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TROPHIC STATE ASSESSMENT OF TROPICAL LOTIC ECOSYSTEMS IN BENIN CITY, NIGERIA

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Background: Freshwater ecosystems provide essential ecological, economic, and social services, yet urbanization and agricultural intensification threaten their integrity through nutrient enrichment and eutrophication. In tropical rivers, phosphorus-driven productivity changes can alter biodiversity, water clarity, and oxygen dynamics. Despite widespread nutrient impacts in West African waters, standardized trophic assessments using indices such as the trophic state index (TSI) remain scarce, limiting effective water quality management. **Objectives:** This study systematically evaluates trophic states in urban water bodies of Benin City, Nigeria, using TSI integrated with physicochemical measurements. Objectives include quantifying eutrophication risk, identifying nutrient drivers, assessing spatial variability, and linking trophic states to anthropogenic pressures. **Methods:** Eighteen lotic water bodies across urban, peri-urban, and relatively undisturbed sites in Benin City, Nigeria, were sampled during the wet season (May–September 2024). Triplicate surface water samples (20–30 cm depth) were collected mid-channel, preserved on ice, and analysed for physicochemical parameters including pH, temperature, dissolved oxygen, conductivity, turbidity, total phosphorus, nitrate, and other nutrients following APHA (2017) protocols. The trophic state index was calculated based on total phosphorus to classify water bodies. Statistical analyses, including ANOVA, Tukey's HSD, effect size (η^2), and Pearson correlation, were conducted in Python 3.10 to assess spatial variability, nutrient drivers, and relationships between TSI and environmental variables. **Results:** River water quality varied across the 18 studied sites. Water temperatures were relatively stable (25–30°C), while turbidity and colour showed notable variation, with the Ogba River exhibiting the highest values (141 NTU; 135 PtCo units), indicating elevated suspended solids. pH ranged from 4.5 to 6.8, while conductivity, total hardness, and total dissolved solids were low, reflecting soft freshwater conditions. Dissolved oxygen was generally high (mean 8.52 mg L^{-1}), although some rivers displayed low DO (2.7–3.0 mg L^{-1}), suggesting localized oxygen stress. Nutrient concentrations were low, with phosphate (8–13 µg L^{-1}) and nitrate (<0.5 mg L^{-1}). The trophic state index ranged from 34.65 to 41.14, classifying most rivers (94.4%) as oligotrophic, while the Ogba River reached mesotrophic conditions. Spatial differences in TSI were significant, with phosphorus, conductivity, turbidity, and colour identified as the main drivers of trophic variability. **Conclusion:** Rivers in the study area are largely oligotrophic, chemically soft, and sensitive to anthropogenic inputs. The Ogba River's mesotrophic shift highlights vulnerability from sediment and nutrient loading. Conductivity, sulphate, and turbidity are effective proxies for early trophic state monitoring.

Keywords: Trophic State Index (TSI); phosphorus-driven eutrophication; mesotrophic rivers; water quality assessment; nutrient enrichment; conductivity proxy; sediment-associated nutrients; tropical lotic ecosystems.

INTRODUCTION

Freshwater ecosystems provide indispensable ecological, economic, and social services worldwide, including potable water supply, biodiversity habitat, fisheries, recreation, agricultural irrigation, water purification, and flood regulation (Wetzel, 2001; Vollmer et al., 2022; Hashemi et al., 2026). Among these, tropical riverine systems are particularly critical, serving as biodiversity hotspots and delivering essential ecosystem services to rapidly expanding urban populations. However, anthropogenic pressures such as nutrient enrichment, land-use changes, urban expansion, and agricultural intensification are increasingly compromising the chemical and biological integrity of these ecosystems (Smith & Schindler, 2009; Engdaw et al., 2025). In urban environments such as Benin City, Edo State, Nigeria, rapid population growth and inadequate wastewater management exacerbate nutrient loading, elevating the risk of eutrophication (Nyenje et al., 2010; Szalińska et al., 2024; Tungwana et al., 2026).

Eutrophication is defined as the enrichment of water bodies with nutrients, primarily nitrogen (N) and phosphorus (P), leading to excessive primary production and structural alterations in aquatic ecosystems (Carpenter et al., 1998; Zhou et al., 2022). While nutrients are essential for biological productivity, anthropogenically elevated concentrations from agricultural runoff, industrial discharge, and domestic effluents can trigger algal blooms, reduce water clarity, deplete dissolved oxygen, and cause significant ecological and economic consequences (Zhou et al., 2022; Fang et al., 2025). Because nutrient enrichment is often cumulative and its ecological effects may lag behind nutrient inputs, systematic monitoring and trophic assessment are vital for effective water quality management.

A widely used metric for assessing trophic status is the trophic state index (TSI), originally developed by Carlson (1977). Although initially intended for lentic systems, TSI application to lotic ecosystems offers a standardized framework for quantifying biological productivity based on nutrient concentrations, particularly phosphorus (Carlson, 1977; Carneiro et al., 2020; Cunha et al., 2021). TSI integrates key biological and chemical indicators, including chlorophyll-a, total phosphorus, and Secchi disk transparency, into a dimensionless scale ranging from oligotrophic to eutrophic conditions (Carlson, 1977; Cunha et al., 2021; Karpowicz et al., 2025). High TSI values correspond to elevated nutrient enrichment and productivity, often reflecting eutrophic states (Mamun et al., 2021). The simplicity and empirical basis of TSI have supported its widespread application in both temperate and tropical limnological studies (Wetzel, 2001; Cunha et al., 2021; Sarma & Nandini, 2026).

In West African rivers, phosphorus is frequently the limiting nutrient, with its dynamics closely linked to sediment transport and turbidity (Akongyuure & Alhassan, 2021). Despite this, TSI-based trophic assessments remain limited in sub-Saharan Africa, even as nutrient enrichment in urban and peri-urban waters is increasingly reported (Nyenje et al., 2010; Lukhele & Msagati, 2024; Jacobs & Breuer, 2024). In Nigeria, urbanization and agricultural intensification have been associated with increased benthic and pelagic productivity, yet systematic trophic classification using standardized indices such as TSI is sparse (Maishanu et al., 2018; Okidhika et al., 2025; Oribhabor, 2016). Benin City, with its network of rivers, lakes, and reservoirs, exemplifies this knowledge gap, as these water bodies face growing land use pressures including domestic waste discharge, stormwater runoff, and industrial effluents, contributing to nutrient enrichment and altered trophic states (Kadiri & Azomani, 1999; Zhou et al., 2022; Jacobs & Breuer, 2024).

Physicochemical parameters such as water temperature, pH, dissolved oxygen, conductivity, and nutrient concentrations are commonly employed as proxies for trophic status (APHA, 2017; Akhere & Kadiri, 2023). Elevated phosphorus and nitrogen levels are often correlated with increased phytoplankton biomass, reduced water clarity, and elevated TSI values (Carpenter et al., 1998). Integrated with biological assays, TSI links nutrient availability to realized productivity, providing mechanistic insights that inform water quality management and eutrophication mitigation (Liu et al., 2025; Meyer et al., 2025).

Despite an increasing body of research on eutrophication in Nigerian inland waters, location-specific, standardized trophic assessments remain scarce (Ighalo & Adeniyi, 2020; Edegbene et al., 2024). The integration of TSI with local data on the physical and chemical parameters is particularly scarce in Nigeria. The heterogeneity of urban water bodies in Benin City, ranging from small ponds and lakes to flowing streams, necessitates systematic trophic classification to support sustainable water management. While previous studies have described general physicochemical characteristics, few have combined these data with formal TSI calculation (Soro et al., 2023; Lukhabi et al., 2023; Lukhele & Msagati, 2024).

This study aims to provide a systematic assessment of trophic state in selected urban water bodies of Benin City, Nigeria, using TSI integrated with physicochemical measurements to identify key drivers and spatial patterns of eutrophication in tropical lotic systems. Specific objectives are:

1. Quantify trophic status using established indicators;
2. Assess eutrophication risk in tropical freshwater ecosystems;
3. Evaluate physicochemical characteristics of the water bodies;
4. Determine relationships between nutrient concentrations and environmental variables (conductivity, turbidity, dissolved oxygen);
5. Analyse spatial variability using inferential statistics;
6. Estimate site effect magnitude using η^2 and partial η^2.

The following hypotheses were formulated based on the Trophic State Theory and eutrophication frameworks (Carlson, 1977; Wetzel, 2001; Carpenter et al., 1998):

H1: Trophic state exhibits significant spatial heterogeneity across urban water bodies, driven by gradients of anthropogenic pressure.

H2: Total phosphorus is the dominant predictor of trophic state variability, exceeding the explanatory power of other physicochemical parameters.

H3: TSI is primarily phosphorus-driven, but conductivity and nitrate co-variation indicate mixed nutrient inputs influence trophic variability.

H4: Water bodies subject to higher anthropogenic influence (e.g., urban runoff, wastewater input) exhibit significantly elevated trophic states compared to less disturbed sites.

H5: The relationship between nutrient concentrations and trophic state is modulated by hydrological and turbidity-related factors, reflecting the complexity of lotic tropical systems.

These hypotheses collectively evaluate both the drivers and ecological consequences of trophic variation in Benin City's water bodies.

MATERIALS AND METHODS

Study area

The study was conducted across 18 lotic water bodies within Benin City, Edo State, Nigeria (Figure 1). The study area is located between $6^{0}12.42'$ – $6^{0}43.024$ °N and $5^{0}14.393$ – $5^{0}50.628$ °E, within the humid tropical rainforest zone. The region experiences a bimodal rainfall pattern, with a wet season from April to October and a dry season from November to March, receiving an average annual precipitation of 2000–2300 mm and mean annual temperatures ranging between 25–30 °C.

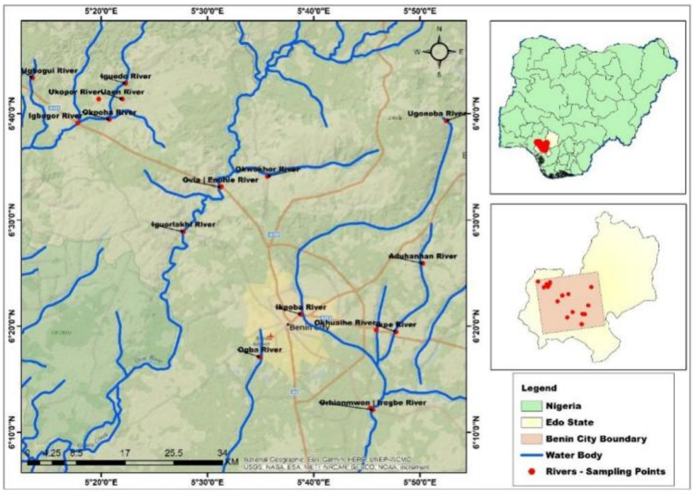

Figure 1. Map of water bodies studied

Sampling sites were selected using a stratified approach to capture gradients of anthropogenic influence, including urban, peri-urban, and relatively undisturbed systems. Selection criteria included surrounding land use, observable pollution sources, hydrological connectivity, and accessibility. Each site was georeferenced using a Garmin eTrex 10, Garmin Ltd; accuracy ± 3–10 m, and riparian vegetation and dominant anthropogenic activities were documented (Table 1).

Sampling design and period

Sampling was conducted during the wet season (15–16 May 2015), corresponding to peak hydrological flow and enhanced nutrient transport processes across the study area. Each site was sampled once, resulting in n = 18 observations. All sampling occurred between 07:00–11:00 h to minimize potential diurnal variability in measured physicochemical parameters.

Table 1. Riparian vegetation and anthropogenic activities around the study rivers

Name of river	Local govt area	Dominant vegetation	Surrounding activities
Aduhanhan River	Uhunmwonde	*Bambusa bambusa, Azolla* sp., *Pennisetum* sp.	Car washing, Laundry
Enohie River	Ovia South	*Nymphaea lotus*	Drinking, Domestic use
Igbogor River	Ovia South	*Pistia stratiotes*	Fishing
Iguedo River	Ovia South	*Elaeis guineensis*	Logging
Iguoriakhi River	Ovia South	*Megathyrsus maximus, Pennisetum purpureum, Eichhornia crassipes, Salvinia* sp.	Spiritual (Fetish sacrifices)
Ikpe River	Ikpoba Okha	*Elaeis guineensis, Panicum maximum*	Swimming, Washing
Ikpoba River	Ikpoba Okha	*Panicum maximum*	Bathing, Washing (cars, carpets, agricultural produce, etc.
Irogbe River	Ikpoba Okha	*Pteridium aquilinum*	Swimming
Ogba River	Oredo	*Pterocarpus santalinoides, Syzygium guineense, Cola laurifolia*	Drainage Channelization
Okhuaihe River	Uhunmwonde	*Fimbristylis dichotoma, Ipomoea aquatica, Pteridium aquilinum*	Source of potable water supply
Okpoha River	Ovia South	*Bambusa vulgaris, Elaeis guineensis*	Bathing, and car washing, Relaxation area
Okwokhor River	Ovia South	*Pennisetum* sp.	Source of water supply
Orhionmwon River	Uhunmwonde	*Elaeis guineensis, Mimosa* sp.	Source of water supply
Ovia River	Ovia South	*Panicum maximum, Eicchornia crassipes*	Fishing, Spiritual (Fetish) use
Ugbogui River	Ovia South	*Commelina* sp., *Ipomoea* sp., *Emilia, Azolla*	Bathing and washing
Ugonoba River	Uhunmwonde	*Ipomoea aquatica, Pteridium aquilinum, Cyrtosperma senegalense*	Bathing, washing, Domestic use
Ukopor River	Ovia South	*Chromolaena odorata, Panicum maximum*	Source of water supply, Bathing, washing
Usen River	Ovia South	*Bambusa vulgaris*	Washing (cars, laundry), Bathing, recreation, swimming

At each site, triplicate surface water samples were collected from the mid-channel at a subsurface depth of 20–30 cm using pre-cleaned high-density polyethylene (HDPE) bottles. Bottles were rinsed three times with water from the sampling point prior to collection (APHA, 2017). Samples were stored in ice-filled coolers (approximately 4 °C) and transported to the laboratory within 3 hours for immediate analysis. Photographs of the sampling sites are provided in Figure 2.

Physicochemical analysis

The following parameters were measured.

In situ measurements

In situ measurements of air and water temperature were determined using a mercury-in-glass thermometer, while pH and electrical conductivity (EC) were measured using a calibrated multiparameter probe (Hach Model CO 150). Calibration was conducted daily using standard buffer solutions (pH 4.01, 7.00, 10.01) and conductivity standards (10 and 80 µS cm^{-1}).

Dissolved oxygen and biochemical oxygen demand

Dissolved oxygen (DO) was determined using the azide modification of the Winkler method. Biochemical oxygen demand (BOD_5) was measured by incubating samples in the dark at 20 °C for 5 days and calculating the difference between initial and final DO concentrations.

Laboratory analysis

Laboratory analyses were conducted following standard methods (APHA, 2017).

Total phosphorus (TP) was determined using the ascorbic acid method following acid-persulfate digestion (121 °C for 30 min), which ensures the conversion of all phosphorus forms into orthophosphate for accurate quantification. Absorbance was measured at 880 nm using a spectrophotometer (Hach Model DR/2000), with readings taken under standardized conditions to ensure analytical precision and consistency.

Nitrate (NO_3^-), sulphate (SO_4^{2-}), chloride (Cl^-), total dissolved solids (TDS), alkalinity, and hardness were analysed using standard procedures (APHA, 2017).

Turbidity was measured using a nephelometric turbidimeter (Hach Model DR/2000), and water colour was determined using the platinum–cobalt method.

Quality assurance and quality control (QA/QC)

QA/QC procedures included analytical blanks, duplicate samples, and calibration standards. Calibration curves were prepared for each analyte with $R^2 \geqslant 0.995$.

Method detection limits (MDL) and analytical precision (±%) were determined as provided in APHA (2017). Storage and handling conditions were monitored to ensure sample integrity.

Aduhanhan River
Enohie River
Igbogor River
Iguedo River
Iguoriakhi River
Ikpe River
Ikpoba River
Irogbe River
Ogba River
Okhuaihe River
Okpoha River
Okwokhor River
Orhionmwon River
Ovia River
Ugbogui River
Ugonoba River
Ukopor River
Usen River

Figure 2. Sampling sites

Trophic state index (TSI) determination

Trophic status was assessed using Carlson's TSI based on total phosphorus concentrations. Total phosphorus values were converted from mg L^{-1} to μg L^{-1} prior to calculation. TSI_{TP} was calculated as:

$$TSI_{TP} = 14.42 \cdot \ln(TP) + 4.15. \quad (1)$$

Water bodies were classified following standard thresholds (Table 2). Phosphorus-based TSI_{TP} was justified due to the predominance of phosphorus limitation in tropical freshwater systems.

Eutrophication risk assessment

Eutrophication risk in the studied water bodies was evaluated using a combination of TSI_{TP} classification and supporting physicochemical indicators. Water bodies with $TSI_{TP} \geqslant 50$ were classified as eutrophic, indicating high nutrient enrichment and elevated primary productivity.

Table 2. TSI classification

TSI range	Trophic status	Inference
≤ 40	Oligotrophic	Low nutrient enrichment and high water clarity
40–50	Mesotrophic	Moderate nutrient enrichment, moderately clear
50–70	Eutrophic	High nutrient enrichment and high primary productivity, high algal blooms, and decreased oxygen
> 70	Hypereutrophic	Extremely high nutrient enrichment, highest algal blooms

Additional criteria were incorporated to enhance ecological interpretation: dissolved oxygen (DO) levels below 5 mg L^{-1} were considered indicative of oxygen depletion associated with eutrophication, while turbidity thresholds exceeding 50 NTU were used to identify waters with reduced clarity. The turbidity threshold was selected based on regional baseline conditions and prior studies of tropical freshwater systems, ensuring that site-specific environmental variability was accounted for.

This combined approach allows a robust and reproducible assessment of eutrophication risk, linking nutrient enrichment (TSI_{TP}) with its ecological consequences (DO depletion and reduced water clarity). Sites meeting one or more of these criteria are classified as high-risk for eutrophication, supporting targeted management interventions and ongoing monitoring.

Statistical analysis

All statistical analyses were performed using Python 3.10 with the SciPy, pandas, and statsmodels libraries.

Prior to inferential analyses, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test at a significance level of $\alpha = 0.05$. When assumptions of normality or homoscedasticity were violated, appropriate data transformations (e.g., logarithmic or square-root) were applied, or non-parametric alternatives were used where necessary.

Differences in physicochemical parameters and the trophic state index among sampling sites were assessed using one-way analysis of variance (ANOVA). The analysis included 3 replicates per site, resulting in a total of total 18 observations. When significant differences were detected, Tukey's Honestly Significant Difference (HSD) post hoc test was applied for pairwise comparisons among sites.

Effect sizes were quantified using eta squared (η^2) and partial eta squared (η^2_p) to assess the magnitude of site-related variability. Calculations followed standard implementations available in the statsmodels library.

Relationships between TSI_{TP} and selected physicochemical parameters (turbidity, pH, total phosphorus, dissolved oxygen, conductivity, sulphate, nitrate, and water colour) were evaluated using Pearson correlation coefficients (r), assuming bivariate normality of the variables.

Statistical significance was defined at $\alpha = 0.05$ for all analyses. All procedures are fully reproducible using the analytical workflow described above.

RESULTS

River water quality

Temperature and physical characteristics

Air temperature across the surveyed area ranged from 23 to 34 °C, with a mean value of 27.0 ± 0.25 °C. Water temperature was relatively stable, ranging from 25 to 30 °C, with an average of 27.56 ± 0.79 °C.

Among the studied rivers, the Ogba River exhibited markedly higher turbidity (141 NTU) and colour (135 PtCo units) compared to other sites, such as the Okhuaihe River, which recorded negligible colour values (0 PtCo units) (Figure 3; Table 3). These elevated values indicate increased levels of particulate matter and dissolved organic substances, likely reflecting local catchment conditions and anthropogenic inputs.

Overall, the investigated rivers display physicochemical characteristics typical of tropical freshwater systems, with observed spatial variability driven by local hydrological conditions and human activities.

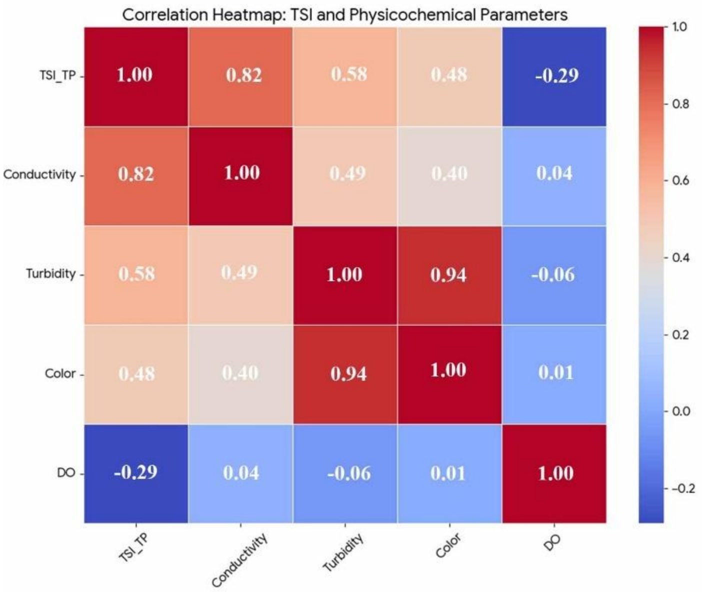

Figure 3. Correlation heatmap of TSI and some physicochemical parameters

Table 3. Summary statistics of physicochemical parameters

Parameter	Range (min–max)	Mean ± SE	Standard limit	
			WHO	SON
Air temperature, °C	23.00–34.00	27.56 ± 0.79	NS	NS
Water temperature, °C	25.00–30.00	27.00 ± 0.25	NS	NS
Turbidity, NTU	1.00–141.00	17.18 ± 7.22	5	5
Colour, PtCo units	0.00–135.00	22.17 ± 7.18	5	15
pH	4.5–6.8	5.99 ± 0.13	6.5–8.5	6.5–8.5
Electrical conductivity, µS cm^{-1}	15.80–58.60	31.76 ± 3.22	1000	1000
Total dissolved solids, mg L^{-1}	7.00–28.00	14.94 ± 1.52	500	500
Dissolved oxygen (DO), mg L^{-1}	2.70–13.70	8.52 ± 0.74	10	10
Biochemical oxygen demand (BOD_5), mg L^{-1}	0.30–9.00	3.71 ± 0.55	3–5	3–5
Total alkalinity, mg L^{-1}	15.00–50.00	24.72 ± 1.94	NS	NS
Chloride, mg L^{-1}	11.25–103.72	39.36 ± 7.05	250	250
Total hardness, mg L^{-1} as $CaCO_3$	0.10–0.37	0.19 ± 0.01	150	150
Calcium hardness, mg L^{-1} as $CaCO_3$	0.03–0.19	0.07 ± 0.009	200	200
Magnesium hardness, mg L^{-1} as $CaCO_3$	0.00–0.34	0.12 ± 0.005	0.2	0.2
Sulphate (SO_4^{2-}), mg L^{-1}	3.21–5.02	3.65 ± 0.11	250	250
Phosphate (PO_4^{3-}), µg L^{-1}	8.29–13.29	10.14 ± 0.29	40	NS
Nitrate (NO_3^-), mg L^{-1}	0.46–0.49	0.47 ± 0.002	50	50

Note: WHO – World Health Organization; SON – standard organization of Nigeria; NS – not specified

Chemical ion composition and acidity

Measured pH values indicate generally acidic to slightly sub-neutral conditions, ranging from 4.5 (Enohie River) to 6.8 (Igbogor River), with an overall mean of 5.99 ± 0.13. Most sites fall below the neutral threshold of 7.0, consistent with either natural organic acid inputs or ongoing decomposition of organic matter.

Electrical conductivity (31.76 ± 3.22 µS cm^{-1}) and total dissolved solids (TDS; 14.94 ± 1.52 mg L^{-1}) were generally low across the rivers, with maximum values recorded in the Iguedo River (58.6 µS cm^{-1}; 28 mg L^{-1}), reflecting the predominantly freshwater and low-mineralized character of these systems.

Oxygen levels and organic loading

Measured dissolved oxygen (DO) concentrations varied widely, ranging from 2.7 to 13.7 mg L^{-1}, with an overall mean of 8.52 ± 0.74 mg L^{-1}. Ikpe and Usen Rivers exhibited relatively high DO levels (>12 mg L^{-1}), while Aduhanhan and Irogbe Rivers showed low concentrations (2.7–3.0 mg L^{-1}), indicating potential oxygen stress conditions (Table 3).

Measured biochemical oxygen demand (BOD_5) ranged from 0.3 mg L^{-1} (Irogbe River) to 9.0 mg L^{-1} (Ikpe River), with a mean of 3.71 ± 0.55 mg L^{-1}. The observed variability suggests spatial differences in organic matter loading. In some low-oxygen sites, low BOD_5 values indicate that oxygen depletion may be driven by factors other than direct organic pollution, such as hydrodynamic conditions or enhanced microbial respiration.

Nutrients and hardness

The rivers are characterized by very soft waters, with total hardness ranging from 0.10 to 0.37 mg L^{-1} and an overall mean of 0.19 ± 0.01 mg L^{-1} across all sites. Chloride concentrations varied from 11.25 mg L^{-1} (Iguedo River) to 103.72 mg L^{-1} (Ikpe River), with a mean value of 39.36 ± 7.05 mg L^{-1}, reflecting both natural and anthropogenic inputs.

Nutrient concentrations were generally low to moderate. Phosphate (PO_4^{3-}) ranged from 8 to 13 µg L^{-1}, with a mean of 10.14 ± 0.29 µg L^{-1}, while nitrate (NO_3^-) remained below 0.5 mg L^{-1}, with an average of 0.47 ± 0.002 mg L^{-1}, suggesting limited agricultural runoff at the time of sampling. These values provide a baseline for assessing trophic status using the TSI (Table 3; Figure 4).

Figure 4 illustrates the relationships between physical and chemical drivers and nutrient status across the studied river systems. The red line represents the linear regression fit, with the shaded area indicating the 95% confidence interval.

Conductivity ($r = 0.82$) exhibited the strongest positive correlation with TSI, indicating a strong linear relationship between ionic content and trophic status. Turbidity and colour showed elevated values associated with higher TSI, particularly influenced by observations from the Ogba River, suggesting the contribution of suspended solids and dissolved organic matter to trophic conditions. In contrast, dissolved oxygen displayed a weak negative relationship with TSI, with higher trophic values generally associated with lower oxygen concentrations, although with considerable variability.

Trophic state index

Overall trophic status

The trophic state index (TSI_{TP}) of the studied rivers ranged from 34.65 to 41.14, indicating relatively low spatial variability despite differences in physical water characteristics (Table 4). Most rivers (17 of 18 observations; 94.4%) were classified as oligotrophic, including the Ikpe River (TSI_{TP} = 34.65) and the Iguedo River (TSI_{TP} = 39.98), reflecting low primary productivity and limited nutrient enrichment. Total phosphorus concentrations in these systems remained consistently below 12 µg L⁻¹, suggesting minimal influence of external nutrient inputs such as agricultural runoff or domestic wastewater.

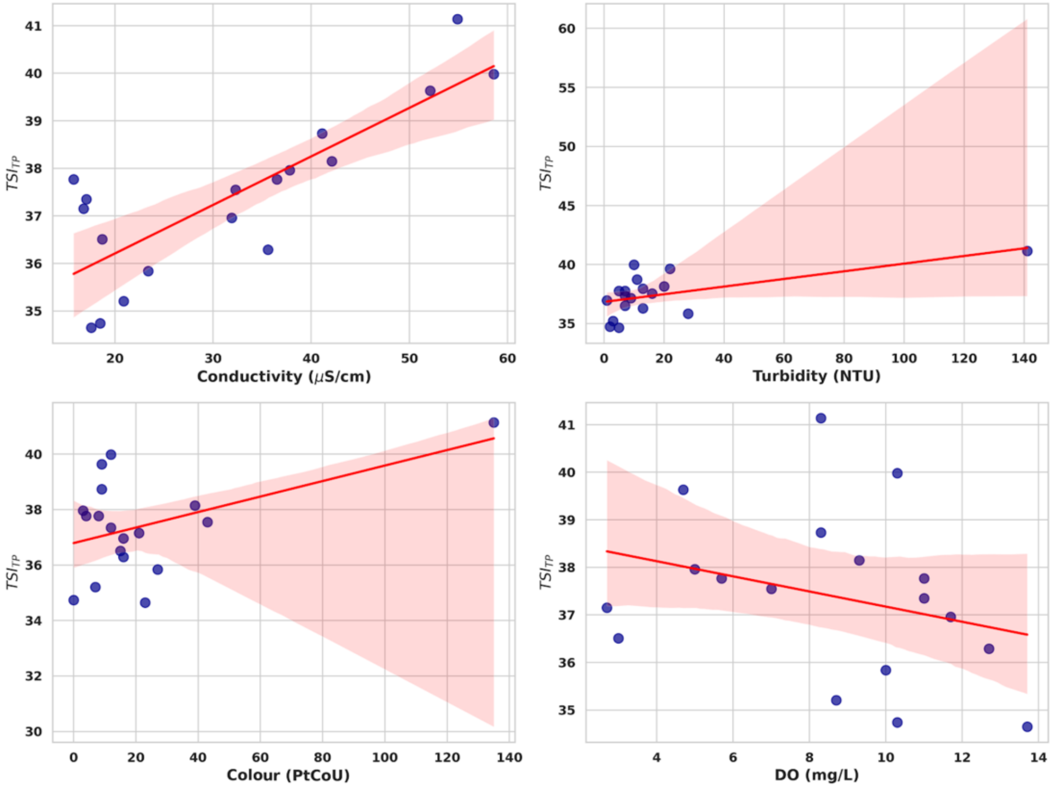

Figure 4. Scatter plots illustrating the linear regression between TSI_{TP} and four key physicochemical parameters: a – conductivity; b – turbidity; c – colour; d – dissolved oxygen

Table 4. Trophic state index of the rivers

Water body	Total phosphorus (TP), µg L⁻¹	TSI_{TP}	Trophic status
Aduhanhan River	9.86	37.15	Oligotrophic
Enohie River	9.71	36.96	Oligotrophic
Igbogor River	10.57	38.15	Oligotrophic
Iguedo River	12.0	39.98	Oligotrophic
Iguoriakhi River	10.29	37.77	Oligotrophic
Ikpe River	8.29	34.65	Oligotrophic
Ikpoba River	11.71	39.63	Oligotrophic
Irogbe River	9.43	36.51	Oligotrophic
Ogba River	13.29	41.14	Mesotropic
Okhuaihe River	8.43	34.74	Oligotrophic
Okpoha River	10.14	37.55	Oligotrophic
Okwokhor River	8.71	35.21	Oligotrophic
Orhionmwon River	10.0	37.35	Oligotrophic
Ovia River	11.0	38.73	Oligotrophic
Ugbogui River	10.43	37.96	Oligotrophic
Ugonoba River	10.29	37.77	Oligotrophic
Ukopor River	9.0	35.84	Oligotrophic
Usen River	9.29	36.29	Oligotrophic

Several rivers were close to the oligotrophic–mesotrophic boundary, including Iguedo (39.98), Ikpoba (39.63), and Igbogor (38.15), indicating a potential shift toward mesotrophic conditions under increased nutrient loading.

Ogba River was the only site classified as mesotrophic (TSI_{TP} = 41.14), consistent with its elevated total phosphorus concentration (13.29 µg L^{-1}). This higher trophic state corresponds with increased turbidity (141 NTU) and colour (135 PtCo units), suggesting enhanced sediment and organic matter inputs.

Overall, the narrow range of TSI_{TP} values (34–41) across geographically distributed sites suggests a relatively uniform baseline of low nutrient availability within the region.

Spatial variability of trophic status

One-way ANOVA revealed significant spatial differences in trophic state index among rivers (F = 6.21, p = 0.024), with substantial effect sizes (partial $\eta^2 = 0.28$), indicating that site identity accounts for a meaningful proportion of trophic variability.

Post-hoc Tukey's HSD analysis identified rivers with significantly higher trophic states relative to others ($p < 0.05$), highlighting spatial clustering of nutrient hotspots.

Correlation with physicochemical parameters

Table 5 presents Pearson correlation coefficients (r) between the trophic state index (TSI_{TP}) and key physicochemical parameters.

Phosphorus and nitrogen

TSI_{TP} showed an almost perfect positive correlation with total phosphorus (r = 0.9928, $p < 0.0001$), indicating that phosphorus is the dominant driver of trophic status variation. A strong positive correlation was also observed with nitrate (r = 0.7928, p = 0.0001), suggesting a combined influence of multiple nutrient sources on river productivity.

Conductivity

TSI_{TP} exhibited a very strong positive correlation with electrical conductivity (r = 0.815, $p < 0.001$), indicating that ionic content and total dissolved solids are closely associated with nutrient enrichment. This pattern suggests co-occurrence of phosphorus inputs with increased mineralization or anthropogenic ionic contributions.

Turbidity and colour

Both parameters show moderate but significant positive correlations with TSI_{TP} (turbidity r = 0.581, p = 0.011; colour r = 0.484, p = 0.042). The Ogba River represents a key driver of these correlations, as it exhibits both the highest TSI_{TP} and the highest turbidity and colour values, reinforcing a "sediment–phosphorus" relationship.

Dissolved oxygen (DO)

DO shows a weak negative correlation with TSI_{TP} (r = −0.292, p = 0.239). Although the regression line indicates a slight decline in oxygen with increasing trophic state, the large scatter suggests that at the predominantly oligotrophic stage of these rivers, DO is not yet strongly controlled by nutrient loading. Physical aeration and flow may remain dominant factors.

The correlation heatmap (Figure 3) summarizes these relationships, highlighting the primary role of phosphorus and conductivity in driving trophic status, the moderate influence of suspended solids (turbidity, colour), and the limited impact on dissolved oxygen at current oligotrophic conditions.

Table 5. Summary statistics of physicochemical parameters

Parameter	r	p-value	Relationship
Phosphate (PO_4^{3-})	0.993***	<0.001	Extremely strong positive
Conductivity	0.815***	<0.001	Strong positive
Nitrate (NO_3^-)	0.793***	<0.001	Strong positive
Turbidity	0.581*	0.011	Moderate positive
Colour	0.484*	0.042	Slightly positive
Dissolved oxygen (DO)	−0.292	0.239	Negative

Note: n = 18; *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Visualization of key relationships

Scatter plots (Figure 3) illustrate the relationships between TSI_{TP} and key physicochemical parameters, providing insights into trophic variability across the studied rivers. Conductivity exhibited a strong positive association with trophic state (r = 0.815, $p < 0.001$), with data points closely aligned along the regression trend.

Turbidity (r = 0.581, p = 0.011) and colour (r = 0.484, p = 0.042) also increased with rising TSI_{TP}, with higher values largely influenced by observations from the Ogba River, which recorded elevated suspended solids and colour levels.

In contrast, dissolved oxygen showed a weak negative relationship with TSI_{TP} (r = −0.292, p = 0.240) and substantial scatter, suggesting limited coupling under the predominantly oligotrophic conditions observed.

Overall, these patterns indicate consistent associations between trophic status and physicochemical variables, particularly conductivity and suspended matter indicators.

DISCUSSION

Spatial variability in trophic status

The modified phosphorus-based trophic state assessment revealed clear spatial heterogeneity in nutrient enrichment across the studied water bodies. TP-derived TSI values demonstrated statistically significant differences among sites (one-way ANOVA, $p < 0.05$), confirming that trophic conditions were not uniform across the system. The magnitude of the effect, as reflected by η^2 and partial η^2, indicated that a substantial proportion of total variance in trophic state was attributable to site-level differences rather than random variability. Ecologically, this suggests that localized nutrient inputs are the principal drivers of trophic differentiation.

Deviation of the Ogba River

The Ogba River was the notable exception, exhibiting a mesotrophic status (TSI_{TP} = 41.14). This shift toward higher productivity is often considered an early indicator of anthropogenic stress. In Nigerian river basins, such transitions are typically linked to urbanization and land-use changes that introduce allochthonous pollutant inputs (Anyanwu et al., 2025). The mesotrophic state of the Ogba River is particularly notable given its high turbidity (141 NTU) and colour (135 PtCo units), suggesting elevated sediment-bound phosphorus inputs via suspended organic and inorganic matter acting as a carrier for phosphorus (Akongyuure & Alhassan, 2021). The strong correlation with conductivity (r = 0.815) indicates that phosphorus loading is associated with total ionic content, a proxy for domestic and agricultural runoff (Engdaw et al., 2025). The transition of the Ogba River from the regional oligotrophic norm to a mesotrophic state may reflect localized urban pressure or enhanced sediment-bound phosphorus inputs, warranting further investigation of land-use patterns in the surrounding catchment.

Statistical strength and interpretation of observed TSI differences

The statistical outputs provide quantitative validation of trophic heterogeneity. One-way ANOVA demonstrated statistically significant differences in TSI_{TP} among water bodies ($p < 0.05$), indicating spatial heterogeneity in nutrient enrichment status. The significant F-ratio derived from ANOVA demonstrates that between-site variability in TSI exceeded within-site variability. Importantly, the calculated effect sizes (η^2 and partial η^2) indicate that a substantial fraction of trophic variance is explained by site identity or site-specific factors rather than random variability, suggesting strong environmental structuring.

Post-hoc Tukey comparisons identified specific water bodies with significantly higher trophic states relative to others. These pairwise differences reinforce the conclusion that nutrient enrichment is spatially clustered rather than evenly distributed. Such clustering is commonly associated with point-source discharges, agricultural runoff corridors, or localized watershed disturbances rather than uniform enrichment (Dodds & Smith, 2016).

From a monitoring perspective, the statistical robustness of these findings strengthens the argument for site-specific management strategies. Rather than implementing uniform basin-wide controls, mitigation efforts should prioritize high-TSI sites identified through post-hoc analysis.

Physicochemical Drivers of Trophic Status

Conductivity as a physicochemical proxy

The statistical analysis showed that, in addition to phosphate, conductivity was one of the strongest predictors of trophic state (TSI_{TP}) ($r = 0.815$, $p < 0.001$). Regression plots indicate a clear linear trend, suggesting that increasing total dissolved mineral content is associated with higher trophic index values. This suggests that conductivity may serve as a useful and cost-effective proxy for rapid field assessments of trophic conditions in the region. The strong positive correlation further indicates that phosphorus loading is associated with total ionic content, consistent with external nutrient inputs from domestic or agricultural sources (Engdaw et al., 2025; Sulastri et al., 2025).

Dominant chemical drivers (PO_4 and NO_3)

Nutrient data revealed a near-perfect correlation between TSI_{TP} and phosphate ($r = 0.993$, $p < 0.001$), consistent with the index being derived from phosphorus concentrations. Circumneutral pH conditions enhance phosphorus bioavailability, facilitating algal assimilation.

This pattern strongly suggests phosphorus-driven productivity dynamics, aligning with classical limnological theory identifying phosphorus as the primary limiting nutrient in freshwater ecosystems (Rizhinashvili, 2022; Chen et al., 2023; Smith & Schindler, 2009). The strong site effect observed in ANOVA supports the hypothesis that spatial variation in phosphorus loading underlies observed trophic gradients. Where phosphorus exceeds mesotrophic thresholds, primary productivity tends to increase nonlinearly due to positive feedbacks, including internal phosphorus recycling from sediments and enhanced microbial mineralization (Wetzel, 2001).

Additionally, a highly significant correlation was observed with nitrate ($r = 0.793$, $p < 0.001$), indicating that nitrogen and phosphorus inputs co-occur, likely from common sources such as agricultural runoff or domestic sewage.

Continued nutrient input will elevate TSI_{TP} values in several sites, placing them within eutrophic to hypereutrophic categories, indicating high algal growth potential and increased bloom risk. These findings reinforce global observations that phosphorus enrichment remains a central determinant of freshwater eutrophication (Smith & Schindler, 2009).

Sediment and Visual Indicators (Turbidity & Colour)

Significant positive correlations between TSI_{TP} and both turbidity (r = 0.581) and colour (r = 0.484) highlight the role of particulate-bound phosphorus. In scatter plots, the Ogba River contributes to the upper range of these trends, with elevated turbidity (141 NTU) and nitrate concentrations (0.49 mg L^{-1}), indicating that the shift from oligotrophic to mesotrophic conditions is associated with both dissolved nutrients and particulate matter.

In many lotic systems, phosphorus is adsorbed onto soil particles; therefore, increased erosion and sedimentation, reflected by higher turbidity, can elevate phosphorus-based trophic indices (Akongyuure & Alhassan, 2021; Bai et al., 2022).

Amplification by tropical thermal regime

Recorded water temperatures (25–30°C) play an important role in supporting trophic development. These temperatures fall within optimal growth ranges for most freshwater phytoplankton (Reynolds, 2006). Tropical systems lack pronounced seasonal dormancy, allowing sustained phytoplankton growth throughout the year. Elevated temperatures enhance metabolic rates, microbial decomposition, enzymatic nutrient uptake, and primary productivity (Fernandes et al., 2014). As a result, even moderate phosphorus concentrations may lead to relatively high trophic responses. Warmer climates also favour cyanobacterial dominance, increasing bloom frequency and persistence (Kosten et al., 2012). Therefore, observed trophic classifications may represent conservative estimates of ecological risk, as temperature-driven feedbacks can intensify eutrophication beyond the influence of nutrient concentrations alone.

Dissolved oxygen and biogeochemical feedbacks

Measured dissolved oxygen levels (mean 8.52 ± 0.74 mg L^{-1}) fall within ecologically acceptable thresholds. However, eutrophic systems are prone to diel oxygen fluctuations. Elevated primary productivity increases daytime oxygen supersaturation but may lead to nocturnal hypoxia due to respiration and decomposition. In systems approaching hypereutrophic conditions, sustained organic matter accumulation can increase sediment oxygen demand, exacerbating hypoxic risk (Wetzel, 2001). High-TSI sites may therefore experience episodic hypoxia, particularly under stratified or low-flow conditions.

Relatively low ionic strength suggests limited geogenic influence, supporting the interpretation that elevated trophic signals are primarily associated with anthropogenic nutrient inputs, including domestic wastewater, diffuse agricultural runoff, and land-use changes.

Mechanistic implications of phosphorus-driven trophic shifts

Phosphorus enrichment triggers cascading ecological effects, including:
1) increased phytoplankton biomass;
2) reduced water transparency;
3) altered food web structure;
4) enhanced internal nutrient recycling.

Advanced eutrophic conditions may favour cyanobacteria due to buoyancy regulation and nitrogen-fixing capabilities (Smith & Schindler, 2009). Such shifts alter ecosystem structure and pose public health risks through toxin production (Kadiri et al., 2020). TP-based TSI values indicate that affected water bodies may approach thresholds beyond which ecological restoration becomes increasingly complex and costly.

Broader regional context and emerging eutrophication pressures

Predominantly oligotrophic status (TSI 34.65–39.98) indicates relatively high water quality with low nutrient enrichment and primary productivity. These findings are consistent with previous zooplankton-based assessments of the Ovia River (Anyanwu et al., 2013). The stability observed across most sampled rivers suggests that these ecosystems have not yet been significantly impacted by urban or agricultural nutrient inputs (Engdaw et al., 2025).

Freshwater systems in Edo State and southern Nigeria are subject to increasing anthropogenic pressures, including urbanization, agriculture, sand mining, riparian vegetation removal, effluent discharge, and watershed disturbance. Limited wastewater treatment infrastructure contributes to direct nutrient inputs into surface waters.

The spatial trophic gradients observed in this study reflect broader sub-Saharan African patterns. Population growth and land-use pressures increase the risk of eutrophication unless proactive nutrient management is implemented. Trophic state index values exceeding mesotrophic thresholds indicate elevated eutrophication risk, which may develop rapidly due to year-round algal growth potential and enhanced microbial decomposition. Limited monitoring frameworks further increase ecological vulnerability, highlighting the importance of TSI as a management tool.

Ecological implications of results

Current results largely portray a healthy, nutrient-poor environment. Lack of a significant correlation between TSI_{TP} and dissolved oxygen ($p = 0.239$) suggests rivers have not yet reached eutrophication-induced hypoxia. However, the presence of pollution-tolerant species in nearby flood retention lakes indicates regional water bodies are increasingly trending toward eutrophic conditions (Anyanwu et al., 2025). Sites classified as eutrophic or hypereutrophic are potentially vulnerable to:
– cyanobacterial dominance and blooms;
– toxin production;
– oxygen depletion events;
– hypoxic episodes;
– reduced biodiversity;
– ecosystem service degradation.

These risks align with global eutrophication patterns observed in developing regions experiencing urban expansion and watershed disturbance (Dodds & Smith, 2016).

Management and policy implications

Nutrient reduction strategies are necessary to prevent progression toward hypereutrophic states. Once hypereutrophic conditions are established, internal phosphorus loading can sustain elevated productivity despite reduced external inputs. Statistically significant site effects and large effect sizes indicate trophic management should prioritize high-impact locations. Recommended interventions include:
– establishment and restoration of riparian buffer zones;
– regulation of fertilizer application rates;
– implementation of decentralized wastewater treatment;
– routine trophic monitoring using multi-metric indices;
– improved wastewater infrastructure.

Adoption of watershed-scale nutrient budgeting models could further support predictive management. Early intervention is critical. Continuous monitoring of the mesotrophic Ogba River is essential to prevent further degradation into a eutrophic state, which could lead to harmful algal blooms and reduced aquatic biodiversity (Bai et al., 2022; Kadiri & Unusiotame-Owolagba, 2020; Kim et al., 2021).

CONCLUSION

This study provides a multi-dimensional assessment of the trophic and hydrochemical status of riverine systems in the study area. The findings demonstrate that, while the regional baseline is characterized by predominantly oligotrophic conditions, the rivers are chemically soft, with low phosphorus concentrations, high dissolved oxygen levels, and limited buffering capacity, making them highly sensitive to anthropogenic inputs.

The transition of the Ogba River to a mesotrophic state serves as an important indicator of this vulnerability. Its classification, together with elevated turbidity, suggests that increased sedimentation and potential urban runoff are contributing to alterations in the nutrient regime. The statistical evidence indicates that trophic status is not solely a function of phosphorus loading but is also associated with sulphate, nitrate concentrations, and conductivity. The observed relationship between sulphate and trophic state index (explaining 78% of variance) suggests a strong association with ionic inputs potentially linked to detergent use or agricultural runoff. Furthermore, the significant relationship between TSI_{TP} and turbidity confirms that sediment transport is an important pathway for nutrient delivery to the rivers.

To preserve the ecological integrity of these aquatic systems, environmental regulatory authorities should go beyond simple nutrient monitoring and implement stricter controls on land-use activities and riparian buffer management. Strategies addressing both ionic loading and sediment inputs are essential. Monitoring programs may benefit from using conductivity and turbidity as rapid, cost-effective proxies for assessing water quality. Using conductivity and sulphate as early indicators could support the development of a cost-effective surveillance framework for detecting early-stage degradation in these sensitive tropical lotic ecosystems.

Author's statements

Contributions

Conceptualization: M.O.K.; Data curation: B.O.N.; Formal Analysis: J.U.O.; Investigation: B.O.N.; Methodology: J.U.O.; Project administration: B.O.N.; Resources: M.O.K.; Software: M.O.K.; Supervision: M.O.K.; Validation: M.O.K.; Visualization: J.U.O.; Writing – original draft: M.O.K.; Writing – review & editing: M.O.K.

Declaration of conflicting interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Financial interests

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

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