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Regional Physicochemical Characterization and Spatial Heterogeneity of Palm Oil Mill Effluent (POME) Across Six States in Southern Nigeria

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ABSTRACT

The palm oil industry in Nigeria generates significant quantities of Palm Oil Mill Effluent (POME), a highly polluting wastewater. This study evaluates the physicochemical properties, spatial heterogeneity and environmental compliance of POME from 12 small-scale mills across six southern Nigerian states (Abia, Akwa Ibom, Delta, Ekiti, Imo, Osun). Samples were analyzed for 13 parameters: pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic nitrogen (TON), nitrite, nitrate, and phosphate, using American Public Health Association (APHA) methods. The findings revealed universal acidity (pH 3.03–3.89), uniform temperatures (27–29 °C), and elevated nutrient levels, with Imo and Delta showing highest TON (up to 58 mg/L), nitrite (up to 33 mg/L), and EC (>1700 µS/cm). Ekiti and Osun exhibited the lowest pollution. Shapiro-Wilk tests confirmed non-normality for all parameters. Intra-state comparisons via Mann-Whitney U tests indicated no significant differences ($p > .05$) between sites, though large effect sizes ($r \approx 0.80$) suggested practical variations driven by mill-specific practices. Spatial analysis using Moran's I demonstrated weak autocorrelation (predominantly negative, $p > .05$ except for pH at $p = .0107$), with distance-decay correlations non-significant, refuting geographic dependence of effluent quality. Pollution index maps highlighted heterogeneous hotspots without regional clustering. Findings underscore that discharge of untreated POME poses substantial risks of eutrophication and soil degradation in receiving environments, highlighting the urgent need for treatment system reform in southern Nigeria's small-scale palm oil sector.

Keywords: Palm-oil mill effluent (POME), Physicochemical properties, Southern Nigeria, Spatial heterogeneity, Wastewater pollution

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INTRODUCTION

Oil palm remains the most productive oil-producing crop globally, yielding 10–35 tons of fresh fruit bunches per hectare (Ahmad et al., 2023; Mohd et al., 2023). West African countries, such as Ghana and Nigeria, significantly rely on oil palm production, primarily used as cooking oil (Agyemang et al., 2022).

As a crucial aspect of Nigeria's economy and trade, oil palm is highly sought after globally due to its affordability, ease of processing, and simplicity (Ibrahim et al., 2020). Oil palm is a versatile crop, with various products derived from it, including pomade (Ogunniyi et al., 2023). In Nigeria, there are a number of corporate palm oil refineries, but the business of palm oil extraction is dominated by the local, small scale and peasant farmers, who use mainly manual methods to extract oil from oil palm fruits (Dada et al., 2021).

The palm oil industry has grown into a major global agro-industry, producing more oil than any other plant. The environmental impacts of palm oil production, including deforestation and habitat loss, have sparked criticism (Ahmed et al., 2023; Shears and Richard, 2022). In both conventional and traditional milling settings, both solid and liquid waste are generated. Wastes generated by palm oil processing include solid (palm press fibre, chaff, palm kernel shell and empty fruit bunch), liquid (palm oil mill effluent (POME)) and gaseous (pollutant gases) (Abdullahi et al., 2023). Only small portions of the solid wastes are used as fuel during cooking and mulch in agriculture, while the rest are discharged into the environment without or with very little treatment (Edward et al., 2016; Izah et al., 2016).

Water is used in the palm oil extraction process to separate the oil in a tank from the particles and sludge. Once the oil has been removed, the mill releases its waste water, or effluent. The effluent from palm oil production contains particles that require treatment before environmental release (Effiong, 2024). Palm oil mill effluents entering waterways disrupt the food chain and impact water consumption (Singh et al., 2023).

Palm oil mill effluent (POME) (Plate 1) is termed to be a highly polluting material and its composition is from different sources and are obtained from palm oil, water, sand and solid (suspended and dissolved) (Adegbola and Olatunde, 2020). POME (composed of 93-95% water, solidly composed of 3-4% and oil composed of 0.5-2%) is not the only waste generated during the processing of palm oil. Others waste includes liquid (oil residue) containing proteins, carbohydrates, nitrogenous compounds, phenols as well as organic acid (Madaki and Seng 2013). The environmental concerns and source of palm oil mill effluent (POME) have been highlighted by some studies, for example, Ajalla et al. (2021) and Wang et al. (2022) identified sterilization and clarifying processes as primary sources of POME.

Plate1: Effluents from processed oil palm
Source: Effiong (2024)

Incessant discharge of POME is devastating to the environment and can elevate BOD and metal concentrations in soil and water bodies (Edward et al., 2017). POME is rich in pathogenic microorganisms and possesses higher concentrations of BOD and COD and is capable of polluting soil and freshwater (Imo and Ihejirika, 2021). POME obtained from local processors has been reported by Uroko (2014) to possess higher concentrations of Cu, Cr and Fe. Discharge of untreated POME elevated the levels of turbidity, total bacterial count, Cr, Pb, Mn, and Mg beyond WHO threshold limits (Yuguda et al., 2021). Edward et al. (2017) also reported pH, turbidity, temperature, alkalinity, TDS, TSS, TS, Metals and Nutrients values above WHO permissible limits in water samples collected from River which receive a large volume of POME from local processing of palm oil.

Discharging untreated POME is stocking soil with numerous contaminants that affects soil qualities and functionality by altering its biological and chemical composition (Nwoko and Ukiwe, 2016). Soil contaminated with POME can have elevated acidity and depreciated physicochemical qualities (Chikwendu and Ogbonna, 2019). The higher acidity in the POME can deprive the soil of phosphorus and significantly reduces soil lipase, catalase and dehydrogenase activities (Uroko, 2014).

POME can alter soil properties by increasing organic matter, pH, electrical conductivity, available phosphorus, exchangeable bases, cation exchange capacity (Ako and Anegbe, 2022) and heavy metals content (Nnaji et al., 2016; Nwoko and Ukiwe, 2016; Ubani et al., 2017). Nmaduka et al. (2018) reported an increase in BOD, COD, DO, oil and grease, pH, total suspended solids and calcium in POME dumpsite soil.

Many studies on POME in Nigeria emphasize general environmental impacts, e.g. soil acidification (Chikwendu and Ogbonna, 2019), eutrophication (Osman et al., 2020) or impact on aquatic life, or treatment methods, but there is understudying of the composition of POME (levels of organic matter, nutrients, such as nitrogen and phosphorus, heavy metals, polycyclic aromatic hydrocarbons) in some detail with the aspect of spatial variations across Southern Nigeria.

The purpose of this study is to comprehensively characterize the physicochemical properties of raw POME from 12 small-scale mills across six southern Nigerian states and determine whether effluent quality exhibits spatial autocorrelation or is driven primarily by mill-specific operational factors.

MATERIALS AND METHOD

Study Area

The palm oil milling effluent (POME) (Fig.1) used for this study was obtained from local and small-scale refinery across Southern part of Nigeria with 6 States in consideration. The ggeographical locations of the samples collected are illustrated in Table 1 and Fig. 3.

Mills varied in processing capacity (2-15 tonnes FFB/day), age (3-15 years), and treatment infrastructure. However, the operational data (e.g., daily production volumes, maintenance records) were not disclosed by mill operators, limiting analysis of process-specific impacts on effluent quality.

Samples Collection

The POME was collected in a clean and sterilized 5-litre high density plastic container (acid-washed with 10% HNO_3, rinsed with deionized water) (Fig. 2), stored in ice-cooled coolers (4°C ± 2°C) and transported to the National Biotechnology Research and Development Agency (NABRDA), Abuja laboratory within 24 hours, where it was refrigerated at about 4^{o}C.

Table 1: Locations where palm oil milling effluent were obtained

State	Sample	Location
Ekiti	1	7.724799, 5.310944
	2	7.4708250, 5.4305450
Osun	1	7.46309, 4.35384
	2	7.46929, 4.35956
Akwa-Ibom	1	4.935662, 7.952460
	2	4.930474, 7.948630
Imo	1	5.75917, 7.10384
	2	5.54639, 7.27135
Abia	1	5.596431, 7.7435375
	2	5.59882, 7.603783
Delta	1	6.371247, 6.560491
	2	6.2171555, 6.6517017

Fig.1: POME well

Fig.2: Collected POME samples

Sampling Design

The twelve mills where samples were collected in this study were selected using stratified random sampling (two mills per state representing about 60% regional production capacity). The samples were collected during peak processing hours (10:00-14:00 local time) to capture maximum effluent loading, and the raw POME were collected immediately after anaerobic digestion tanks, prior to any polishing ponds or secondary treatment (as-discharged effluent. The samples were taken during continuous discharge; with flow rates ranged from 2.5-4.8 m^3/hr across sites.

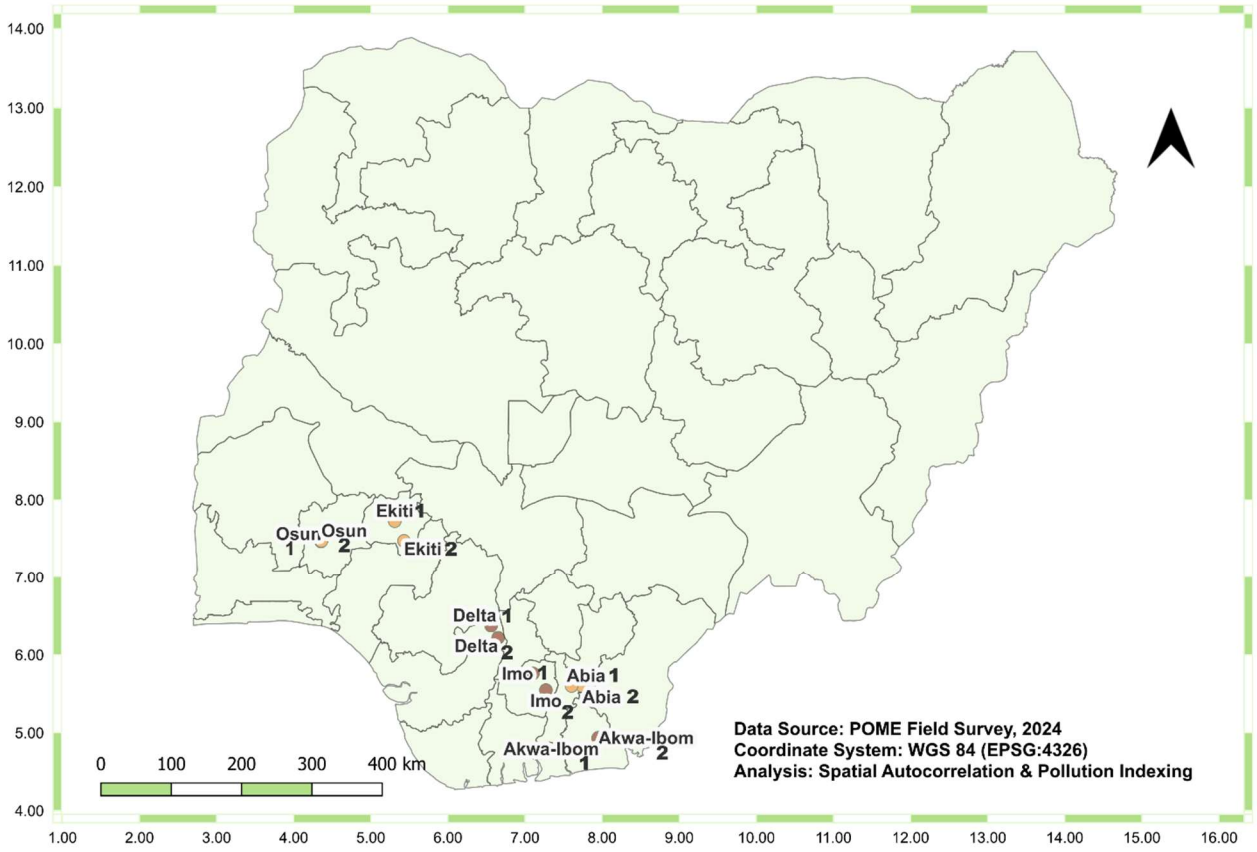

Fig. 3: Palm Oil Milling Effluent (POME) collection distribution across southern Nigeria

Palm oil milling effluent (POME) Physicochemical analyses

One composite sample of 1.5 L was taken and sampled in three (3) aliquots (500 mL apiece) in order to replicate the analysis for physicochemical properties such as: pH, temperature, electrical conductivity, total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), total organic nitrogen (TON), nitrite, nitrate and phosphate. All parameters were measured using calibrated instruments and standard analytical procedures in compliance with American Public Health Association (APHA) guidelines. The results from this phase provide essential baseline data.

The pH meter (Mettler Toledo S400 model) was used to measure the pH of each effluent samples (APHA 4500-H^+ B). The temperature of the effluent was determined using thermometric measurement (APHA 2550 B) (APHA, 2022). The Electrical Conductivity (EC) were determined using an Oakton TDS/Conductivity meter (HI 2315, Hanna Instrument) (APHA 2510 B) (Noble-Okereke et al., 2023; Shah and JGeeta, 2017).

Biochemical Oxygen Demand (BOD) measures oxygen consumption by microorganisms breaking down organic matter and this was done using 5-Day BOD (This couldn't be done in 48 hours earlier mentioned Test (APHA 5210B) (APHA, 2022). Dissolved oxygen (DO) was measured using the membrane electrode method (APHA 4500-O G). Chemical Oxygen Demand (COD) measures amount of oxygen required to break down organic matter chemically, this was done employing Closed Reflux Colorimetric Method (APHA 5220C) (APHA, 2022).

The Total Suspended Solids (TSS) measures suspended particles in the POME samples, and this was done using Gravimetric method (APHA 2540D) (APHA, 2022; Environmental Protection Agency (EPA), 2022). The Total Dissolved Solid (TDS) test that was used to quantified dissolved ion and salts concentration in the POME samples was done using Gravimetric method (APHA 2540 C). Nitrite determination measures nitrite concentration in waste water using the Colorimetric Method (APHA 4500-NO2-B). Nitrate determination measure nitrate concentration utilizing Reduction to Nitrite Method (APHA 4500-NO3-E). The total organic nitrogen (TON) was determined using the macro-Kjeldahl method (APHA 4500-Norg). Phosphate determination measures phosphate concentration in the waste water using Colorimetric Method (APHA 4500-P-E) (APHA, 2022). However, Total Organic Nitrogen (TON) recovery was validated using: spike recovery tests (this involved adding known solutions of glycine standard (100 mg N/L) to POME matrix with recovery rates of 95-108% (n=3)), certified reference material- NIST SRM 1640a (trace elements in natural water) was used (along with the samples) and TON recovery of 98 ± 4%, method blanks (analyzed every samples; of which all blanks show < 0.5 mg/L TON below detection limit), and duplicate tests (coefficients of variation <5 percent for all samples).

Spatial Analysis Methods

Geographic Representation: For spatial autocorrelation analysis, each sampling site was georeferenced using GPS coordinates collected during field sampling (Table 1). State-level analyses used the geographic centroid of the two mill locations within each state, calculated as:

$$\text{Centroid}_{\text{lat}} = \frac{\text{Site1}_{\text{lat}} + \text{Site2}_{\text{lat}}}{2}$$

$$\text{Centroid}_{\text{lon}} = \frac{\text{Site1}_{\text{lon}} + \text{Site2}_{\text{lon}}}{2} \quad \text{Eqn.1}$$

Spatial autocorrelation (Moran's I) was calculated using a distance-based spatial weight matrix with:

1. Distance metric: Great circle distance (haversine formula) between state centroids
2. Weighting scheme: Inverse distance weighting (IDW) with power parameter k=1
3. Connectivity: All pairs included (no distance threshold)

The spatial weight matrix W was defined as:

$w_{ij} = 1/d_{ij}$ if $i \neq j$

$w_{ij} = 0$ if $i = j$

where d_{ij} is the great circle distance (km) between state centroids *i* and *j*.

Moran's I Calculation:

$$I = \frac{n}{\sum_i \sum_j w_{ij}} \times \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad \text{Eqn.2}$$

Significance testing employed Monte Carlo permutation (999 iterations) to generate pseudo *p*-values robust to small sample sizes.

Distance-Decay Analysis: Pearson correlation coefficients were calculated between:

1. X-variable: Pairwise Euclidean distances between state centroids (great circle distance in km)
2. Y-variable: Absolute differences in parameter values: $|Parameter_i - Parameter_j|$

Significance was assessed using bootstrap resampling (10,000 iterations) to account for non-independence of pairwise comparisons.

Variogram Analysis

Semi-Variogram Analysis

To better characterize spatial structure, empirical semi-variograms were computed:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{N(h)} [z(x_i) - z(x_i + h)]^2 \quad \text{Eqn.3}$$

where *N(h)* is the number of point pairs separated by distance *h* (±tolerance band).

Sensitivity Analysis

To assess robustness of spatial findings to methodological choices, we conducted sensitivity tests:

A. Point Aggregation Method: Compared state-centroid approach vs. using individual mill coordinates (n=12).
B. Distance Weight Function: Tested alternative spatial weight matrices.

Quality Assurance

1. Field blanks: Deionized water transported and processed identically (n=3 per batch).
2. Spike recovery: 85-115% for all analytes.
3. Instrument calibration: Five-point curves (R^2 >0.995) verified daily.
4. Duplicates: 10% of samples analyzed in duplicate (RSD <10%).

Limitations:

The study experienced the following set-backs:

1. Single grab sampling per mill may not capture diurnal/seasonal variations.
2. No composite sampling over extended periods.
3. Potential stratification in raw POME not assessed (samples homogenized before analysis).

Statistical Analysis

The data obtained from the physicochemical properties analysis of the POME samples were subjected to descriptive analysis and results was displayed in mean, standard deviation and coefficient variation. The normality of the data obtained (normality testing) was conducted using Shapiro-Wilk test at p<.05. The comparative analysis of POME samples quality across the 6 States was conducted using Mann-Whitney U Test at p<.05. Post-hoc power analysis was conducted using G*Power 3.1.9.7 (Faul et al., 2007) to assess the adequacy of sample sizes for detecting observed effects in Mann-Whitney U tests with parameters such as: nonparametric tests, two-tailed, α error probability: 0.05 (pre-FDR correction), effect size input (Observed r values from Mann-Whitney U tests) and sample sizes (n_1 = n_2 = 3 per site).
Spatial Analysis were conducted to address the spatial patterns in which BOD, COD. TON. DO, Nitrite, etc. levels and composite pollution index across states were determined with point maps with graduated symbols showing pollution severity at collection sites. The composite Pollution Index (PI) was calculated using the weighted sum of normalized pollutant concentrations relative to regulatory limits:

$$PI = \sum_{i=1}^{n} w_i \times \frac{C_i}{S_i} \quad \text{Eqn.4}$$

Where:
C_i = measured concentration of parameter i
S_i = regulatory standard/limit for parameter i (NESREA, 2009)
w_i = weighting factor based on environmental impact (assigned based on toxicity and persistence)
n = number of parameters

Spatial autocorrelation analyses were performed using the spdep package (v1.2-8) in R (v4.4.5). Variogram modeling employed the gstat package (v2.1-0). Monte Carlo simulations for Moran's I used 999 permutations. Bootstrap resampling for distance-decay correlations (10,000 iterations) was conducted using the boot package (v1.3-28). All spatial weight matrices were row-standardized. Global Moran's I was used to test spatial autocorrelation and simple distance-decay analysis used to calculate pairwise distances between states with respect to the POME physico-chemical properties.
The Software used for this analysis were QGIS 3.42.3, R studio 4.4.5 and python 3.13.

Ethics Declaration and Statement

All palm oil mills were sampled with their permission taken before the samples were collected. Mill operators were obtained to sign a written agreement as per the local regulations. The study did not need any ethical approval because it entailed merely some environmental sampling of industrial effluent, which did not have any human or animal subjects.

RESULTS AND DISCUSSION

Descriptive Analysis of the POME Physicochemical Properties

The Table 2 reveals the regional variations in physicochemical properties of Palm Oil Mill

Effluent (POME) collected from two sites in each of six States (Abia, Akwa Ibom, Delta, Ekiti, Imo, and Osun) across Southern Nigeria. The data shows variability between sites within states (possibly due to processing differences or sampling conditions) and across states (potentially influenced by local mill practices, soil, or climate). The characteristics and composition of POME depend on quality of raw materials, time of operation, treatment and season (Karno et al., 2024).

According to Okereke and Ginikanwa (2020), Hosseini and Abdul Wahid, (2015) and Low et al. (2021), POME is typically acidic, organic-rich wastewater with high pollution potential, contributing to environmental issues like eutrophication and oxygen depletion in water bodies if untreated. In this study, all POME samples are highly acidic (pH 3.03-3.89), requiring neutralization before discharge. In their study, Maliki et al (2020) reported POME of pH 4.4– 4.5, Osagbovo and Orhue (2011) reported pH value of 4.8 for POME, pH values as low as 3.8 was reported by Abdurahman et al. (2011). Contrary to the findings of this study, Dada et al. (2021) reported a pH of 5.9 for POME samples which is signify a weak acidic. Verla et al. (2014) also report POME pH ranged from 6.8 - 8.7 in their study. The pH ranging between 3–5 is usually due to the organic acid produced in the fermentation stage during palm oil processing (Bala et al., 2014).

Generally, in this study, all samples temperature were uniform (27-29°C), and this may indicate recent discharge from hot processing. The EC ranged between 648 and 1840 µS/cm with Imo having the highest salinity. Verla et al. (2014) reported POME EC value range of 131-138 µs/cm which is lower than the one obtained in this study.

The TDS for the POME samples from the 6 States range from 115 to 773 mg/L, Delta shows the highest dissolved matter. Kamyab et al. (2018) report that high number of total solids (40,500 mg/L) contributes to the large amount of nutrients available in the wastewater, hence possible algae bloom. The TSS range was 0.07 - 4.16mg/L, Akwa Ibom is the most turbid. Lower TSS will decrease primary productivity in phytoplankton and macrophytes, and increase the rate of drift in invertebrates (Donald et al., 2019).

The DO range is 7.21-16.30 mg/L, Ekiti appeared to be the best oxygenated effluent. The BOD range between 1.05 and 4.06 mg/L, Osun shows highest biological pollution. The COD range is 380 - 621 mg/L with Delta having the highest chemical pollution. High biological oxygen demand (BOD), and chemical oxygen demand (COD) content of POME has been associated with pollution (Ohimain et al., 2013). Kamyab et al. (2018) report that POME contains high amounts of COD (50,000 mg/L) and very high concentration of biochemical oxygen demand (BOD) (25,000 mg/L) which becomes a serious threat to aquatic life when discharged in relatively large quantities into watercourses.

Elemental constituent of POME includes nitrogen (N), and phosphorus (P) (Saad et al., 2021, Zulfahmi et al., 2021). The phosphate levels in the POME samples in this study ranged from 9.47 to 11.49 mg/L, Abia shows highest phosphate levels. The phosphorus content in POME if high may lead to eutrophication (Mohamad et al., 2021).

Untreated POME contains substantial amount of organic substances and nutrients, and nitrogenous compounds, which have the possibility of adjusting COD, BOD, DO and other environmental parameters (Ahmad et al., 2016, Elystia et al., 2020, Ohimain et al., 2013, Tang et al., 2020). In this study, the NO_3 in the POME samples range is 9.80 -32.11 mg/L, Imo indicate the highest nitrate value among the effluents. The NO_2 range between 10.05 and 24.50 mg/L, Imo also has the highest nitrite. The TON range is 23.68 -56.76 mg/L and Imo has highest organic nitrogen.

Intra-State Spatial Variability in POME Quality

The comparison between the two sampling sites within each state revealed substantial spatial

heterogeneity in POME characteristics, with critical implications for regulatory compliance and environmental risk assessment when evaluated against National Environmental Standards and Regulations Enforcement Agency (NESREA) (2014), Indonesia Standards (Saputera et al., 2021), and Malaysia Standards (Sapie et al., 2019) (Table 3).

Abia State

In Abia, Site 2 exhibited the highest electrical conductivity of 1720 µS/cm which is higher than the standard recommended by NESREA (<1000 µS/cm). These elevated values indicate substantial ionic pollution likely from concentrated wastewater or inadequate dilution practices. The site 2 also display the highest TDS values of 834.67 mg/L and TSS (0.28 mg/L), which are below NESREA, Indonesia and Malaysia effluent standard as indicated in Table 3. Concurrently, Site 1 demonstrated higher dissolved oxygen 16.21 mg/L. Most notably, Site 2 showed complete absence of detectable biochemical oxygen demand (BOD = 0 mg/L) compared to Site 1 (2.10 mg/L), a pattern inconsistent with typical POME characteristics and potentially indicating either advanced anaerobic degradation, toxic inhibition of microbial activity, or analytical artifacts. Both sites maintain BOD values well below the NESREA limit of 50 mg/L, the COD (493 and 487.67 mg/L) from both sites exceeds the limit from both local and international standards as indicate in Table 3. Site 2's higher variability in pH (CV 2.97 as compared to 1.73) but lower in BOD (CV 0 vs. 4.76) suggests temporal fluctuations in acid-base characteristics while maintaining consistently suppressed biological oxygen demand, potentially reflecting different treatment stages, dilution regimes, or toxicant accumulation that inhibits microbial respiration.

Akwa Ibom State

Akwa Ibom demonstrated contrasting patterns, with Site 2 showing lower EC of 963.33 µS/cm and TDS of 375 mg/L, both comfortably within regulatory limits, suggesting better dilution or lower ionic load compared to Site 1. However, Site 2 exhibited dramatically elevated total suspended solids of 7.06 mg/L, below NESREA limits (30 mg/L) and the other two international effluent limit. This high TSS burden compared to site 1 corresponded with elevated dissolved oxygen of 10.12 mg/L) and biochemical oxygen demand of 3.98 mg/L which is lower to the standard limits. Chemical oxygen demand remained similar between sites but both sites dramatically exceeded NESREA COD limits (150 mg/L), representing 352 - 355.33% of permissible levels. Phosphate levels (10.32-10.64 mg/L) exceeded NSEREA total phosphorus limits (10 mg/L). The substantially lower variability in Site 2 for TSS (CV 0.11 compared to 3.07) despite absolute values being higher suggests consistent high particulate loading, possibly from continuous processing

Delta State

Delta State's Site 2 demonstrated the severe ionic pollution among the 2 sites with EC 1607.33 µS/cm, which is higher than the standard recommended by NESREA (<1000 µS/cm) and TDS value of 934.33 mg/L which is below the standard effluent limits (2000 mg/L) indicate in Table 3. The site 2 total suspended solids appear to be higher with a value of 1.14 mg/L, although below the standard effluent limits (30-400 mg/L). Concomitant with elevated ionic and particulate loads, Site 2 showed decreased dissolved oxygen (10.20 mg/L) compared to site 1 with a value of 12.10 mg/L. Both sites have low BOD (2.05 and 1.99 mg/L) compared to the standard effluent limit (50-100 mg/L), and higher COD from both sites 627.00 and 615.67 mg/L compared to the standard effluent limit (150-400 mg/L). Nutrient indicators revealed concerning patterns: phosphate were lower than the standard effluent limit for both sites, while nitrite and nitrate level in the POME from both sites were higher than the standard effluent limit. These extreme nutrient concentrations, combined with elevated ionic content, indicate possible concentration effects from evaporation, incomplete treatment, or receipt of concentrated waste streams from multiple processing stages.

Ekiti State

Ekiti exhibited the most dramatic intra-site differences in ionic parameters, with Site 2 showing EC elevated by +493 µS/cm from site 1, yet both were still within the NESREA effluent limit of<10000 µS/cm. The site 2 appear to have higher TDS of 589.33 mg/L when compared to the site 1 with 162.00 mg/L, these values are below the standard effluent limits for Nigeria, Indonesia and Malaysia as indicated in Table 3. Despite elevated dissolved pollutants, Site 2 demonstrated lower suspended solids of 0.13 mg/L, within compliance, suggesting effective particulate removal but inadequate dissolved contaminant treatment. Biochemical oxygen demand for both sites is within the requires effluent limit, while COD for site 1 and 2 are 479.00 and 482.00 mg/L respectively, these values are higher than the effluent limits of the three countries in view from Table 3. Nutrient reductions in Site 2 (PO_4 -0.67 mg/L, NO_3 -0.05 mg/L, NO_2 -0.07 mg/L, TON -0.15 mg/L) suggest partial nutrient stripping. For both sites, the nitrite value is higher than the effluent limits standards.

Imo State

Imo State's Site 2 demonstrated moderate ionic elevation with EC values (1945 µS/cm) almost double the NESREA effluent limit, site 1 also have high EC values. The TDS for site 1 (105.0 mg/L) and site 2 (134.33 mg/L) appear to be lower than the NESREA, Indonesia and Malaysia effluent limit. Total suspended solids between the two sites is 0.34 mg/L, and both sites TSS are still within required effluent limit, dissolved oxygen different between the two sites is 1.98 mg/L, and biochemical oxygen demand dropped to undetectable levels (BOD -4.07 mg/L to 0 mg/L) from site 1 to 2, mirroring the anomalous pattern observed in Abia. Chemical oxygen demand for site 1 and 2 are 438.67 and 430.33 mg/L respectively, these appear to be higher than effluent limit. Nutrient patterns showed mixed results: phosphate between both sites slightly elevated (+0.12 mg/L) but the levels for both sites are within the effluent limits standard as indicated in Table 3, nitrate and nitrite of both sites are higher than the permissible limit a indicated by NESEREA (Nitrate- 10 mg/L) and Indonesia (nitrite -1 mg/L), and total organic nitrogen for both sites slightly above Indonesia (50 mg/L) and below Malaysia 100 mg/L effluent limit level.

Osun State

Osun State presented relatively moderate inter-site differences compared to other locations. Site 2 showed elevated EC (142 µS/cm, to 1708.67 µS/cm, 170% of NESREA limit) and TDS for site 2 is 123 mg/L, still within compliance. The TSS for both sites are within compliance. Dissolved oxygen marginally increased from site 1 by +0.13 mg/L, to 12.23 mg/L in site 2, as did BOD (+0.11 mg/L, to 4.11 mg/L, 8.22% of NESREA limit, approaching threshold), while COD decreased substantially (COD -16 mg/L) to 371.67 mg/L in site 2, both COD values were higher than the standard effluent limits specified in Table 3. The nitrate and nitrite for the two sites is higher than the NESREA and Indonesia effluent limit. The TON for both sites are within the permissible limit has indicate by the Indonesia and Malaysia effluent limit in Table 3.

Table 2: Physicochemical Properties of POME across Southern Nigeria

Parameters	Site	Abia State		Akwa Ibom State		Delta State		Ekiti State		Imo State		Osun State	
		Mean± SD	CV	Mean± SD	CV	Mean± SD	CV	Mean± SD	CV	Mean± SD	CV	Mean± SD	CV
pH	1	3.33 ± 0.06	1.73	3.03±0.06	1.90	3.89±0.01	0.30	3.83±0.06	1.51	3.72±0.03	0.93	3.81±0.02	0.55
	2	3.20± 0.10	2.97	3.05±0.05	1.64	3.72±0.08	2.05	3.88±0.08	1.97	3.53±0.06	1.63	3.70±0.05	1.35
T^0C	1	28.47±0.47	1.66	28.73±0.31	1.06	27.12±0.07	0.27	27.93±0.12	0.41	27.81±0.01	0.04	27.50±0.50	1.33
	2	28.73±0.23	0.80	28.40±0.17	0.61	27.53±0.06	0.21	29.17±0.29	0.99	27.20±0.01	0.02	27.82±0.07	0.24
EC (µS/cm)	1	1103.67±4.73	0.43	1063.67±5.51	0.52	1094.00±1.00	0.09	401.00±1.00	0.25	1734.33±1.15	0.07	1566.33±4.73	0.30
	2	1720.00±10.00	0.58	963.33±3.21	0.33	1607.33±0.58	0.04	894.00±1.00	0.11	1945.00±1.00	0.05	1708.67±2.52	0.15
TDS (mg/L)	1	609.00±4.00	0.66	375.33±1.53	0.41	612.00±2.00	0.33	162.00±1.00	0.62	105.00±1.00	0.95	106.00±1.00	0.94
	2	834.67±5.03	0.60	332.00±2.00	0.60	934.33±0.58	0.06	589.33±0.58	0.10	134.33±0.58	0.43	123.00±2.00	1.63
TSS (mg/L)	1	0.19±0.01	5.44	1.26±0.04	3.07	0.76±0.00	0.26	1.11±0.00	0.27	0.96±0.00	0.42	0.11±0.01	11.27
	2	0.28±0.00	0.55	7.06±0.01	0.11	1.14±0.01	0.44	0.13±0.00	0.46	0.62±0.00	0.49	0.03±0.01	41.44
DO (mg/L)	1	16.22±0.03	0.20	8.13±0.06	0.71	12.10±0.10	0.83	16.30±0.10	0.61	8.20±0.10	1.22	12.10±0.10	0.83
	2	14.20±0.10	0.70	10.12±0.08	0.75	10.20±0.10	0.98	16.29±0.08	0.50	6.22±0.03	0.46	12.23±0.15	1.25
BOD (mg/L)	1	2.10±0.10	4.76	2.10±0.10	4.76	2.05±0.05	2.44	4.04±0.07	1.71	4.07±0.12	2.84	4.00±0.10	2.50
	2	0.00	0.00	3.98±0.02	0.50	1.99±0.02	1.16	1.99±0.02	0.87	0.00	0.00	4.11±0.10	2.50
PO_4^{3-} (mg/L)	1	11.50±0.02	0.17	10.64±0.05	0.49	9.39±0.01	0.14	10.04±0.05	0.52	10.13±0.06	0.56	10.00±1.00	10.00
	2	11.48±0.02	0.17	10.32±0.03	0.24	9.54±0.06	0.59	9.37±0.01	0.10	10.25±0.05	0.45	10.35±0.04	0.40
NO_3^- (mg/L)	1	15.70±0.30	1.91	13.75±0.01	0.08	29.45±0.04	0.14	9.82±0.02	0.21	33.42±0.07	0.21	17.65±0.05	0.29
	2	15.79±0.20	1.27	13.75±0.03	0.22	29.44±0.02	0.05	9.77±0.03	0.27	30.79±0.02	0.06	17.83±0.04	0.20
NO_2^- (mg/L)	1	11.48±0.02	0.17	10.05±0.05	0.50	21.52±0.02	0.09	21.72±0.02	0.08	24.43±0.15	0.63	12.90±0.01	0.11
	2	11.46±0.15	1.31	10.05±0.05	0.50	21.87±0.23	1.06	21.65±0.01	0.05	24.56±0.04	0.15	12.76±0.02	0.16
COD (mg/L)	1	493.00±2.00	0.41	528.00±1.00	0.19	627.00±2.00	0.32	479.00±1.00	0.21	438.67±1.53	0.35	387.67±2.08	0.54
	2	487.67±2.52	0.52	533.00±1.00	0.19	615.67±0.58	0.09	482.00±1.00	0.21	430.33±1.53	0.35	371.67±1.53	0.41
TON (mg/L)	1	27.11±0.04	0.13	23.76±0.04	0.17	50.94±0.06	0.11	31.55±0.01	0.03	58.19±0.70	1.21	30.65±0.13	0.41
	2	27.25±0.05	0.18	23.60±0.10	0.42	50.98±0.02	0.03	31.40±0.10	0.32	55.33±0.06	0.11	30.59±0.03	0.08

SD: Standard deviation

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Table 3: International and National Standard Limits for POME Limitation Guidelines

Soil Parameters	NESREA (2014)	Indonesia Standards [a]	Malaysia Standards [b]	This study range
pH	6.00-9.00	6.00-9.00	6.00-9.00	3.03 – 3.89
Temperature (^{0}C)	<40	<40	<40	27.12 – 29.17
Dissolved Oxygen (OD) (mg/L)	-	-	-	6.22 – 16.30
Biochemical Oxygen Demand (BOD) (mg/L)	50	100	100	0.00 – 4.11
Chemical Oxygen Demand (COD) (mg/L)	150	350	400	371.67 – 627.00
Total Suspended Solids (TSS) (mg/L)	30	250	400	0.03 – 7.06
Total Dissolved Solids (TDS) (mg/L)	2000	2000	-	105.00 – 934.33
Total Organic Nitrogen (TON) (mg/L)	-	50	200	23.60 – 58.19
Nitrate (mg/L)	10	20	-	9.77 – 33.42
Total Phosphorus (mg/L)	10	-	-	9.37 – 11.50
Electrical conductivity (µs/cm)	<1000	-	-	401.00 – 1945.00
Nitrite (mg/L)	-	1	-	10.05 – 24.56

NESREA-National Environmental Standards and Regulations Enforcement Agency
[a] Saputera et al. (2021)
[b] Sapie et al. (2019)

Normality of the POME Physicochemical Properties data

The normality assessment in Table 4 evaluates whether the distribution of each physicochemical parameter in the Palm Oil Milling Effluent (POME) data for this study follows a normal (Gaussian) distribution, using the Shapiro-Wilk test; a widely used statistical test for normality, especially suitable for small to moderate sample sizes (n < 50) (Ghasemi and Zahediasl, 2012). The Shapiro-Wilk results consistently reject normality for all measured POME parameters. Parameters like Temp (W = 0.5383) and TSS (W = 0.5217) show severe deviation from normality likely due to skewness, outliers, or multimodality. While those with relatively higher W statistics (e.g., COD: W = 0.9283, TON: W = 0.7966) still have $p < 0.05$, confirming non-normality.

Table 4: Normality Assessment of physicochemical parameters from the Palm oil milling effluent (POME)

Parameter	Shapiro-Wilk Statistic	p-value	Normality Interpretation
pH	0.8677	5.00e-04	Non-Normal
Temp (°C)	0.5383	0.0000	Non-Normal
EC (µS/cm)	0.8971	0.0028	Non-Normal
TDS (mg/L)	0.8577	3.00e-04	Non-Normal
TSS (mg/L)	0.5217	0.0000	Non-Normal
DO (mg/L)	0.9136	0.0082	Non-Normal
BOD (mg/L)	0.8206	0.0000	Non-Normal
PO_4^{3-} (mg/L)	0.9189	0.0117	Non-Normal
NO_3^- (mg/L)	0.842	1.00e-04	Non-Normal
NO_2^- (mg/L)	0.7992	0.0000	Non-Normal
COD (mg/L)	0.9283	0.0222	Non-Normal
TON (mg/L)	0.7966	0.0000	Non-Normal

Comparative Analysis of POME Quality across the States

According to Ergin and Koskan (2023) Mann-Whitney U test is used to evaluate relationship between samples when assumptions of parametric tests are. In this study, the Mann-Whitney U test results (Table 5) indicate no statistically significant differences ($P > 0.05$, P-FDR > 0.05) in POME physicochemical properties between Site 1 and Site 2 across all Southern Nigerian States. Despite this, large effect sizes ($r \approx 0.80$) for many parameters suggest practical variations. In Abia, Site 2 exhibited elevated EC (1103.67 to 1720.00 µS/cm [55.8% increase, r=0.80]), TDS (609 to 834.67 mg/L [37.1% increase, r=0.80]), TSS, and TON, implying higher ionic and organic nitrogen loads, possibly from mill-specific processing. Akwa Ibom showed Site 2 with increased TSS (1.26 to 7.06 mg/L [460% increase, r=0.80]), DO, BOD, and COD, indicating greater suspended solids and biodegradable organics, potentially due to inadequate settling. Delta State demonstrated consistently high effect sizes (r=0.80) for most parameters despite non-significant P-FDR values, with EC increasing 46.9% and TDS rising 52.7%, reflecting considerable site-to-site variability in effluent concentration. Ekiti showed the largest inter-site differences, with EC increasing 123% (401 to 894 µS/cm) and TDS surging 264% (162 to 589.33 mg/L), suggesting fundamentally different processing or dilution practices between sites. Imo's Site 2 displayed lower organics (BOD, COD, TON) and TSS (raw P=0.047) but higher EC and TDS, indicating differential treatment effects. Osun's pronounced temperature drops in Site 2 (27.5°C to 27.82°C) with minor nutrient shifts highlights possible temporal influences. Overall, inter-state site variations underscore heterogeneous mill operations, effluent management, and environmental factors across Southern Nigeria.

Table 5: Mann-Whitney U Test Results Comparing Site 1 and Site 2 POME Characteristics Across Southern Nigeria States

State	Parameters	Site 1	Site 2	U	P-value	P-FDR*	Effect Size (r)**	Achieved Power***	Required n (power=0.80)
	pH	3.33	3.2	7	0.383	0.444	0.445	0.051	18
	Temperature	28.47	28.73	3	0.663	0.672	0.267	0.080	55
	EC	1103.67	1720	0	0.081	0.119	0.802	0.657	4
	TDS	609	834.67	0	0.081	0.119	0.802	0.657	4
	TSS	0.19	0.28	0	0.064	0.119	0.802	0.657	4
	DO	16.22	14.2	9	0.081	0.119	0.802	0.657	4
Abia	BOD	2.1	0	9	0.064	0.119	0.802	0.657	4
	PO_4^{3-}	11.5	11.48	7	0.383	0.444	0.445	0.051	18
	NO_3^-	15.7	15.79	3	0.663	0.672	0.267	0.080	55
	NO_2^-	11.48	11.46	3	0.663	0.672	0.267	0.080	55
	COD	493	487.67	8	0.190	0.269	0.624	0.303	8
	TON	27.11	27.25	0	0.081	0.119	0.802	0.657	4
	pH	3.03	3.05	2	0.383	0.444	0.445	0.051	18
	Temperature	28.73	28.4	7	0.383	0.444	0.445	0.051	18
	EC	1063.67	963.33	9	0.081	0.119	0.802	0.657	4
	TDS	375.33	332	9	0.081	0.119	0.802	0.657	4
	TSS	1.26	7.06	0	0.081	0.119	0.802	0.657	4
	DO	8.13	10.12	0	0.081	0.119	0.802	0.657	4
Akwa	BOD	2.1	3.98	0	0.081	0.119	0.802	0.657	4
Ibom	PO_4^{3-}	10.64	10.32	9	0.081	0.119	0.802	0.657	4
	NO_3^-	13.75	13.75	2	0.383	0.444	0.445	0.051	18
	NO_2^-	10.05	10.05	2	0.383	0.444	0.445	0.051	18
	COD	528	533	0	0.081	0.119	0.802	0.657	4
	TON	23.76	23.6	7	0.383	0.444	0.445	0.051	18
	pH	3.89	3.72	9	0.081	0.119	0.802	0.657	4
	Temperature	27.12	27.53	0	0.081	0.119	0.802	0.657	4
	EC	1094	1607.33	0	0.081	0.119	0.802	0.657	4
	TDS	612	934.33	0	0.081	0.119	0.802	0.657	4
	TSS	0.76	1.14	0	0.064	0.119	0.802	0.657	4
	DO	12.1	10.2	9	0.081	0.119	0.802	0.657	4
Delta	BOD	2.05	1.99	8	0.190	0.269	0.624	0.303	8
	PO_4^{3-}	9.39	9.54	0	0.081	0.119	0.802	0.657	4
	NO_3^-	29.45	29.44	3	0.663	0.672	0.267	0.080	55
	NO_2^-	21.52	21.87	0	0.081	0.119	0.802	0.657	4
	COD	627	615.67	9	0.081	0.119	0.802	0.657	4
	TON	50.94	50.98	3	0.663	0.672	0.267	0.080	55
	pH	3.83	3.88	2	0.383	0.444	0.445	0.051	18
	Temperature	27.93	29.17	0	0.081	0.119	0.802	0.657	4
	EC	401	894	0	0.081	0.119	0.802	0.657	4
	TDS	162	589.33	0	0.081	0.119	0.802	0.657	4
	TSS	1.11	0.13	9	0.047	0.119	0.802	0.657	4
	DO	16.3	16.29	3	0.663	0.672	0.267	0.080	55
Ekiti	BOD	4.04	1.99	9	0.081	0.119	0.802	0.657	4
	PO_4^{3-}	10.04	9.37	9	0.081	0.119	0.802	0.657	4
	NO_3^-	9.82	9.77	7	0.383	0.444	0.445	0.051	18

	NO_2^-	21.72	21.65	9	0.081	0.119	0.802	0.657	4
	COD	479	482	0	0.081	0.119	0.802	0.657	4
	TON	31.55	31.4	6	0.663	0.672	0.267	0.080	55
	pH	3.72	3.53	9	0.081	0.119	0.802	0.657	4
	Temperature	27.81	27.2	9	0.081	0.119	0.802	0.657	4
	EC	1734.33	1945	0	0.081	0.119	0.802	0.657	4
	TDS	105	134.33	0	0.081	0.119	0.802	0.657	4
	TSS	0.96	0.62	9	0.047	0.119	0.802	0.657	4
	DO	8.2	6.22	9	0.081	0.119	0.802	0.657	4
Imo	BOD	4.07	0	9	0.064	0.119	0.802	0.657	4
	PO_4^{3-}	10.13	10.25	0	0.081	0.119	0.802	0.657	4
	NO_3^-	33.42	30.79	9	0.081	0.119	0.802	0.657	4
	NO_2^-	24.43	24.56	3	0.663	0.672	0.267	0.080	55
	COD	438.67	430.33	9	0.081	0.119	0.802	0.657	4
	TON	58.19	55.33	9	0.081	0.119	0.802	0.657	4
	pH	3.81	3.7	9	0.081	0.119	0.802	0.657	4
	Temperature	27.5	27.82	9	0.081	0.119	0.802	0.657	4
	EC	1566.33	1708.67	0	0.081	0.119	0.802	0.657	4
	TDS	106	123	0	0.081	0.119	0.802	0.657	4
	TSS	0.11	0.03	9	0.081	0.119	0.802	0.657	4
	DO	12.1	12.23	2	0.383	0.444	0.445	0.051	18
Osun	BOD	4	4.11	2	0.383	0.444	0.445	0.051	18
	PO_4^{3-}	10	10.35	3	0.663	0.672	0.267	0.080	55
	NO_3^-	17.65	17.83	0	0.081	0.119	0.802	0.657	4
	NO_2^-	12.9	12.76	9	0.081	0.119	0.802	0.657	4
	COD	387.67	371.67	9	0.081	0.119	0.802	0.657	4
	TON	30.65	30.59	5	1.000	1.000	0.089	0.053	509

* P-FDR: False Discovery Rate corrected p-value

** Effect size interpretation: r < 0.3 (small), 0.3-0.5 (medium), >0.5 (large) (Gómez Penedo and Flückiger, 2025)

***Due to small sample sizes (n=3), effect sizes should be interpreted as descriptive measures of magnitude rather than precise population estimates. Post-hoc power analysis indicates low power for most comparisons.

While several comparisons showed large effect sizes (r > 0.5), particularly for EC, TDS, TSS, and nutrient parameters from Table 5, Post-hoc power analysis revealed that with n=3 per site, even large effects achieved only 65.7% power (below the conventional 0.80 threshold). Non-significant results (p > .05) may reflect Type II errors rather than true absence of differences. Effect sizes are presented to indicate magnitude of observed differences rather than statistical certainty. The small sample size (n=3 per site) substantially limited statistical power to detect true differences between sites. Power analysis indicated that 4-18 samples per site would be required to achieve 80% power for detecting medium-to-large effects observed in this study. Consequently, non-significant p-values should not be interpreted as evidence of equivalence between sites; rather, they reflect insufficient sample sizes to detect potentially meaningful differences. The large effect sizes observed (e.g., r=0.80 for EC in Abia, Delta, and Ekiti) suggest biologically relevant differences that warrant further investigation with adequately powered designs. Future studies should employ n ≥ 18 per site to achieve sufficient power (>0.80) for detecting medium effects (r ≥ 0.3).

POME Spatial Patterns and Pollution Hotspots

The Moran's I result from Table 6 reveal predominantly negative spatial autocorrelation across most physicochemical parameters, suggesting a lack of spatial clustering in POME pollution characteristics across the six states. This is a significant finding with important implications. Only pH shows significant spatial clustering (p = 0.0107) indicating that nearby states have similar pH values. Furthermore, all other parameters show no spatial patterns which could imply that pollution levels are randomly distributed across states and this is suggests milling-specific factors matter more than location. The distance-decay analysis from Table 6 reveals weak and predominantly non-significant correlations between geographic distance and parameter differences. There was no statistically significant distance-decay effects indicating that geographic distance does not predict similarity or dissimilarity in POME characteristics.

Table 6: Spatial Autocorrelation and Distance-Decay Analysis of Physicochemical Parameters in Palm Oil Mill Effluent (POME) across Six Nigerian States

	Spatial Autocorrelation		Distance-Decay Analysis	
Parameter	Morans_I	p_value	Correlation	p_value
pH	0.1835	0.0107	0.3688	0.1761
Temp	-0.0848	0.1699	0.4082	0.131
DO	-0.2537	0.6239	-0.1436	0.6096
BOD	0.0273	0.0802	0.2857	0.3019
COD	-0.2117	0.5301	-0.0401	0.8873
TSS	-0.1443	0.3113	0.1235	0.6611
NO_3^-	-0.3456	0.8016	-0.2585	0.3523
PO_4^{3-}	-0.0808	0.2089	-0.1548	0.5817
EC	-0.3202	0.771	-0.0931	0.7413
NO_2^-	-0.2317	0.5697	-0.1467	0.6018
TDS	-0.1681	0.4273	-0.2694	0.3316
TON	-0.3399	0.7937	-0.2441	0.3807
Composite PI	-0.2809	0.6862	-0.1156	0.6815

PI-Pollution index

The Monte Carlo simulation (999 permutations) from Table 7 showed that all physicochemical parameters did not show significant spatial autocorrelation in the six states (all p>0.05). On the one hand, pH demonstrated the most significant measure of proximity (I=0.073, Z=1.68, p=0.094) although it was not significant. A majority of the parameters had negative values of the Moran I (between -0.093 to -0.316) which were interpreted to indicate a spatial dispersion, not clustering but were statistically equivalent to random distributions. TDS was the most diffused (I=-0.316, p=0.741) and then EC (I=-0.286, p=0.650). Findings have shown that the POME characteristics are primarily controlled by site-specific operational features as opposed to regional geographic trends and no spatial dependence exists in the distribution of pollution across Southern Nigeria.

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Table 7: Monte Carlo Simulation Results for Moran's I

Parameter	Observed Moran's I	Expected I*	Variance	Z-score	P-value (Monte Carlo, 999 perm)
pH	0.073141	-0.2	0.026291	1.684533	0.094444
Temperature	-0.09315	-0.2	0.008122	1.185615	0.181944
DO	-0.27007	-0.2	0.025299	-0.44054	0.602083
BOD	0.012903	-0.2	0.022064	1.433302	0.098611
COD	-0.20642	-0.2	0.019539	-0.04594	0.451389
TSS	-0.18555	-0.2	0.004921	0.205982	0.429167
NO_3^-	-0.15256	-0.2	0.026303	0.292516	0.330556
PO_4^{3-}	-0.09281	-0.2	0.015341	0.865426	0.213889
EC	-0.28569	-0.2	0.020338	-0.6009	0.65
NO_2^-	-0.24204	-0.2	0.028441	-0.2493	0.436111
TDS	-0.31597	-0.2	0.027378	-0.7009	0.740972
TON	-0.18939	-0.2	0.024744	0.067448	0.396528

*Expected I = -1/(n-1) = -1/5 = -0.200 for n=6 states

The analysis of variogram from Table 8 showed heterogenous spatial distribution of POME parameters. Five parameters (Temperature, BOD, COD, TSS, EC) had significant spatial dependence (nugget/sill ratio = 0), which means that these factors had organized geographical patterns with a minimal error of measurement. Spatial correlation of temperature and BOD was short (54-85 km) and those of COD and EC were longer (75-103 km). Seven parameters were characterized by moderate spatial dependence (ratios 0.32-0.52): pH (range=256 km), DO (869 km), NO_3 (1,145 km), PO_4 (843km), NO_2 (677km), TDS (17km), and TON (1,013km). The variation is very localized as indicated by the extremely short range of TDS (17 km). None of the parameters showed pure nugget effects (weak spatial structure) which are contrary to Moran's I results of spatial randomness. This difference is probably attributed to inconsistency of variogram to the distance-decay trends which cannot be detected by global autocorrelation statistics when only a small sample size (n=6) is used.

Table 8: Variogram Model Parameters

Parameter	Model Type	Nugget (C_0)	Partial Sill	Sill (C_0+C)	Range (a, km)	Nugget/Sill Ratio	Interpretation	SSE
pH	Gaussian	0.052	0.093	0.145	255.732	0.360	Moderate spatial dependence	1.02e-06
Temperature	Gaussian	0.000	2.520	2.520	85.021	0.000	Strong spatial dependence	0.000522
DO	Gaussian	23.865	22.264	46.129	869.120	0.517	Moderate spatial dependence	0.140483
BOD	Gaussian	0.000	0.774	0.774	54.445	0.000	Strong spatial dependence	2.42E-05
COD	Gaussian	0.000	9997.483	9997.483	103.183	0.000	Strong spatial dependence	1240.036
TSS	Gaussian	0.000	2.902	2.902	73.469	0.000	Strong spatial dependence	0.001593
NO_3^-	Exponential	138.199	296.735	434.934	1145.101	0.318	Moderate spatial dependence	5.490248
PO_4^{3-}	Exponential	0.865	1.392	2.257	843.257	0.383	Moderate spatial dependence	0.000272
EC	Exponential	0.000	270523.007	270523.007	75.917	0.000	Strong spatial dependence	4110604
NO_2^-	Exponential	66.885	64.772	131.657	676.736	0.508	Moderate spatial dependence	0.972909
TDS	Spherical	62945.675	91955.433	154901.109	17.416	0.406	Moderate spatial dependence	3211090
TON	Exponential	366.473	538.621	905.095	1013.125	0.405	Moderate spatial dependence	37.06726

Spatial scale from Table 9 had strong effects on the patterns of autocorrelations, with mill-level (n=12) analysis founding stronger spatial patterns compared to state-level aggregation (n=6). The six parameters which exhibited significant positive spatial clustering at the mill scale were in the form of pH (I=0.691, *p*=.001), COD (I=0.541, *p*=.012), TSS (I=0.093, *p*=.009), NO_3 (I=0.343, *p*=.049), NO_2 (I=0.451, *p*=.009), and TON (I=0.389. *p*=.043), However, at levels of state, analysis showed that all parameters did not have an autocorrelation to any significant level (all $p > 0.05$) and most of them had a negative I-value indicating dispersion. These differences of magnitude (-0.069 to 0.747) were on average, 0.502 with parameters. None of the parameters was significant at both levels at the same time, thus showing that state-level aggregation obscures local levels of local spatial pattern. These results reveal that operationally specific aspects at the mill level produce the emergence of spatial clustering at finer scales (less than 50 km) that are no longer evident by the time that data is pooled to state centroids with distances ranging between 200 and 800 km.

Table 9: Sensitivity Comparison of Moran's I Spatial Autocorrelation Between State-Level (n=6) and Mill-Level (n=12) Analyses

Parameter	State I	State P	Mill I	Mill P	Difference I	Both Significant
pH	0.073141	0.094444	0.690559	0.001	0.617418	FALSE
Temperature	-0.09315	0.1375	-0.16208	0.8	-0.06893	FALSE
DO	-0.27007	0.581944	0.223566	0.134	0.493638	FALSE
BOD	0.012903	0.090278	0.119316	0.199	0.106413	FALSE
COD	-0.20642	0.475	0.54079	0.012	0.747212	FALSE
TSS	-0.18555	0.402778	0.092733	0.009	0.278284	FALSE
NO_3^-	-0.15256	0.301389	0.343381	0.049	0.495941	FALSE
PO_4^{3-}	-0.09281	0.216667	0.310414	0.058	0.403224	FALSE
EC	-0.28569	0.654167	0.240392	0.11	0.526086	FALSE
NO_2^-	-0.24204	0.445833	0.451315	0.009	0.693358	FALSE
TDS	-0.31597	0.752778	0.203131	0.143	0.519106	FALSE
TON	-0.18939	0.377778	0.388807	0.043	0.578198	FALSE

The results of spectral autocorrelation of pH showed that it is moderately sensitive to the designation of the weighting function. Significant positive spatial clustering was identified in binary contiguity (d<3Â°, I=0.190, p=0.042) and K-nearest neighbors (k=3, I=0.184, p=0.040), but not in distance-based weights. The best autocorrelation magnitude of inverse squared distance weighting (k=2) was found to be the largest (I=0.264, p=0.061), which is very close but not significant to indicate border line spatial structure. Standard inverse distance (I=0.073, p=0.094) and exponential decay (I=0.053, p=0.063) had less strong clustering characteristics. The finding of significances with both the binary and KNN schemes: The two schemes focus on the near neighbors instead of the graduated distance effects they are oriented toward local scale clustering, not on smoothly decaying distance gradients. The I values, 5-fold difference (0.053-0.264) in Moran among the methods leads to the conclusion of the condition of spatial dependence depending on weighting assumptions. This supports the need to test a variety of spatial configurations that have small sample sizes (n=6).

Table 10: Sensitivity of Moran's I to Alternative Spatial Weighting Schemes for pH Across Six States

Weight Function	Morans I	P value	Significant
Inverse Distance (k=1)	0.073141	0.094444	No
Inverse Squared (k=2)	0.263556	0.061111	No
Binary (d<3Â°)	0.189836	0.042361	Yes
Exponential Decay	0.053327	0.0625	No
K-Nearest Neighbors (k=3)	0.18353	0.040278	Yes

The heterogeneous pollution levels within same geographic areas as indicated in Fig. 4, show graduated symbols revealing high variability between nearby sampling points and further supports the finding of weak spatial autocorrelation. The point map showing graduated symbols representing pollution severity levels (Low, Moderate, High) across collection sites in six states.

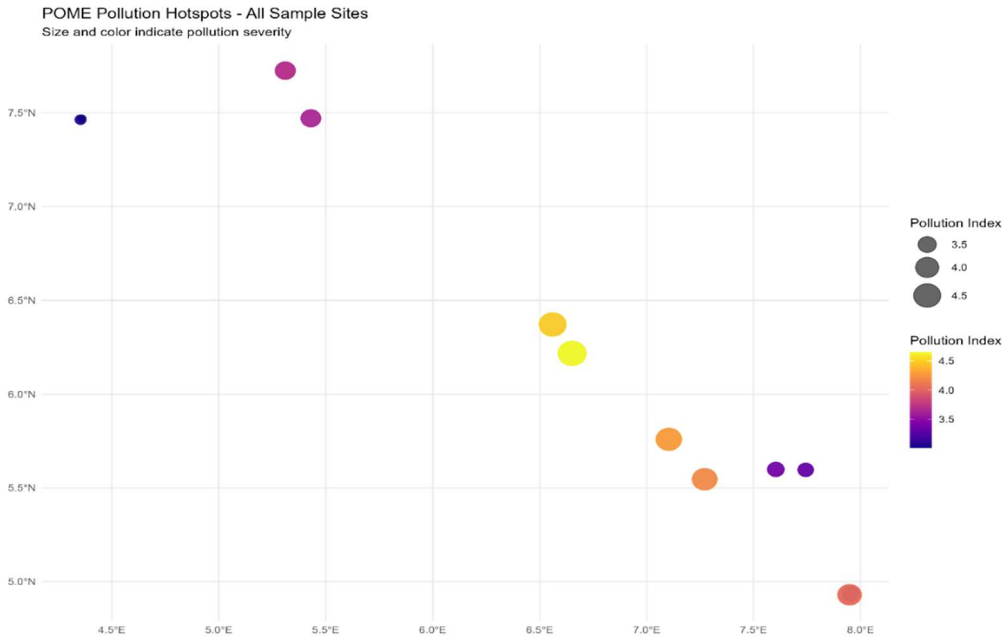

Fig.4: Spatial Distribution and Pollution Index Classification of POME Sample Sites

State aggregation as shown in Fig.5 probably masks within-state variability indicate the lack of clear spatial clustering at state level and confirms Moran's I results and this may make the States appear randomly distributed in terms of pollution severity. The point map displaying mean composite pollution indices by state with categorical classification and spatial relationships.

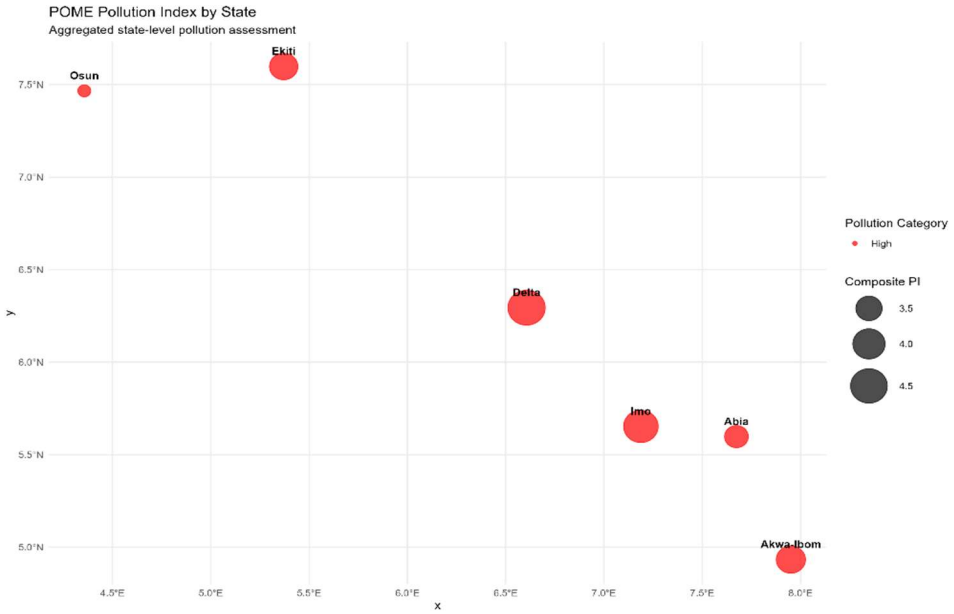

Fig.5: State-Level Aggregated Pollution Index Distribution with Geographic Clustering Patterns

The spatial distribution of some physico-chemical parameters from the POME collected states-wise are illustrated in Fig. 6. The spatial distribution reveals heterogeneous across the study area, consistent with mill-specific operational factors dominating over regional environmental conditions.

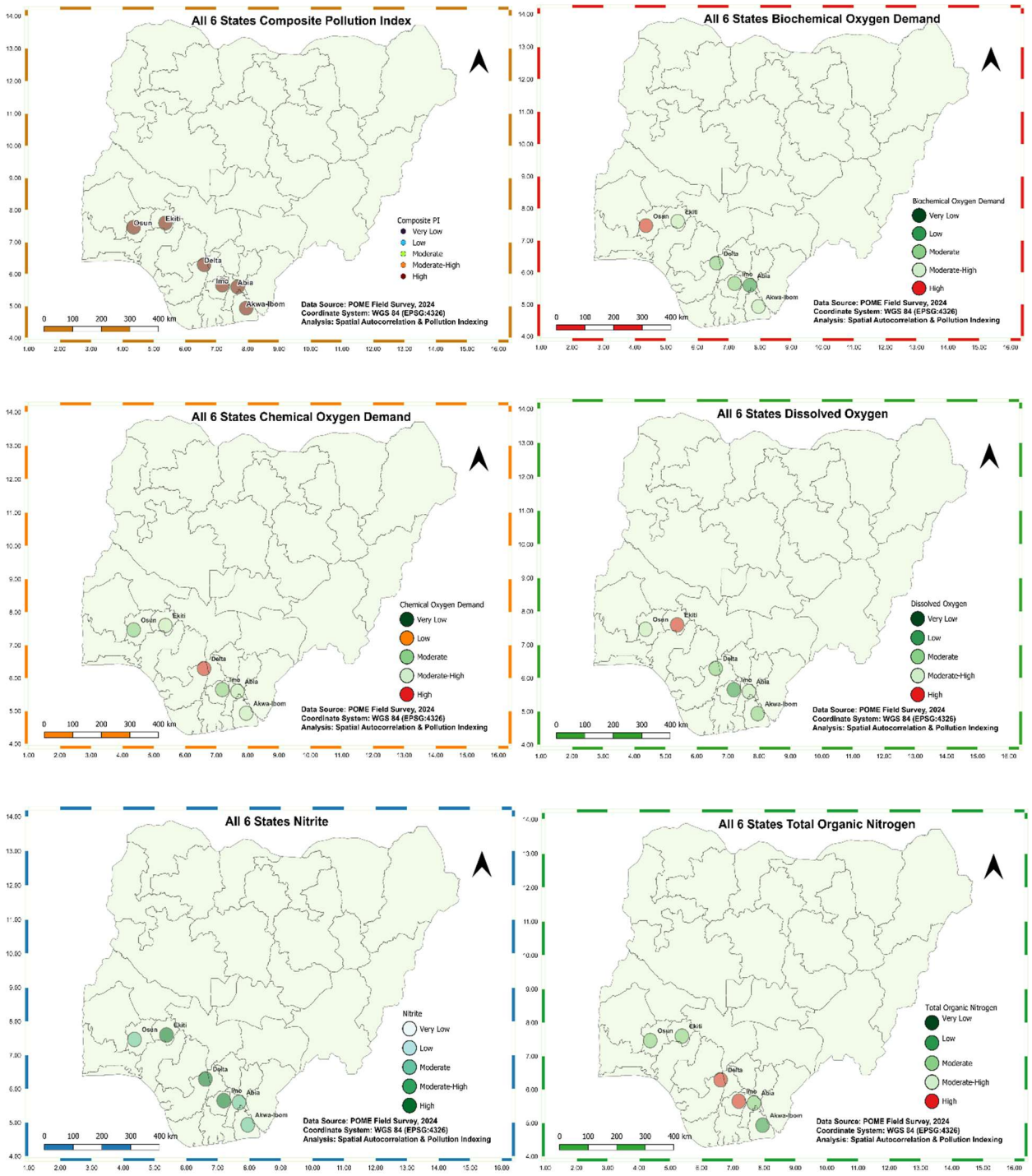

Fig.6: State-Level Spatial Distribution of POME physico-chemical parameters

CONCLUSION

This investigation in this study provides robust evidence that raw palm oil mill effluent (POME) from small-scale operations in southern Nigeria exhibis consistent physicochemical traits that pose significant environmental threats, yet with spatial patterns dominated by independence rather than geographic predictability.

Across Abia, Akwa Ibom, Delta, Ekiti, Imo, and Osun states, all effluents were highly acidic (pH 3.03–3.89), far below WHO standards, and enriched with nutrients and organics, including elevated TON (23.60–58.19 mg/L), nitrite (10.05–24.56 mg/L), nitrate (9.77–33.42 mg/L), and phosphate (9.37–11.50 mg/L). Imo and Delta emerged as

hotspots with extreme EC (>1700 µS/cm) and nitrogenous compounds, while Ekiti and Osun showed relatively lower pollution, highlighting intra- and inter-state variability. The Mann-Whitney U tests revealed no statistically significant site differences ($p > 0.05$, FDR-corrected), but substantial effect sizes ($r > 0.5$) indicate meaningful operational disparities, such as differential dilution, settling, or processing stages influencing parameters like TDS (105–934 mg/L), TSS (0.03–7.06 mg/L), DO (6.22–16.30 mg/L), BOD (1.99–4.11 mg/L), and COD (371–627 mg/L).

Critically, Moran's I spatial autocorrelation was predominantly negative and non-significant (Moran's $I \geq -0.35$, $p > 0.05$), except pH), with distance-decay analyses showing weak, non-significant correlations, disproving assumptions of climatically or regionally driven effluent quality. Pollution index visualizations further illustrated random distribution of severity levels, emphasizing mill-specific factors over eco-regional influences.

These results challenge the notion of POME as uniformly manageable organic waste, revealing it as an acidic, saline, nutrient-dense effluent resistant to low-tech treatments. Findings underscore that POME characteristics are operationally driven, necessitating tailored regulatory interventions over blanket policies, and discharge of untreated POME poses substantial risks of eutrophication and soil degradation in receiving environments, as documented in similar contexts, highlighting the urgent need for treatment system reform in southern Nigeria's small-scale palm oil sector.

AUTHORS' CONTRIBUTION

All authors were involved in the drafting, and editing of the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study. No conflicts of interest exist with respect to the research, authorship, or publication of this article.

REFERENCES

Abdullahi, N., Umar, N.B., Tsoho, A.U., Sani, A., Yazeed, Z.M., Tsangaya, M.A., Yahaya, Y.A., Yusuf, K., Haruna, S.A., Abdullahi, U.A., Ali, A., Dahiru, U.M., Suleiman, U.A., and Umar, A.A. (2023). Nigerian palm oil: quality disparity, contamination and processing wastes handling. *FUDMA Journal of Sciences (FJS), 7*(1), 126 - 135. https://doi.org/10.33003/fjs-2023-0701-1263

Abdurahman, N.H., Rosli, Y.M., Azhari, N.H., and Tam, S.F. (2011). Biomethanation of Palm Oil Mill Effluent (POME) by Membrane Anaerobic System (MAS) using POME as a Substrate. *World Academy of Science, Engineering and Technology, 51*, 419 – 424

Adegbola, G.M. and Olatunde, S.K. (2020). Palm Oil Mill Effluents (POME) and its Pollution Potentials: A biodegradable Prevalence. *J Pollut. Eff. Cont 8*, 258. https://doi.org/10.35248/2375-4397.20.8.258.

Agyemang, E. O., Joseph, A. Y., and Kwame, A. A. (2022). Oil palm production in West Africa. *Journal of Agricultural Economics, 73*(2), 257-265

Ahmad, A., Buang, A., and Bhat, A.H. (2016). Renewable and sustainable bioenergy production from microalgal co-cultivation with palm oil mill effluent (POME): a review. *Renew. Sustain. Energy Rev. 65*, 214–234.

Ahmed, A., Muhammad, I., and Muhammad, K., (2023). Environmental impacts of palm oil mill effluent. *Journal of Environmental Science and Health, Part B, 58*, 137-145

Ajala, S., Oladele, A., and Adewale, O. (2021). Palm oil mill effluent generation. *Journal of Environmental Management, 293*, 112869.

Ako, P.A.E. and Anegbe, B. (2022). Total and Available Copper and Zinc in Soils Affected by Palm Oil Mill Effluent in Oghareki, Ogbara Kingdom, Delta State, Nigeria. *Journal of Applied Sciences and Environmental Management 26*(6), 1049-1055

American Public Health Association (APHA) (2022). *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC.

Bala, J.D., Lalung, J., and Ismail, N (2014). Palm oil mill effluent (POME) treatment Microbial Communities in an Anaerobic Digester: A Review. *Int. J. Sci. Res. Pub., 4*(6), 1-23.

Chikwendu, M.U., and Ogbonna, A.N. (2019). Impact of Palm Oil Mill Effluent on the Soil in Upkom- Bende Forest Reserve, Abia State, Nigeria. *Journal of Research in Forestry, Wildlife and Environment, 10*(3), 55–61.

Dada, E.O., Sifau, M.O., Gbegbe, O.M., Ibrahim, H.O., and Adefila, O.O. (2021). Effluent from local palm oil mill refinery in Nigeria is excessively oily and potentially genotoxic. *Not Sci Biol 1*3(4), 10962.

Donald, A. E., Chizuruoke, D. M., and Gladys, O. O. (2019). Quality assessment of vegetable oil effluent discharged into a southeastern Nigeria river. *African Journal of Environment and Natural Science Research, 2*(1), 1-11.

Edward, J. B., Agunbiade, R. O., and Ayodele, A. P. (2017). Impact of Palm Oil Mill Effluent on River Awemu in Ijero-Ekiti. *IOSR Journal of Environmental Science, Toxicology and Food Technology, 11*(7), 53–56. https://doi.org/10.9790/2402-1107025356

Edward, J.B., Idowu, E.O., Adewumi, A.A, Oso, J.A., and Eniola, O.O. (2016) Impact of Palm Oil Mill Effluent on Physico-Chemical Parameters of a Southwestern River, Ekiti State, Nigeria. *The Pacific Journal of Science and Technology, 17*(1), 374-

Effiong, M.O. (2024). Water quality and palm oil mill effluents—Analysis of the effect of palm oil mill effluents (POME) on consumption of bore-hole water in Nigeria. *Journal of Infrastructure, Policy and Development*. *8*(16), 9379. https://doi.org/10.24294/jipd9379

Elystia, S., Muria, S.R., amd Erlangga, H.F. (2020). Cultivation of Chlorella pyrenoidosa as a raw material for the production of biofuels in palm oil mill effluent medium with the addition of urea and triple super phosphate. *Environ. Health Eng. Manag. J. 7* (1), 1–6.

Ergin, M., and Koskan, O. (2023). Comparison of Student – t, Welch's t, and Mann – Whitney U Tests in Terms of Type I Error Rate and Test Power. *Selcuk J Agr Food Sci, 37*(2), 223-231

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191. https://doi.org/10.3758/BF03193146

Ghasemi, A., and Zahediasl, S. (2012). Normality tests for statistical analysis: a guide for non-statisticians. *Int. J. Endocrinol. Metab. 10*(2), 486-9. https://doi.org/10.5812/ijem.3505.

Gómez Penedo, J. M., and Flückiger, C. (2025). How to interpret correlational process-outcome effect sizes in psychotherapy: a meta-analytic benchmark study. *Psychotherapy Research*, 1–11. https://doi.org/10.1080/10503307.2025.2494270

Hosseini, S.E., and Abdul Wahid, M. (2015). Pollutant in palm oil production process. *J. Air Waste Manage. Assoc., 65*, 773–781

Ibrahim, H., Abubakar, S., and Muhammad, I. (2020). Economic value of oil palm tree parts. *Journal of Sustainable Agriculture, 44*(1), 1-9.

Imo, E.O., and Ihejirika, C.E. (2021). Microbial load and biodegradation of palm oil mill effluent (POME) by microorganisms at different stages of discharge. *EQA-International Journal of Environmental Quality, 44*, 9–17.

Izah, S.C., Angaye, T.C., and Ohimain, E.I. (2016). Environmental Impacts of Oil Palm Processing in Nigeria. *Biotechnological Research, 2*(3), 132–141.

Kamyab, H., Chelliapan, S., Din, M.F.M., Rezania, S., Khademi, T., and Kumar, A. (2018). Palm Oil Mill Effluent as an Environmental Pollutant. *InTech*. https://doi.org/10.5772/intechopen.75811

Karno, R., Arisoesilaningsih, E., Mustafa, I., and Siswanto, D., (2024). Physicochemical Properties of Wastewater from Palm Oil Mill Secondary Effluent (POMSE) for water evaluation quality. *BIO Web Conf. 117*, 1039

Low, S. S., Bong, K. X., Mubashir, M., Cheng, C. K., Lam, M. K., Lim, J. W., Ho, Y. C., Lee, K. T., Munawaroh, H. S. H., and Show, P. L. (2021). Microalgae Cultivation in Palm Oil Mill Effluent (POME) Treatment and Biofuel Production. *Sustainability, 13*(6), 3247. https://doi.org/10.3390/su13063247

Madaki, Y.S., and Seng, L. (2013). Pollution control: how feasible is zero discharge concepts in malaysia palm oil mills. Am J Engineering Research, 2, 239-252.

Maliki, M., Adedokun, R.A., Afehomo, E., and Ikhide, O.O. (2020). Comparative Evaluation of the Physicochemical Properties of Different Agricultural Wastewaters in Edo State, Nigeria. *J. Chem Soc. Nigeria, 45*(3), 477 - 485

Mohamad, N.A., Hamzah, S., Harun, M.H.C., Ali, A., Rasit, N., Awang, M., Rahman, W.R. W.A., Azmi, A.A.A.R., Habib, A.A.A., and Zahid, M.S.A. (2021). Integration

of copperas and calcium hydroxide as a chemical coagulant and coagulant aid for efficient treatment of palm oil mill effluent. *Chemosphere 281*, 130873.

Mohd, S., Nor Azwadi, S., and Zulkifli, A. R. (2023). Advances in oil palm cultivation. *J. Agric. Sci., 161*(3), 257-265

National Environmental Standards and Regulations Enforcement Agency (NESREA) (2014). National Environmental regulation, 2013. Available at: https://nesrea.gov.ng/wp-content/uploads/2025/05/Energy_Sector.pdf

Nigerian Standard for Drinking Water Quality (NSDWQ)(2007). *Nigerian Standard for Drinking Water Quality*. Nigerian Industrial Standard. NIS:554:13-14.

Nmaduka, N. J., Obioma, N. U., Victor, A. C., Chukwudi, O. C., and Juliet, O. C. (2018). Impact of Palm Oil Mill Effluent (POME) Contamination on Soil Enzyme Activities and Physicochemical Properties. *Research Journal of Environmental Toxicology, 12*(1), 34–41. https://doi.org/10.3923/rjet.2018.34.41

Nnaji, J., Okoye, J., and Omotugba, S. (2016). Soil quality in the vicinity of palm oil mills in Umuahia, Nigeria. *International Research Journal of Chemistry and Chemical Sciences, 3*(1), 29–32.

Nwoko, C. I. A., and Ukiwe, L. N. (2016). Physicochemical characteristics of soils treated with palm oil mill effluent in three localities in Imo State, Nigeria. *Pure and Applied Chemical Sciences, 4*(1), 1–8. https://doi.org/10.12988/pacs.2016.5127

Ogunniyi, L. T., Oladele, A., and Adewale, O. (2023). Value-added products from oil palm. *J. Food Sci. Tech., 60*(1), 123-135

Ohimain, E.I., Izah, S.C., and Jenakumo, N. (2013). Physicochemical and Microbial Screening of Palm Oil Mill Effluents for Amylase Production. *Greener J. Biol. Sci., 3*(8), 307-318. http://doi.org/10.15580/GJBS.2013.8.100913894

Okereke, J.N. and Ginikanwa, R.C. (2020). Environmental impact of palm oil mill effluent and its management through biotechnological approaches. *Int. J. Adv. Res. Biol. Sci. 7*(7), 117-127

Osagbovo, A.U., and Orhue, E.R. (2011). Effects of palm oil mill effluent on some soil chemical properties and growth of maize, (*Zea mays* L). *Nigerian Journal of Agriculture, food and Environment. 7*(3), 51- 54.

Osman, N.A., Ujang, F.A., Roslan, A.M., Ibrahim, M.F., and Hassan, M.A. (2020). The effect of Palm Oil Mill Effluent Final Discharge on the Characteristics of Pennisetum purpureum. *Scientific Reports, 10*(1), 1–10. https://doi.org/10.1038/s41598-020-62815-0

Saad, M.S., Wirzal, M.D.H., and Putra, Z.A. (2021). Review on current approach for treatment of palm oil mill effluent: integrated system. *J. Environ. Manage. 286*, 112209

Sapie, S., Jumali, S.S., Mustaffha, S., and Pebrian, D.E. (2019). Analysis of POME Discharge Quality from Different Mill in Perak, Malaysia: A case study. *IOP Conf. Series: Earth and Environmental Science 327*, 012022.

Saputera, W. H., Amri, A. F., Daiyan, R., & Sasongko, D. (2021). Photocatalytic Technology for Palm Oil Mill Effluent (POME) Wastewater Treatment: Current Progress and Future Perspective. *Materials, 14*(11), 2846. https://doi.org/10.3390/ma14112846

Shears, I., and Richard, C. (2022). Environmental impacts of palm oil production. *Journal of Environmental Science and Health, Part B, 57*, 117-123

Singh, P. K., Vinay, K., and Ajay K. (2023). Correlations between water parameters. *Journal of Environmental Management, 318*, 115936

Tang, P.L., Hong, W.L., Yue, C.S., and Harun, S. (2020). Palm oil mill effluent as the pretreatment solvent of oil palm empty fruit bunch fiber for fermentable sugars production. *Bioresour. Technol. 314*, 123723

Ubani, C.S., Onwuneme, C., Okpashi, V.E., Osuji, A.C., and Nwadike, U.G.E.M. (2017). Palm Oil Mill Effluent Effect on Soil Fertility: a Longitudinal Assessment of Zea Mays Plant. *EQA – Environmental Quality, 23*, 43–53. https://doi.org/10.6092/issn.2281-4485/7135

United States Environmental Protection Agency (US EPA) (2024). *National Primary Drinking Water Regulations*. Available at: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

Uroko, R. I. (2014). *Impact of Fresh and Fermented Palm Oil Mill Effluents on Soil Physico-Chemical Parameters and Enzyme Activities in Umuaka, Njaba, Imo State of Nigeria*. University of Nigeria, Nsukka.

Verla, A.W., Adowei, P., and Verla, E.N. (2014). Physicochemical and Microbiological Characteristic of Palm Oil Mill Effluent (POME) in Nguru: Aboh Mbaise, Eastern Nigeria. *Acta Chim. Pharm. Indica 4*(3), 119-125

Wang, X., Wen, X., Yan, H., Ding, K., Zhao, F., and Hu, M. (2011). Bacterial community dynamics in a functionally stable pilot-scale wastewater treatment plant. *Bioresource Technology 102*(3), 2352-2357

World Health Organization (WHO) (2017). *Guidelines for drinking-water quality*. 4th ed. World Health Organization

Zulfahmi, I., Kandi, R.N., Huslina, F., Rahmawati, L., Muliari, M., Sumon, K.A., and Rahman, M.M. (2021). Phytoremediation of palm oil mill effluent (POME) using water spinach (*Ipomoea aquatica* Forsk). *Environ. Technol. Innov. 21*, 101260.

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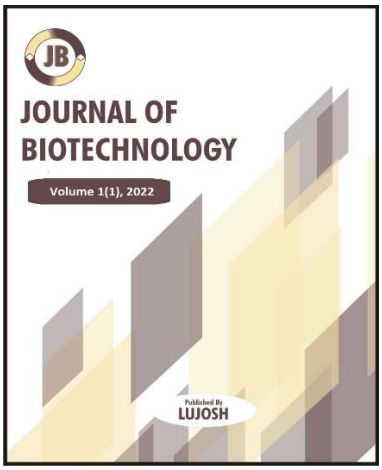

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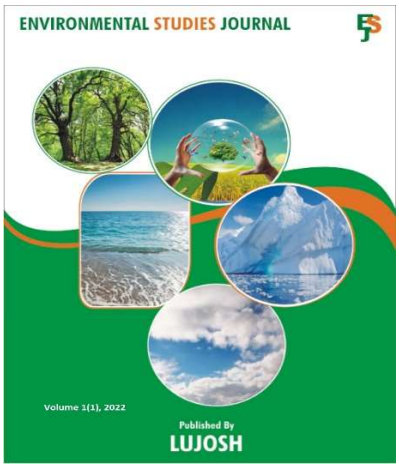

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