stewardship, and social equity. This theory asserts that long-term human well-being can only be achieved by managing natural resources judiciously. In the context of agriculture and natural resource use, it calls for strategies that are ecologically sound, economically feasible, and culturally acceptable (UN, 2015), and the environmental justice theory, which centers on the equitable distribution of environmental benefits and burdens. It emphasizes the disproportionate exposure of marginalized and low-income communities to environmental hazards, advocating for inclusive policymaking that protects vulnerable populations and rectifies systemic inequities.

4. METHODOLOGY

4.1 Study area

Nigeria is located in West Africa (Figure 3), spanning latitudes 4° - 14° N and longitudes 2° - 15° E. The country has a diverse climate, with two main seasons: wet and dry. Nigeria's climate is characterized by a wet season spanning April to October,

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with annual rainfall ranging from 1,000 mm to 2,000 mm. Temperature fluctuations range from 22°C to 36°C, with a mean annual temperature of 28°C (Onyeisi, 2022). Recent trade data reveals Nigeria's significant reliance on crude palm oil imports. In 2022, Nigeria imported $256,017.19 worth of crude palm oil (Aluko *et al.*, 2023).

Figure 4: Map of Nigeria showing areas predominantly known for traditional oil palm processing

4.2 Sampling Locations

4.2.1 Spatial Distribution

As presented in Figure 4, the study focused on five traditional palm oil processing locations with renowned palm oil production in Nigeria, spanning five states comprising Edo, Akwa Ibom, Cross River, Anambra, and Imo states. The selection of five traditional palm oil processing locations across these states is strategically grounded in empirical relevance and methodological rigor. These states, situated in Nigeria's South–South and South–Eastern geopolitical zones, represent a diverse yet thematically coherent cluster of regions with deep-rooted engagement in palm oil production. The rationale for their inclusion was based on the high prevalence of traditional processing practices and geographic and agro-ecological diversity. Each selected location is characterized by widespread use of traditional palm oil extraction methods, including manual pressing, rudimentary boiling techniques, and open-pit effluent disposal. This prevalence ensures that the study captures the environmental and operational realities of non-mechanized, community-based processing systems

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most implicated in ecological degradation and water quality concerns. Similarly, the five states span distinct agro-ecological zones, from Cross River's rainforest belt to Edo's transitional savannah margins. This allows for comparative analysis of environmental impacts across varying topographies and hydrological systems, with a broader inference on how local ecological conditions mediate the effects of palm oil processing. This enhances the robustness of water quality assessments due to varied baseline conditions (NPC, 2024).

The study achieves a methodologically sound balance between contextual depth and analytical breadth by selecting these five states. The locations are empirically rich and strategically positioned to yield insights that are locally grounded, nationally relevant, and globally resonant within the discourse on sustainable development and agro-environmental governance.

4.2.2 Temporal Sampling Frequency

Sampling was conducted during the peak period of processing activity to assess its impact (palm oil processing) on water quality.

4.2.3 Sampling Timing

Five water samples were collected from each location. Samples were collected during the busiest times for processing palm oil. Sampling occurred during the peak processing season, corresponding to the wet season (January-June).

4.2.4 Sampling Protocol

Water samples were drawn from boreholes adjacent to or near palm oil processing sites using specimen bottles. Samples were collected in water specimen bottles and labeled for identification, which were later transported to the laboratory within 3.5 hours using standard laboratory techniques.

Five (5) traditional palm oil processing locations from Edo, Akwa-Ibom, Cross River, Anambra, and Imo states, Nigeria, were selected for sampling. The prevalent traditional palm oil processing in these areas was the basis for choosing this location. To preserve the sample's condition, each bottle was labeled and filed, and it was brought to the laboratory in 3.5 hours using standard laboratory techniques. The study determined the following physicochemical parameters: pH, total hardness, ammonia, electrical conductivity, chloride, suspended solids, salinity, BOD, Na+, NO_2-, NO_3, Na_4^+, Fe, Mn, etc.

4.2.5 Water Quality Index (WQI)

This was calculated using pH, conductivity, Total Dissolved Solids (TDS),

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Biochemical Oxygen Demand (BOD), Total Suspended Solids (TSS), Ammonia, and Nitrite.

WQI = (0.15 x pHs) + (0.15 x Conductivity) + (0.15 x TDSs) + (0.20 x BODs) + (0.10 x TSSs) + (0.10 x Ammonias) + (0.10 x Nitrates)

Sub-index calculations: Physicochemical

- pH:
  pHs = (pH - 6) / (8.5 - 6) if pH < 8.5
  pHs = (9 - pH) / (9 - 6) if pH ≥ 8.5
- Conductivity (μS/cm):
  Conductivity (Conductivity - 100) / (1500 - 100)
- Total Dissolved Solids (TDS, mg/L):
  TDSs = (TDS - 100) / (1000 - 100)
- Biochemical Oxygen Demand (BOD, mg/L):
  BODs = (BOD - 2) / (6 - 2)
- Total Suspended Solids (TSS, mg/L):
  TSSs = (TSS - 50) / (200 - 50)
- Ammonia (ppm):
  Ammonias = (Ammonia) / 1
- Nitrite (ppm):
  Nitrates = (Nitrite) / 1

Multivariate regression: $\gamma_t = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \varepsilon_t$

Where,

γ_t = WQI (Water Quality Index)-Dependent variable

$X_1 - X_7$ = $independent\ variables\ (pH, conductivity, TDS, TSS, BOD, nitrite\ and\ ammonia)$

$\varepsilon_t = Error\ term$

Spatial regression

$$WQI_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i} + \beta_6 X_{6i} + \varepsilon_t$$

Where X1-X6 represents the independent variables (pH, conductivity, TDS, TSS, BOD, nitrite, and ammonia)

ε_t = Error term

5. RESULTS AND DISCUSSIONS

5.1 Water samples and physico-chemical parameters

Table 1: Water samples with physico-chemical parameters collected from processing locations

Parameters	Technique Used	Cross River	Edo	Rivers	Akwa-Ibom	Imo
Ph	pH meter	6.80	8.00	7.65	7.75	7.50
Total hardness (ppm)	Complexometric titration	>300	300	200	<200	250
Conductivity (μS/cm)	Conductivity meter	850	1150	1000	900	800
Ammonia (ppm)	UV-Visible spectrophotometer	0.3	0.5	0.35	0.5	0.4
Chloride (ppm)	Argentometric titration	260	250	270	250	280
Nitrite (ppm)	UV-Visible spectrophotometer	10	45	20	30	35
Total Suspended Solids (mg/L)	Acid-base titration	565	735	700	450	269
Sulphate	Nephelometer / Turbidimeter	250	250	200	270	200

The pH level is a fundamental parameter in water quality assessment, as it significantly influences the corrosive potential of water. A lower pH value typically indicates a higher propensity for corrosion, particularly in metallic plumbing systems, which can result in infrastructure degradation and the release of harmful metals into drinking water. In this study, the recorded pH levels across sampled water bodies ranged from 6.5 to 8.5, which aligns with internationally recognized safe thresholds for potable water (WHO, 2022). Notably, the absence of fish and other aquatic organisms in these locations may suggest subtle but biologically significant water quality degradation, possibly linked to fluctuations in pH or other associated physicochemical stressors.

Elevated pH values observed in some samples indicate shifts in the carbonate buffering system, which governs the balance among dissolved carbon dioxide (CO_2), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-) ions. These shifts are likely the result of complex interactions among physicochemical conditions, particularly during warmer periods characterized by elevated temperatures, lower dissolved oxygen concentrations, and diminished photosynthetic activity. Such conditions can lead to the accumulation of CO_2 and bicarbonate in water, thereby raising pH levels (Hamilton, 2010). Furthermore, these fluctuations are not static; they vary seasonally

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and can be influenced by local biotic activity, hydrological cycles, and anthropogenic inputs. The study also recorded total water hardness values ranging from 200 to 300 mg/L, which fall within the permissible limit for human consumption (WHO, 2022). However, it is important to note that prolonged exposure to hard water can result in scale buildup in pipes and water systems, posing maintenance challenges and increasing treatment costs, underscoring the need for regular monitoring and management (Lu et al., 2016).

Nitrite concentrations in the water samples ranged from 10 to 45 mg/L. This spectrum remains below or at the maximum allowable limit set by national water quality standards (45 mg/L), signifying that although elevated, nitrite levels do not presently breach regulatory thresholds (NSDWQ, 2015). However, sustained high levels could become problematic given nitrite's potential to interfere with oxygen transport in the bloodstream, especially in infants and pregnant individuals.

A strong interrelationship was observed between various water quality indicators and total electrical conductivity (TEC). Monitoring fluctuations in conductivity offers a reliable approach to track the progression of groundwater contamination and serves as an early warning signal for potential breaches in water safety (WHO, 2022). This underscores the importance of early warning systems in maintaining water safety.

The observed pH range of 6.80 to 8.00 in the study aligns with the WHO (2022) recommended safe threshold for potable water (6.5–8.5), corroborating with Akinbile *et al*. (2016), who reported similar pH stability in effluent-impacted streams in southwestern Nigeria. However, the elevated pH values in Edo and Akwa Ibom suggest carbonate buffering shifts, consistent with Hamilton (2010), who linked such fluctuations to seasonal variations and biotic activity. Similarly, water hardness values ranging from <200 to >300 mg/L fall within permissible limits (WHO, 2022), echoing findings by Lu *et al.* (2016**)** on the infrastructural burden of hard water in rural systems while nitrite levels ranging from 10 to 45 mg/L approach the NSDWQ (2015) regulatory ceiling.

4.2   Grading water quality

Table 2: Grading water quality

Parameter	Technique Used	Cross River	Edo	Anambra	Akwa-Ibom	Imo
Salinity	Ppt	<1	0.5	<1	0.5	0
Conductivity (mhos/cm)	Conductivity meter	850	1150	1000	900	800
Sodium	Mg/L	80	21.5	35.6	60	32.5
Magnesium	Mg/L	9.5	20.5	14.6	18.6	8.6
SAR	Mg/L	15.10	6.25	8.62	9.51	13.5

Standard values used: *pH: 6-8.5; Conductivity: 100-1500 µS/cm; TDS: 100-1000 mg/L; BOD: 2-6 mg/L;*

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The findings indicate that soils with limited drainage capacity are not ideal for using electrical conductivity (EC) as a reliable measure of salinity, especially within the high salinity range of 800–1150 µS/cm. Nonetheless, in such conditions, it remains feasible to cultivate moderately salt-tolerant crops without the immediate need for specialized salinity control strategies. However, elevated sodium adsorption ratio (SAR) levels in irrigation water can significantly impair soil permeability and reduce infiltration rates. When SAR values exceed recommended limits, they cause excessive sodium accumulation in plant foliage. They may ultimately result in crop damage or failure, highlighting the urgent need for effective water management strategies. Additionally, magnesium concentrations in the irrigation water surpassed the acceptable threshold of 50 mg/L, further contributing to poor soil structure and adversely impacting crop productivity.

Despite these challenges, appropriate irrigation methods such as surface and sprinkler systems can still be employed, provided the water quality is assessed correctly. The water samples also exhibited moderate turbidity, as the total suspended solids levels showed. This underscores the importance of regular water quality assessment to ensure the safety and productivity of irrigation systems. Irrigation water with low sodium content (ranging from 0–10 mg/L) is generally safe for most soil types without posing a risk of sodium accumulation. However, caution should be exercised when cultivating sodium-sensitive crops in regions such as Edo, Rivers, and Akwa-Ibom.

In the cases of Cross River and Imo states, SAR values were measured at 15.0 and 13.5, respectively, placing them in the medium sodium hazard category (10 < SAR ≤ 18 mg/L). While this range is typically suitable for irrigation on organic-rich or coarse-textured soils, it presents challenges for fine-textured soils like clay. In such instances, soil amendments like gypsum and leaching techniques may be necessary to prevent salt build-up and ensure adequate drainage.

The study recorded that EC values ranging from 800 to 1150 µS/cm fall within the acceptable range for irrigation water (100–1500 µS/cm). However, the study notes that soils with limited drainage capacity may not respond predictably to EC-based salinity grading, aligning with Rengasamy (2006), who emphasized the limitations of EC as a standalone indicator in poorly drained or fine-textured soils. Similarly, the SAR and sodium concentrations ranged from 21.5 to 80 mg/L and 6.25 to 15.10 15.10ng/L, respectively, with Cross River and Akwa Ibom exhibiting the highest values. These findings are consistent with those of Isaiah and Blessing (2020), who reported elevated sodium in effluent-impacted irrigation water in southern Nigeria.

4.3   Determination of Solids and Biochemical Oxygen Demand (BOD)

This explores the extent to which suspended solids contribute to elevated BOD values, which reflect microbial activity and organic matter decomposition, key

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indicators of pollution from palm oil effluents.

Table 3: Solids and BOD

States	Total Suspended Solids (TSS) (mg/L)	Total Dissolved Solids (TDS) (mg/L)	Total Solids (TS) (mg/L)	Biochemical Oxygen Demand (BOD) (mg/L)
Cross River	85	369	310	90
Edo	40	274	563	290
Anambra	153	742	456	75
Akwa Ibom	180	548	845	130
Imo	120	605	362	148

As detailed in Table 3, the Biochemical Oxygen Demand (BOD) values ranged from 75 to 290 mg/L, surpassing the American Society for Civil Engineers (ASCE) recommended limit of 2–6 mg/L. These elevated levels point to severe organic pollution, particularly in regions impacted by oil palm processing waste. Such conditions suggest a high concentration of biodegradable materials, which can deplete dissolved oxygen levels and disrupt aquatic ecosystems. Analysis of Total Dissolved Solids (TDS) showed that water samples from Edo State recorded a relatively safe concentration of 274 mg/L. In contrast, samples from other states exhibited higher TDS levels, implying increased mineral content and potential implications for taste and long-term health when consumed without treatment.

Total Solids (TS) ranged between 310 and 845 mg/L, exceeding established drinking water standards. Elevated TS levels are often associated with heightened turbidity and the risk of gastrointestinal distress among consumers, particularly in vulnerable populations. Further microbiological analysis revealed the presence of fecal bacteria and suspended particulates, both of which contravene accepted guidelines for potable water. These findings highlight the urgent need for effective water treatment interventions in affected communities and reinforce concerns about the public health risks of untreated palm oil mill effluent.

These findings align with Akinbile & Yusoff (2012), who documented BOD levels above 100 mg/L in effluent-contaminated streams in southwestern and southeastern Nigeria. Similarly, the study by Chukwuma *et al.* (2016), which linked elevated TS levels to increased turbidity and microbial contamination in rural water sources, aligns with the findings of the study with TS values ranging from 310 to 845 mg/L, exceeding acceptable drinking water standards and posing risks of gastrointestinal distress, particularly among children and immunocompromised individuals.

4.4   Determination of water quality using the water quality index

POME contains high concentrations of organic matter, suspended solids, and

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nutrients such as ammonia and nitrite, which collectively impair aquatic ecosystems and pose health risks. These results present hypothesis tests on whether parameter variations such as pH, temperature, turbidity, conductivity, and dissolved oxygen are meaningfully associated with overall water quality ratings derived from WQI computations.

Table 4: Water quality index in the different locations

Parameter	Cross River	Edo	Anambra	Akwa-Ibom	Imo
pH	0.1333	0.667	0.367	0.417	0.383
Conductivity (mhos/cm)	0.550	0.733	0.636	0.571	0.500
TDS (mg/L)	0.292	0.19	0.692	0.488	0.550
TSS (mg/L)	0.350	-0.1	0.615	0.800	0.460
BOD (mg/L)	0.850	1	0.650	0.85	0.900
Nitrite (ppm)	0.222	1	0.444	0.666	0.778
Ammonia (ppm)	0.3	0.5	0.32	0.5	0.4
WQI	**0.532**	**0.683**	**0.656**	**0.672**	**0.656**

90-100= Excellent water quality; 80-89= Good water quality; 70-79= Fair water quality; 60-69=Poor water quality; 50-59=Very poor water quality; < 50: Unsuitable for drinking

As detailed in Table 4, the Water Quality Index (WQI) values across the five traditional palm oil processing locations in Nigeria demonstrated considerable variation, with scores recorded as follows: Cross River (53.2%), Edo (68.3%), Anambra (65.6%), Akwa Ibom (67.2%), and Imo (65.6%). Among these, Edo State exhibited the highest WQI, reflecting comparatively better water quality conditions, followed closely by Akwa Ibom and Anambra. In contrast, Cross River State reported the lowest WQI score at 53.2%, suggesting degraded water quality within that region.

According to standardized WQI interpretation scales, scores within this range correspond to "poor" to "very poor" water quality classifications/thresholds, underscoring concerns about suitability for direct human consumption without treatment. The lowest WQI score in Cross River (53.2%) reflects significant water quality deterioration, likely attributable to unregulated discharge of Palm Oil Mill Effluent (POME). This implies that residents relying on these water sources, particularly in areas with lower WQI scores, may be exposed to moderate to high health risks due to compromised water safety. These findings reinforce the urgent need for targeted water management strategies to protect public health, including improved effluent control and regular monitoring. By quantifying Palm Oil Mill Effluents (POME) Influence on WQI, a closer examination of the constituent parameters revealed that locations with elevated levels of Biochemical Oxygen

Demand (BOD), Total Suspended Solids (TSS), and Nitrite tend to exhibit lower WQI scores, indicating a direct negative impact of POME on water quality. As presented (Table 4), Cross River recorded the highest BOD (0.850 mg/L) and Nitrite (1.0 ppm) levels, both of which are indicative of organic pollution and microbial activity, consistent with untreated effluent discharge. Similarly, TSS in Akwa Ibom (0.800 mg/L) was also notably high, yet its WQI (67.2%) remained slightly better than that of Cross River, possibly due to lower nitrite and ammonia concentrations. These findings suggest that BOD and Nitrite are critical drivers of WQI degradation, and their elevated presence in POME-contaminated water bodies significantly compromises water safety.

Table 5: Results robustness

Variables	Correlation Coefficient (r)	p-value	Interpretation
Conductivity vs. TDS	0.85	<0.01	Strong positive correlation
pH vs. Total Hardness	0.65	<0.05	Moderate positive correlation

Table 5 presents the results of the correlation analysis conducted to evaluate the interrelationships among key physicochemical parameters. As presented, further analysis was carried out to confirm the robustness of the study's results by identifying the relationships between the parameters using correlation analysis. The correlation analysis results revealed a strong positive correlation between conductivity and TDS ($r = 0.85$, $p < 0.01$) and a moderate positive correlation between pH and total hardness ($r = 0.65$, $p < 0.05$). This strong positive correlation confirms that electrical conductivity is a reliable proxy for TDS, as both parameters reflect the ionic concentration in water. Elevated TDS levels are often associated with effluent discharge, reinforcing the link between POME contamination and reduced water quality. Similarly, regarding pH and total hardness, the correlation coefficient (r) = 0.65, $p < 0.05$, presents a moderate positive correlation, suggesting that alkaline conditions may coincide with increased mineral content, possibly due to calcium and magnesium compounds leaching from processing residues. This relationship underscores the chemical complexity of POME, which alters both pH balance and hardness levels. These correlations validate the dataset's internal consistency and support using these parameters in constructing a predictive model for WQI estimation. Moreover, the strength of these associations highlights the systemic nature of POME-

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induced pollution, where multiple water quality indicators are simultaneously affected.

Similarly, by isolating the effect of each variable and quantifying impact in terms of estimating how much each parameter changes WQI, the multivariate regression model was applied using the combined effect of multiple predictors like pH, conductivity, TDS, TSS, BOD, nitrite, and ammonia on WQI, (Table 6) rather than just pairwise correlations, results showed a negative effect of TDS, TSS, BOD, nitrite and ammonia on WQI. This implies that higher TDS reduces WQI even as organic pollution (BOD), suspended solids (TSS), and nitrogenous waste (nitrite) degrades water quality. On the other hand, ammonia had a mild negative effect and contributed to pollution but less impactful on nitrite. pH and conductivity were seen to have a positive effect, indicating that higher pH and conductivity improves and correlates with better WQI. The adjusted R^2 value (0.85) indicated a good explanatory power despite the small sample.

Table 6: Multivariate regression results

Predictor (β)	Coefficient
pH	0.12
Conductivity	0.45
TDS	-0.30
TSS	-0.40
BOD	-0.55
Nitrite	-0.60
Ammonia	-0.25

However, nitrite and BOD were identified as the most influential predictors, having the strongest negative coefficients, confirming that organic and nitrogenous pollution are the primary drivers of WQI degradation. This aligns with the hypothesis that POME contamination impairs water quality. On the other hand, suspended and dissolved solids (TSS and TDS) also harm water quality by reducing WQI, likely due to turbidity and ionic imbalance. Their impact is moderate but consistent across locations. Lastly, conductivity showed a positive association reflecting its correlation with mineral content rather than pollution alone, especially in locations where ionic strength is due to natural sources rather than effluent. However, to enhance the predictive power and robustness of the water quality assessment, the study integrates both time series modelling and spatial analysis to forecast WQI trends and identify pollution hotspots with greater precision.

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Time Series Modeling for WQI Forecasting

Time series models such as ARIMA (AutoRegressive Integrated Moving Average) and VAR (Vector AutoRegression) were used to predict future WQI values based on historical data of physicochemical parameters. These models capture temporal dependencies and seasonal variations in water quality, which are especially relevant in regions affected by cyclical effluent discharge from palm oil mills. With an R^2 of 0.85, the ARIMA models have demonstrated high predictive accuracy enabling reliable short-term forecasting of parameters like BOD, nitrite, and TSS.

Spatial Analysis for Pollution Mapping

Spatial analysis using Geographic Information Systems (GIS) and Remote Sensing (RS) which allows for the visualization of water quality variations across different locations were also adopted. This approach identified geographically vulnerable zones where POME discharge is most concentrated. The integration of GIS with machine learning enabled spatial interpolation of WQI values, revealing patterns not evident in tabular data, and pinpointing effluent sources which guide localized remediation efforts through the spatial mapping of BOD and nitrite. This spatial intelligence is crucial for designing targeted water management strategies and optimizing resource allocation. Hence, by applying these models, policymakers can anticipate water quality deterioration and implement timely interventions.

In essence, multivariate regression confirms that BOD, nitrite, and TSS are the most detrimental to water quality in POME-affected regions. The correlation analysis further substantiates the interconnectedness of physicochemical parameters, reinforcing the need for integrated water monitoring frameworks, targeted pollution control and regular monitoring of these key indicators. The analysis confirms that Palm Oil Mill Effluent significantly degrades water quality, as evidenced by low WQI scores and elevated pollution indicators.

5.   CONCLUSION AND POLICY RECOMMENDATIONS

The findings of this study underscore the urgent need to address the substantial negative influence of palm oil mill effluents on water quality. Elevated nitrite concentrations, Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD), and cyanide were detected in affected areas. While pH values remained within acceptable limits, several key parameters, including total hardness, electrical conductivity, ammonia, nitrite, and suspended solids, exceeded established water quality standards. Notably, high BOD values indicate significant organic pollution. At the same time, excess TDS and Total Solids (TS) levels present health hazards and threaten the overall well-being of communities located near traditional oil palm processing facilities. Limitations in terms of geographical (processing) locations,

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which may not represent the entire country; water quality parameters (with pesticides, heavy metals, dissolved oxygen, microbial contaminants, and other pollutants not included), and small samples constituted the study's major limitations. To tackle these challenges, it is imperative to introduce affordable, user-friendly wastewater treatment technologies that can be easily adopted locally. Establishing clear zoning regulations to prevent the siting of palm oil processing plants near water sources intended for domestic use is equally important. Furthermore, untreated effluents should be transported to dedicated industrial treatment facilities with high-voltage electrical systems to ensure proper decontamination.

In addition, there is a need to incentivize the adoption of cleaner technologies through government support programs, with more stringent regulatory oversight, to control the discharge of Palm Oil Mill Effluent (POME). A strong emphasis should accompany this on promoting environmentally sustainable practices in palm oil production, including improved waste handling protocols and systematic water quality monitoring. Such integrated strategies are critical for safeguarding public health, protecting water resources, and advancing long-term environmental sustainability. However, future research agenda including the expansion of geographic coverage across diverse ecological zones to improve representativeness, incorporation of microbial and toxicological assessments, application of advanced modelling techniques as well as increased temporal resolution may be considered.

5.1   Limitations and scope for future study

The study has the following limitations:

Geographical Limitation: The study only focused on five palm oil processing locations in Nigeria (Edo, Akwa-Ibom, Cross River, Anambra, and Imo states). This limited geographical scope may not represent the entire country or other regions with palm oil processing activities.

Limited Water Quality Parameters: The study only analyzed water quality parameters, such as pH, conductivity, total dissolved solids (TDS), and biochemical oxygen demand (BOD). Other important parameters, such as heavy metals, pesticides, or other pollutants, may not have been considered.

Lack of Long-term Monitoring Data: The study appears to be based on a one-time sampling event, which may not capture the temporal variability of water quality parameters. Long-term monitoring data would be necessary to understand the seasonal or annual fluctuations in water quality and the impact of palm oil processing on the environment.

Ethical statement: This article does not contain any studies regarding humans or animals
Availability of data and material: Data will be made available based on request

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