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Spatio-temporal dynamics of nutrient enrichment and eutrophication risk in Dadin Kowa Reservoir, Nigeria

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Abstract

This study investigates the spatio-temporal variation of nitrogen and phosphorus compounds in Dadin Kowa Reservoir, particularly seasonal hydrology and nutrient drivers that remains poorly quantified in Nigerian reservoirs. A stratified random sampling design was employed to capture spatial variability across the reservoir, and the water samples collected from two stations (SWD1 and SWD2) over six months were analyzed for nitrogen and phosphorus compounds alongside key physico-chemical parameters. The analysis revealed markedly elevated concentrations of nitrogen and phosphorus compounds (5.291- 55.4 mg/l and 0.0031-0.646 mg/l) that exceeded USEPA thresholds, indicating strong anthropogenic loading from agricultural runoff, domestic effluents, and internal nutrient regeneration. Principal component analysis showed the first component (F1), explained 48-66% of variance across sampling stations, represents a dominant nutrient-enrichment axis integrating bioavailable nitrogen, phosphorus, and chlorophyll-a, while the second component (F2; 14-27%) reflects hydrological and physicochemical processes linked to wet-season mixing, turbidity, and dissolved oxygen variation. PCA loadings showed co-alignment of N and P variables along F1, indicating dual-nutrient enrichment and potential N:P co-limitation, particularly during the dry season when reduced inflow concentrates nutrients. Spatially, SWD1 exhibited strong clustering of N and P forms, whereas SWD2 displayed greater nutrient heterogeneity associated with upstream land-use pressures. Temporally, nutrient surges in May-June reflected dry-to-wet season transitions, while July-September indicated active internal cycling driven by runoff and phytoplankton dynamics, and December showed decomposition that driven oxygen depletion. These findings emphasize the urgent need for integrated reservoir management strategies focusing on nutrient source reduction, sediment control, and seasonal oxygenation to mitigate eutrophication risk and sustain aquatic ecosystem health.

Nomenclature and units

PCA	Principal Component Analysis
NTU	Nephelometric Turbidity Unit
Chl_a	Chlorophyll_a
KMO	Kaiser-Meyer-Olkin
SWD	Dadin Kowa Reservoir Sampling Point

1.0 Introduction

Water quality monitoring and management are crucial for evaluating the current state of water resources and its suitability for various uses, and ability to sustain aquatic life (Blaen *et al.*, 2016; Gitau *et al.*, 2016). Excessive nutrient loading into surface waters is a leading cause of water quality degradation, driven by both point and non-point sources, particularly in developing countries (Chen *et al.*, 2019; Sinha & Michalak, 2016; Yuan *et al.*, 2018). Surface water quality is influenced by a complex interplay of natural factors such as climate and topography, and anthropogenic pressures including mining, agriculture, industrial effluents, and municipal discharges (Viaroli *et al.*, 2018; Uddin *et al.*, 2018). These pressures diminish available water resources, threatening human health, biodiversity, and ecosystem services (Sotomayor *et al.*, 2018). Reservoirs play a vital role in surface water management by supporting water supply, irrigation, hydropower, flood control, and recreation. However, they also act as nutrient sinks, making them particularly susceptible to eutrophication from nutrient accumulation in sediments and inflows (Thornton, 1990; Chmiel *et al.*, 2020). Nitrogen and phosphorus are the two primary nutrients driving eutrophication, exist in multiple forms with varying bioavailability and ecological impacts (Ballard *et al.*, 2019; Shen *et al.*, 2020). Excessive nutrients in reservoirs resulting in harmful algal blooms, particularly cyanobacteria (blue-green algae) that deplete oxygen and harm aquatic life (Smith & Schindler, 2009; Han *et al.*, 2017; Paerl *et al.*, 2020; Li *et al*., 2023). Reservoirs in Nigeria are influenced by various anthropogenic factors and ecological conditions, primarily from agricultural runoff and land use changes (Ladapo & Aminu, 2017; Mustapha, 2008; Mohammed *et al.*, 2018).

The spatial and temporal variation of nutrients in reservoir systems is influenced by multiple factors, including land use patterns, hydrodynamics, seasonal changes, and human activities (Lv *et al*., 2019; Wang *et al.*, 2020a; Viaroli *et al.*, 2018). Seasonal patterns in the release of nitrogen and phosphorus from sediments (internal loading) in reservoirs are significantly influenced by environmental conditions such as temperature, dissolved oxygen, and hydrological changes (Saha *et al.*, 2021; Cai *et al.*, 2023; Shafiei, 2021; Sun *et al*., 2023). Several studies have examined nutrient concentrations in Nigerian reservoirs (Akindele *et al*., 2013; Ladapo & Aminu, 2017; Mustapha, 2008; Mohammed *et al.*, 2018), however, most investigations have been descriptive, focusing on nutrient concentrations without integrating spatio-temporal variability or exploring multivariate relationships among nitrogen, phosphorus, and ecological indicators. Moreover, inconsistencies exist regarding the dominant nutrient sources (external and internal loading) and the seasonal dynamics of nutrient transformation. This gap limits the development of predictive models and management interventions for reservoirs such as Dadin Kowa, which are subject to intense agricultural and domestic pressures. This study aims to explore the spatial and temporal variation of nutrient concentrations and identify the primary nutrient drivers influencing water quality in the Dadin Kowa reservoir for effective water quality management.

2.0 MATERIALS AND METHODS

2.1 Study Area

The Dadin Kowa Reservoir is situated between latitudes 10°20′-10°55′ N and longitudes 11°25′-11°35′ E, which lies approximately 37 km east of Gombe, northeastern Nigeria. It was created on the River Gongola, the major tributary of the Benue River with principal inflows from the Dindima, Nafada, Gombe Abba, Ashaka, and Dukku rivers as shown in Figure 1. The reservoir extends about 56 km, covering a surface area of roughly 300 km² and a catchment of 22,467 km². At maximum operating level, storage capacity reaches 2.63×10^9 m³, with a live storage of 1.77×10^9 m³ and a mean inflow of 3,160 m³/s against an outflow of 1,110 m³/s (NWRI, 2020; UBRDA, 2020). The reservoir's elongated shape and gentle basin slopes facilitate nutrient accumulation and limited mixing in deeper zones, particularly during low-flow dry seasons. The surrounding catchment is dominated by agricultural land use, with expanding irrigation schemes, livestock rearing, and rural settlements contributing significant non-point nutrient inputs (UBRDA, 2020). Upstream sand mining, fertilizer runoff, and untreated domestic wastewater further intensify external nutrient loading, while fluctuating inflow-outflow regimes enhance sediment resuspension and internal nutrient recycling. The region experiences a tropical continental climate with a distinct wet season (June-October) and dry season (November-May), averaging 440-1,400 mm annual rainfall and mean temperatures between 22 °C and 37 °C, conditions that strongly modulate hydrological exchange and nutrient transformation (UBRDA, 2020) as shown in Figure 2.

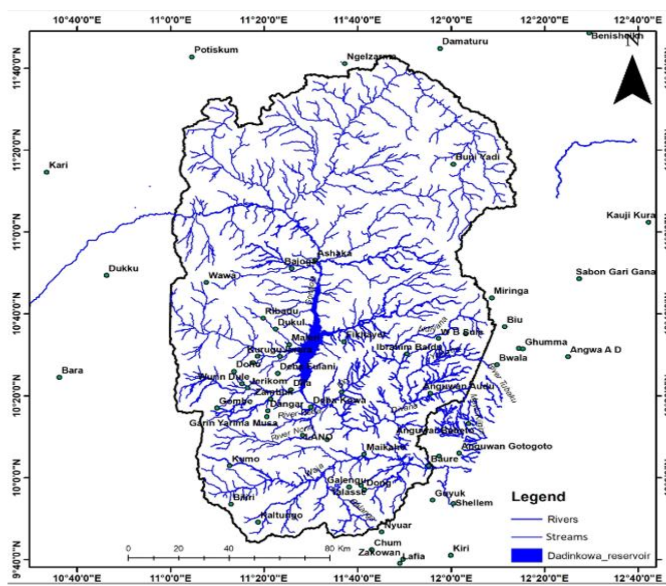

Figure 1: Dadin Kowa reservoir catchment

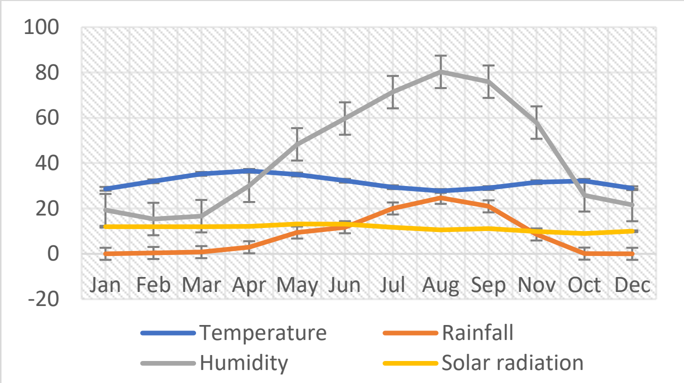

Figure 2: Dadin Kowa climatic conditions

2.2 Water Sampling and Analysis

A stratified random sampling design was employed to capture spatial variability across Dadin Kowa Reservoir, dividing the reservoir into two longitudinal segments encompassing all major tributaries. Two sampling stations (SWD1: 11.478439° N, 10.324333° E; SWD2: 11.503899° N, 10.548684° E), approximately 25.4 km apart were selected to represent upstream and mid-reservoir conditions as shown in Figure 3. Water samples were collected monthly from May to September and in December 2023 at a consistent depth of 1 m using sterilized plastic bottles, which were immediately stored in ice packs. The May sampling represented peak dry season conditions, while the June to September collections captured the wet season transition and associated hydrological variability influencing nutrient dynamics. The December sampling reflected post-wet-season conditions to enable assessment of nutrient retention and redistribution following peak inflows. This six-month sampling period effectively encompassed both dry and wet seasonal regimes, ensuring temporal representativeness that minimize bias from short-term fluctuations or localized pollution events. Samples were transported immediately to the Chemistry Analytical Laboratory, Yobe State University, Damaturu, Nigeria, for analysis following APHA (2005) protocols. Measured parameters included water temperature, pH, dissolved oxygen (DO), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), organic nitrogen (ON), total nitrogen (TN), ortho-phosphorus (PO_4^{3}), organic phosphorus (OP), and total phosphorus (TP). In-situ measurements for temperature, pH, and DO were taken using calibrated meters (TDS & EC E51M0, pH meter, DO-510), while nitrogen and phosphorus compounds were analyzed using LaMotte colorimetry (SMART3).

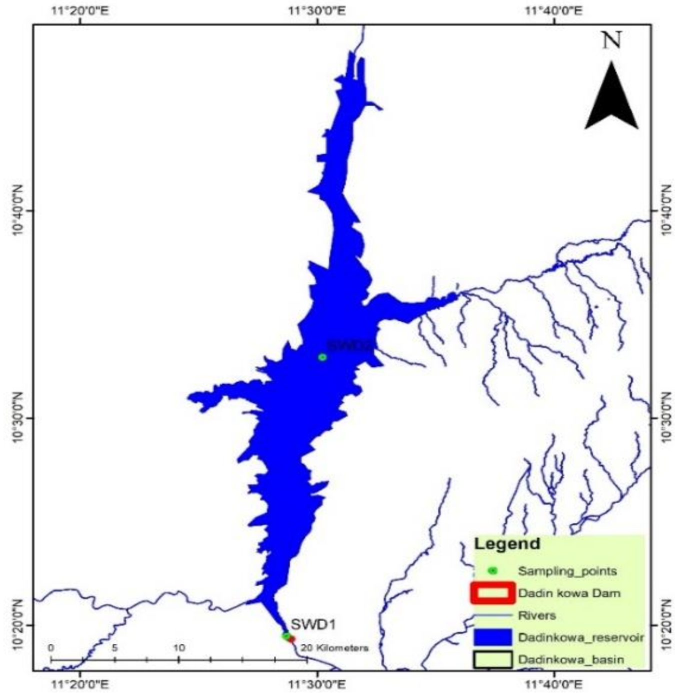

Figure 3: Dadin Kowa Reservoir Sampling Points

2.3 Data Analysis

Descriptive statistics summarized temporal and spatial nutrient variations was adopted. Principal Component Analysis (PCA) was applied to identify dominant nutrient drivers and their spatio-temporal patterns. Prior to PCA, sampling adequacy and data suitability were assessed using Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were performed, confirming sufficient inter-variable correlations for meaningful multivariate analysis (KMO ≥ 0.5; Bartlett's $p < 0.05$). The PCA identifies major variance patterns, the outcomes are presented as indicative rather than definitive, highlighting primary drivers of nutrient enrichment rather than exhaustive quantitative characterization.

3.RESULTS AND DISCUSSION

3.1 Physio-chemical Properties of Dadin Kowa Reservoir

The Table 1& 2 presents nutrient profile of Dadin Kowa reservoir at the sampling points SWD1 and SWD2, reflects strong anthropogenic influence and land-use intensity within the catchment, and compared against USEPA (2000) standards. The statistical measures provided include the minimum, maximum, mean and standard deviations that provide insight into the variability and distribution of these compounds.

Table 1: Analysis of Nitrogen and phosphorus Compounds Concentration in Dadin Kowa Reservoir Sampling Point I (SWD2)

Variable	Min.	Max.	M/STDV	USEPA
NH_3-N (mg/l)	4.46	6.17	5.37±0.618	0.5-2
NO3-N (mg/l)	18.5	27.48	23.455±3.213	<10
Org-N (mg/l)	15.1	21.2	18.059±2.312	-
TN (mg/l)	41.9	55.4	49.399±4.125	0.5-1.5
Orth-P(mg/l)	0.0028	0.0038	0.0034±0.0004	0.5-2
Org-P (mg/l)	0.12	0.15	0.1343±0.0121	<10
P (mg/l)	0.403	0.566	0.507±0.0617	-
TP (mg/l)	0.537	0.714	0.646±+0.0667	0.5-1.5
DO (mg/l)	4.12	5.95	4.728±0.643	45785
pH	5.24	6.9	6.315±0.584	6.5-8.5
Chl_a (mg/l)	0.18	0.25	0.221±0.024	5
Turb. (NTU)	18	28	22.512±3.328	45807
W. temp. (0C)	25.8	28.7	27.63±0.946	15-25

Table 2: Analysis of Nitrogen and phosphorus Compounds Concentration in Dadin Kowa Reservoir Sampling Point II (SWD2)

Variable	Min.	Max.	M/STDV	USEPA (2000)
NH_3-N (mg/l)	4.53	6.48	5.291±0.722	0.5-2
NO3-N (mg/l)	18.22	27.85	23.86±3.551	<10
Org-N (mg/l)	14.7	21.04	18.166±2.274	-
TN (mg/l)	38.35	54.4	49.802±5.539	0.5-1.5
Orth-P(mg/l)	0.0023	0.0039	0.003±0.0006	0.5-2
Org-P (mg/l)	0.12	0.15	0.138±0.0121	<10
P (mg/l)	0.001	0.583	0.3876±0.2171	-
TP (mg/l)	0.135	0.749	0.548±0.2218	0.5-1.5
DO (mg/l)	4.02	5.85	4.705±0.632	45785
pH	5.7	6.95	6.553±0.475	6.5-8.5
Chl_a (mg/l)	0.18	0.26	0.21±0.03	5
Turb. (NTU)	18	27	22.401±3.571	45807
W. temp. (0C))	25.6	29.23	27.992±1.3	15-25

Ammonia (NH_3-N) and nitrate (NO_3-N) concentrations at both SWD1 (5.29 mg/L, 23.86 mg/L) and SWD2 (5.37 mg/L, 23.45 mg/L) substantially exceed USEPA guidelines, indicating substantial agricultural runoff, domestic sewage, and upstream inputs. Elevated organic nitrogen further suggests decomposition of plant or animal waste, contributing to total nitrogen (49.6 mg/L) enrichment. This indicates potential contamination likely from agricultural runoff or sewage discharge that could be detrimental to aquatic organisms, causing issues such as reduced growth rates and reproductive problems as reported in Ladapo & Aminu (2017) and WHO (2020). Total phosphorus is also high, particularly at SWD2 (0.646 mg/L), pointing to phosphorus loading from fertilizers, urban runoff, and sediment inputs. Although ortho- and organic phosphorus remain relatively low, their presence signals ongoing organic matter decomposition that sustains internal nutrient cycling. The higher total phosphorus levels at SWD2 suggest greater phosphorus loading, potentially from agricultural runoff or urban runoff (Ladapo & Aminu, 2017). The combination of high nutrient loads and moderate dissolved oxygen (4.02-5.95 mg/L) reflects oxygen depletion from microbial decomposition, creating hypoxic conditions that threaten aquatic life and exacerbate eutrophication risks. Slightly acidic pH values and elevated water temperatures further amplify nutrient transformations, consistent with patterns observed in Gubi and Kazaure reservoirs under intensive land-use influence (Muhammad *et al.*, 2025; Oladeji, 2020). Turbidity levels (18-28 NTU) indicate significant sediment and runoff contributions, likely from soil erosion, construction, and catchment disturbances, reducing light penetration and limiting algal growth despite high nutrient concentrations. High turbidity can result from sediment runoff, organic matter, and algal growth, leading to reduced light penetration and impacting aquatic ecosystems as indicated in Oyatola *et al.* (2021). Increased turbidity is often associated with soil erosion, construction activities, or wastewater discharge. Chlorophyll-a remains low (0.21–0.22 mg/L), suggesting additional limiting factors such as light, grazing, or inhibitory compounds inhibitors (Caissie, 2006).

3.2 PCA Eigenvalues of Nutrient in Dadin Kowa reservoir

The first two principal components (F1 and F2) effectively summarized most nutrient behaviors at SWD1 and SWD2 as presented in Table 3.

Table 3: PCA Eigenvalues of Nutrient in Dadin Kowa Reservoir

SWD1(Nitrogen)	F1	F2	F3	F4	F5
Eigenvalue	5.23	2.09	1.18	0.29	0.22
Variability (%)	58.11	23.21	13.07	3.21	2.41
Cumulative (%)	58.11	81.32	94.38	97.59	100
SWD2					
Eigenvalue	4.33	2.40	1.49	0.61	0.17
Variability (%)	48.09	26.63	16.57	6.78	1.94
Cumulative (%)	48.09	74.72	91.29	98.06	100
SWD1 (Phosphorus)					
Eigenvalue	5.88	1.49	0.87	0.54	0.22
Variability (%)	65.33	16.52	9.71	5.96	2.48
Cumulative (%)	65.33	81.84	91.56	97.52	100
SWD2					
Eigenvalue	5.92	1.25	1.07	0.71	0.06
Variability (%)	65.77	13.85	11.84	7.89	0.65
Cumulative (%)	65.77	79.62	91.46	99.35	100

At both stations F1 have largest eigenvalues ranged from 4.33-5.92, represents the primary nutrient-enrichment axis and high inorganic nitrogen and bioavailable phosphorus together with Chl_a. This explains the dry-season accumulation and internal loading. At F2 the eigenvalue explains a smaller but substantial share (1.25–2.4) and aligns with physiochemical and hydrological processes (DO, turbidity, pH), reflecting wet-season mixing, runoff pulses and sediment resuspension (Saha *et al.*, 2021). The strong loadings of both N and P on F1 indicate they co-vary periods when both TN and TP rise (high F1 scores) correspond to elevated Chl-a and low DO, implying co-enrichment and potential co-limitation rather than single-nutrient control (Mohammed *et al.*, 2018). In practical terms, agricultural fertilizer runoff, manure and domestic sewage in the catchment supply both N and P simultaneously, altering N:P stoichiometry and promoting blooms under low-flow dry conditions, as reported by Abdullahi *et al.*, (2017) in Kanye reservoir. SWD2's slightly lower shared variance for N (and higher F2 contribution) suggests more heterogeneous upstream inputs and localized hotspots like tributary and land-use effects (Saha *et al.*, 2021). Similar seasonal patterns were reported by Mustapha (2008) and Raji *et al.* (2020) that dry-season nutrient retention and bloom risk are driven by internal loading and reduced flushing, and wet-season pulses alter stoichiometry and turbidity. The F1 captures the bulk of nutrient variance, management should prioritize early dry-season source control (N & P) and targeted monitoring of F1 indicators (TN, NH_4, TP, ortho-P, Chl-a). F2-related metrics (DO, turbidity, pH) should inform wet-season response to mitigate runoff and sediment control.

3.3 PCA Factor Loadings for Nutrients in Dadin Kowa Reservoir

The PCA factor loading patterns at SWD1 and SWD2 reveal that nutrient dynamics in Dadin Kowa are driven by seasonal hydrology, with dry-season nutrient concentration and wet-season nutrient transport jointly enhancing N-P interactions and co-limitation potential as presented in Table 4 & 5.

Table 4: PCA Factor Loadings for Nitrogen in Dadin Kowa Reservoir

Parameter	SWD1		SWD2		
	F1	F2	F1	F2	F3
NH_3-N	18.227	0.114	0.884	0.210	0.170
NO_3-N	12.593	11.209	0.384	0.512	-0.604
Organic nitrogen	0.652	27.891	-0.182	0.722	0.637
Total nitrogen	4.345	33.050	0.237	0.935	-0.250
Total organic carbon	16.131	2.912	0.928	0.162	-0.203
Dissolved oxygen	7.521	10.605	-0.637	0.551	-0.326
Chl_a	18.015	0.212	0.911	0.262	0.278
Turbidity	12.214	0.434	-0.885	0.206	-0.366
pH	10.303	13.573	-0.655	0.503	0.519

Table 5: PCA Factor Loadings for Phosphorus in Dadin Kowa Reservoir

Parameter	SWD1		SWD2		
	F1	F2	F1	F2	F3
Orth-Phosphate	0.785	-0.461	0.824	-0.290	0.467
Organic Phosphorus	0.777	-0.239	0.967	0.126	0.142
Phosphorus	0.792	0.531	0.819	-0.564	-0.026
Total phosphorus	0.834	0.529	0.870	-0.479	0.029
Total organic carbon	0.728	-0.510	0.759	0.568	0.136
Dissolved oxygen	-0.800	-0.466	-0.675	-0.042	0.713
Chl_a	0.860	-0.401	0.837	0.392	0.354
Turbidity	-0.854	-0.108	-0.863	-0.328	0.311
pH	-0.836	0.075	-0.632	0.118	0.278

The PCA loadings indicate that dry-season months (F1 scores) are dominated by nutrient accumulation, with strong positive loading of NH_3-N, TN, Chl_a, and all phosphorus forms at both SWD1 and SWD2 (0.87- 0.91). This corresponds to low inflow and high evaporation, concentrating nutrients and enhancing algal growth. In contrast, the wet season is associated with higher loadings of organic nitrogen (0.72), turbidity, and DO, reflecting runoff-driven sediment inputs and enhanced mixing (Akindele, 2014). Across both sampling points, PCA shows co-alignment of nitrogen (NH_3-N, TN) and phosphorus variables (TP, OP, PO_4^3) along F1, indicating that both nutrients jointly structure productivity. High simultaneous loadings (Chl_a = 0.86 with TP; NH_3-N = 0.88) suggest N-P co-limitation, especially during the wet season when agricultural drainage and household waste elevate both nutrient groups, as by Abdullahi *et al.*, (2017) in Kanye reservoir. The integrated loading patterns implicate elevated N:P ratios, which may shift algal communities toward cyanobacteria, similar to patterns reported in Kanye and Tiga reservoirs (Abdullahi *et al.*, 2017; Akindele *et al.*, 2013). Strong nutrient loadings in both F1 axes reflect runoff from farmlands, particularly given Dadin Kowa's extensive upstream agriculture practices. High organic nitrogen and turbidity during the wet season indicate topsoil erosion and fertilizer wash-in, while strong NH_3-N and TP loadings in the dry period likely reflect nutrients internal loading. Similar to Kainji reservoir, the PCA pattern shows nitrogen and phosphorus co-loading with algal biomass, reflecting dual-nutrient enrichment (Akindele, 2014). The DO loads negatively against nutrient variables, indicating hypoxia risk during bloom decay Abdullahi *et al.* (2017). These consistencies suggest Dadin Kowa follows a typical Sahelian reservoir nutrient regime, dictated by alternating dry-season concentration and wet-season wash-in.

3.4 Spatial variation of nitrogen and phosphorus compounds

The correlation circle captured 81.51% and 74.72% for nitrogen compounds, and 81.84 & 79.62% for phosphorus compounds at SWD1 and SWD2 in Dadin Kowa reservoir as shown in Figures 4-7. The spatial distribution of nitrogen and phosphorus compounds in Dadin Kowa Reservoir shows distinct patterns influenced by reservoir hydrology and localized anthropogenic inputs.

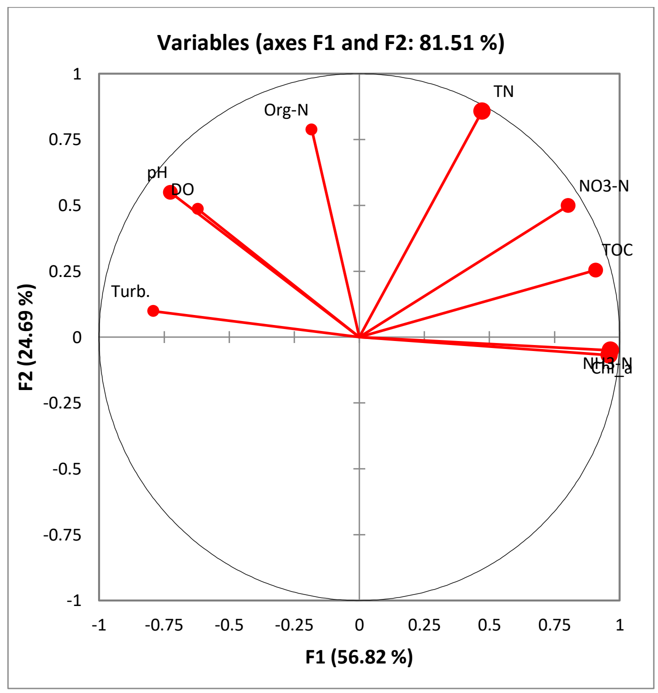

Figure 4: PCA Correlation Circle for Nitrogen Compound at SWD 1

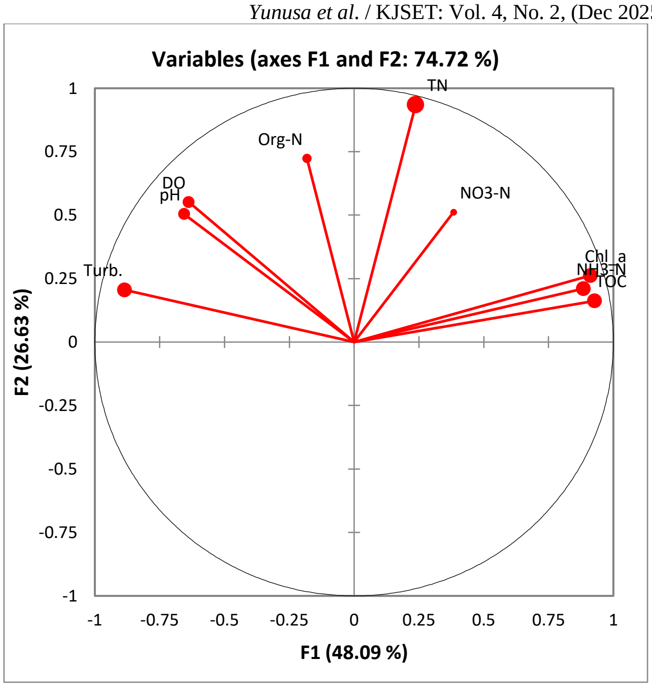

Figure 5: PCA Correlation Circle for Nitrogen Compound at SWD 2

At SWD1, nitrogen forms (NH_4-N, NO_3-N) and phosphorus species (TP, PO_4^{3}, OP) cluster closely along the principal component representing nutrient enrichment and algal productivity. Chlorophyll_a co-locates with both N and P, highlighting that nutrient availability drives primary productivity, consistent with the nutrient-productivity observed in Kanye and Kainji reservoirs (Abdullahi *et al.*, 2017; Mohammed *et al.*, 2018). The spatial coherence of N and P at SWD1 suggests that inflows from upstream agricultural runoff and domestic wastewater are the dominant nutrient sources, with minimal hydrodynamic dispersion, particularly during the dry season when reduced inflow concentrates nutrient. At SWD2, the spatial variability of nitrogen, particularly organic and total nitrogen, is more dispersed compared to SWD1, while phosphorus species remain tightly grouped. This heterogeneity implies multiple nitrogen sources and in-situ transformations such as organic matter decomposition or nitrification-denitrification cycles. The co-alignment of NH_4-N with Chl-a reinforces ammonium's role as a readily bioavailable nitrogen source that promotes algal blooms, whereas NO_3-N is moderately associated with physical-chemical axes, reflecting its dual role in productivity and microbial processes; This is in line with Mustapha (2008) and Raji *et al.* (2020), spatial nutrient dynamics were observed from Oyun Reservoir, where inflow points and catchment land use strongly modulate N and P distributions. N:P ratios at SWD2 indicate potential co-limitation during the wet season, suggesting that phosphorus inputs may regulate algal growth when nitrogen is abundant, a pattern comparable to seasonal N:P dynamics reported in Sokoto-Rima basin (Raji *et al.*, 2020).

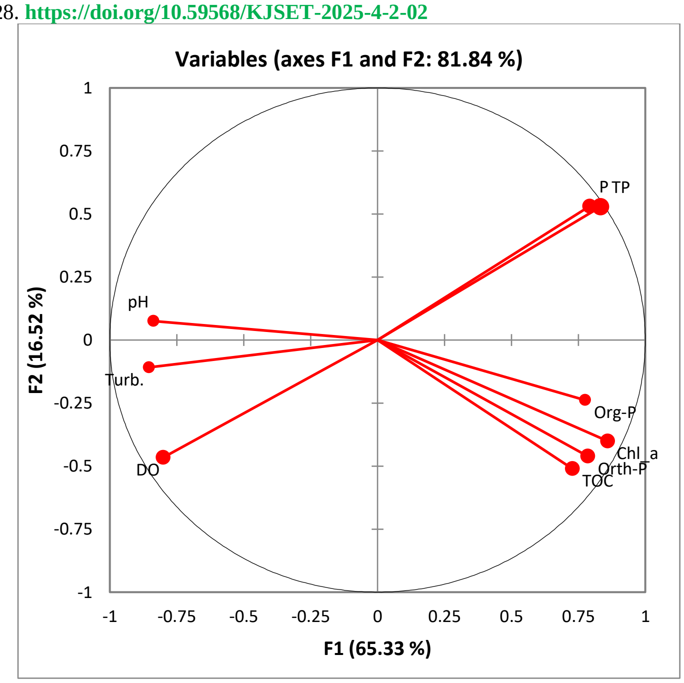

Figure 6: PCA Correlation Circle for Phosphorus Compound at SWD1

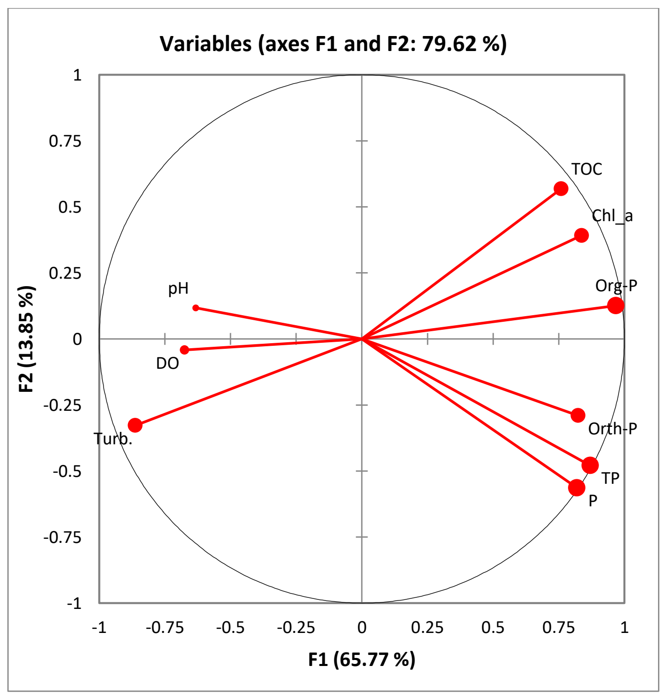

Figure 7: PCA Correlation Circle for Phosphorus Compound at SWD2

The spatial variations between SWD1 and SWD2, includes higher total phosphorus and greater nutrient variability at SWD2, highlight localized input hotspots influenced by upstream land use and tributary inflows. SWD2, with higher nitrogen heterogeneity, likely reflects localized hotspots of agricultural runoff, while SWD1 exhibits more uniform nutrient patterns. The overall nutrient enrichment patterns in Dadin Kowa Reservoir are closely linked to land-use intensity, catchment runoff potential, and upstream anthropogenic activities. These spatial distinctions emphasize the need for site-specific nutrient management strategies that account for co-limitation, seasonal variations, and hydrological regime impacts, reinforcing the importance of N:P ratios as indicators for predicting eutrophication risk and designing adaptive mitigation interventions such as modelling (Oyatola *et al.*, 2021).

3.5 Temporal Variation of Nitrogen and Phosphorus Compounds

The PCA biplots for temporal dynamics of nitrogen and phosphorus in Dadin Kowa reservoir reflect distinct seasonal and hydrological patterns as shown in Figures 8-11.

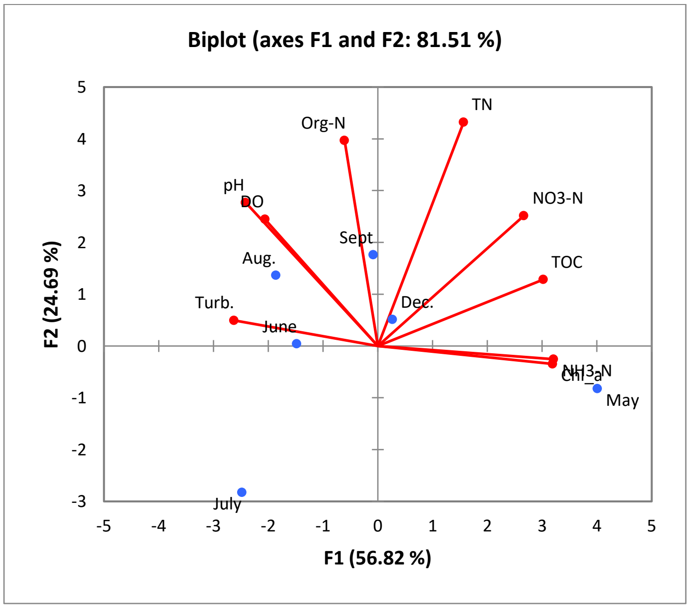

Figure 8: PCA observation plot for nitrogen compound at SWD1

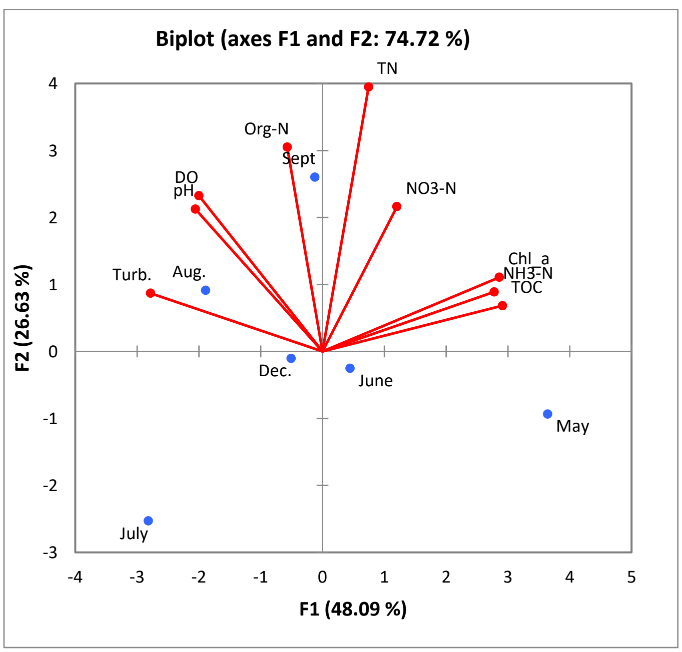

Figure 9: PCA observation plot for nitrogen compound at SWD2

The peak dry season (May) and early rainy season (June) exhibited elevated NH_3-N, NO_3-N, total nitrogen, and total phosphorus concentrations at both SWD1 and SWD2, suggesting strong internal loading and runoff influence. High temperatures during this period accelerate microbial activity and nutrient mineralization, increasing the availability of bioactive N and P and setting the stage for early-season eutrophication (Saha *et al.*, 2021; Zhang *et al.*, 2020). The strong co-alignment of chlorophyll-a with both N and P in PCA plots indicates a potential co-limitation scenario, where simultaneous availability of nitrogen and phosphorus promotes algal growth. These patterns mirror observations in Kainji and Tiga reservoirs, where peak nutrient enrichment and bloom initiation often occur at the onset of the wet season due to concentrated inflows and reduced dilution (Mohammed et al., 2017; Oyatola *et al.*, 2021; Akindele *et al.*, 2014). During the wet season (July-September), stratification occurs with increased runoff, and higher temperatures drove intense biological activity and nutrient cycling. PCA results show elevated DO and chlorophyll-a in these months, coupled with high turbidity, indicating active phytoplankton growth and sediment resuspension. The temporal alignment of nitrogen and phosphorus suggests that N:P ratios during this period may favour rapid algal proliferation, with ammonium and orthophosphate serving as the dominant bioavailable forms. This co-limitation and internal nutrient cycling correspond to mid-season bloom dynamics documented in Tiga and Kainji reservoirs, where summer precipitation and stratification amplify nutrient mobilization and productivity (Oyatola *et al*., 2021; Mohammed *et al*., 2017).

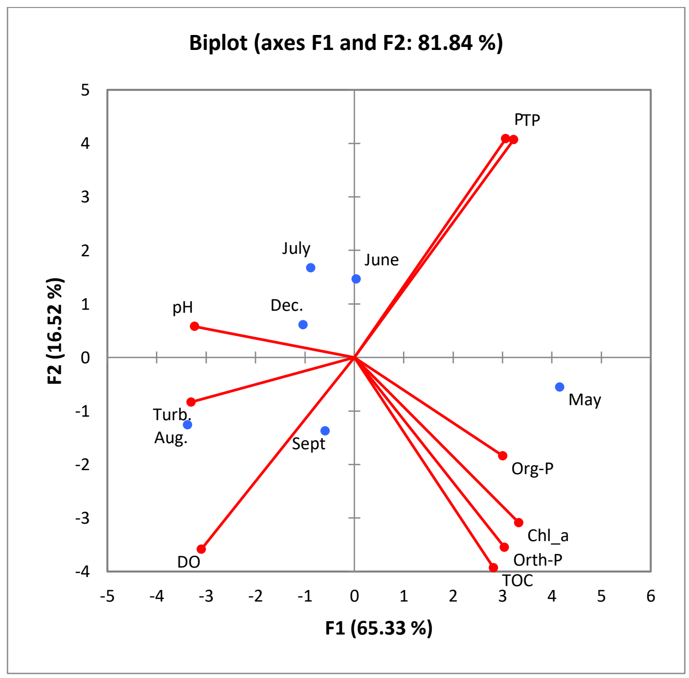

Figure 10: PCA observation plot for phosphorus compound at SWD1

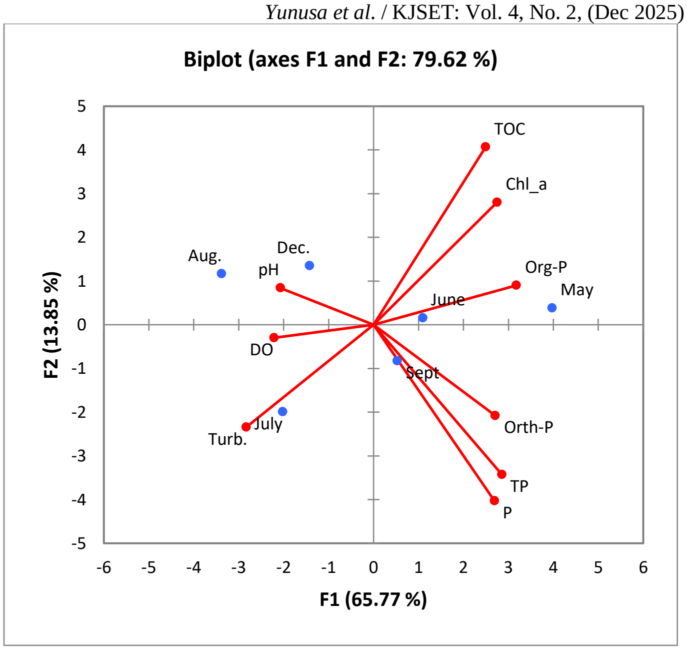

Figure 11: PCA observation plot for phosphorus compound at SWD2

Late-season month (December) display a transition to decomposition-dominated processes. PCA positioning indicates reduced nitrogen and phosphorus concentrations at SWD1, while SWD2 exhibits greater variability, reflecting localized inflows or anthropogenic impacts. Decomposing algal biomass contributes to organic nitrogen and phosphorus release, but oxygen depletion due to microbial respiration becomes dominant. This seasonal mismatch between nutrient availability and oxygen levels underscores the risk of hypoxia, particularly in stratified zones, and parallels post-bloom conditions observed in Tiga and Kainji reservoirs, where late-season organic matter decay drives DO stress (Oyatola *et al.*, 2021; Mohammed *et al.*, 2017). The comparison of nitrogen and phosphorus dynamics highlights critical N:P interactions that influence co-limitation and eutrophication risk. Early-season nutrient surges favor synchronized algal growth, while mid-season stratification and runoff reinforce nutrient availability, and late-season decomposition promotes oxygen stress. These insights suggest that nutrient mitigation strategies should focus on controlling early- and mid-season runoff, managing N:P ratios to limit algal blooms, and monitoring late-season oxygen depletion

4. Conclusion

The findings revealed that the Dadin Kowa Reservoir exhibits substantial nutrient enrichment driven by seasonal hydrology, intensive agricultural activities, and internal nutrient cycling. The result shows an elevated concentrations of nitrogen and phosphorus compounds at both sites far exceed ecological thresholds, confirming significant anthropogenic loading from agriculture, domestic sewage, and sediment-bound nutrients. The principal component analysis revealed consistent nutrient enrichment (F1) dominates overall variability, with nitrogen and phosphorus co-loading alongside chlorophyll-a, demonstrating co-limitation and synchronous nutrient-driven productivity. Wet-season processes reflected in F2 highlight the role of runoff, turbidity, and mixing in redistributing nutrients and altering stoichiometry (N:P ratios). Spatial heterogeneity, particularly at SWD2, underscores the influence of upstream tributaries and localized land-use activities. Temporal patterns reveal dry-season accumulation, early-wet-season wash-in, mid-season productivity peaks, and late-season decomposition-driven hypoxia. These findings provide a baseline for nutrient monitoring, eutrophication modelling, and watershed management in Nigerian reservoirs. Future research should incorporate continuous in-situ monitoring, sediment nutrient flux analysis, and ecological modeling to predict eutrophication under changing climate and land-use conditions.

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Declaration of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The research was collectively conducted by the authors in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest, and no external organization had any influence on the study design, data collection, analysis, interpretation of results, or the decision to submit the work for publication.

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