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## EVALUATION OF PHOSPHORUS COMPOUND ENRICHMENT AND EUTROPHICATION RISK OF ALAU RESERVOIR, NIGERIA

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### ABSTRACT

This study assessed the enrichment and eutrophication response variables of phosphorus fractions in Alau Reservoir because of limited information on the contribution of individual phosphorus fractions, their seasonal variations and relationship with eutrophication risk. High levels of phosphorus enrichment continue to be a significant cause of eutrophication as it can stimulate algal growth, lead to an increase in organic matter and can decrease dissolved oxygen. Water samples were taken from two sampling points (SWA1 and SWA2) for six months, which included the late dry season, rainy season and post-rainy dry season. Orthophosphate, organic phosphorus, phosphate, total phosphorus, pH, dissolved oxygen, chlorophyll-a and turbidity were measured by standard laboratory methods. Descriptive statistics and principal component analysis were used to identify the distribution patterns of phosphorus and its association with eutrophication indicators. The results indicated that the mean orthophosphate concentration at SWA2 (0.0059 mg/L) was higher than SWA1 (0.0043 mg/L), while the mean organic phosphorus concentration at SWA2 (0.2308 mg/L) was higher than SWA1 (0.1633 mg/L). The mean soluble phosphorus concentration at SWA2 (0.9948 mg/L) was higher than SWA1 (0.9159 mg/L), and the mean total phosphorus concentration at SWA2 (1.1735 mg/L) was higher than SWA1 (1.0442 mg/L). The principal component analysis accounted for 77.57% and 87.29% of the total variation at SWA1 and SWA2, respectively, with higher nutrient-biological interactions at SWA2. The monthly variations revealed that September was closely associated with the response of phosphate and chlorophyll-a, suggesting periods of higher eutrophication pressure. The relationship between phosphorus fractions and chlorophyll-a and the inverse relationship with dissolved oxygen suggest an increasing eutrophication risk, especially at SWA2. The study suggests that the phosphorus fractions should be monitored continuously and that catchment management practices like modeling should be implemented to decrease the nutrient load to the reservoir.

**Keywords:** Chlorophyll-a; eutrophication; phosphorus enrichment and water quality

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### 1. INTRODUCTION

Freshwater reservoirs are important sources of water for domestic use, fisheries, irrigation, livestock, conservation of biodiversity and livelihoods, but their ability to provide these services is highly dependent on nutrient balance and ecological stability, which can only be achieved through water quality monitoring and management (Akinawo, 2023). The reservoir water quality is often a combination of the effects of rainfall, erosion, agricultural runoff, domestic discharge, shoreline activities and internal sediment processes. These pressures may be more acute in tropical and semi-arid areas where seasonal rainfall may lead to a high concentration of nutrients in reservoirs, and dry-season evaporation and longer water residence time can result in an increase in dissolved substances (Fabian *et al.*, 2023; Ahmed and Ibrahim, 2024). Eutrophication is one of the most significant types of freshwater degradation, as excess nutrient loading can lead to algal growth, decreased water clarity, increased organic matter decomposition, and decreased dissolved oxygen (Wurtsbaugh *et al.*, 2019). Phosphorus has particular importance in reservoir assessment because it often limits primary productivity in freshwater systems. Excessive phosphorus levels can lead to algal blooms, oxygen depletion,

degradation of fish habitat, and increased treatment costs for potable water supply (Ayoade & Aderogba, 2020; Fabian *et al.*, 2023; Usman *et al.*, 2025). Phosphorus, chlorophyll-a, transparency and dissolved oxygen have therefore been considered as related measures of nutrient pressure and ecological response in general eutrophication literature (Wurtsbaugh *et al.*, 2019; USEPA, 2000; Akinlawo, 2023).

Phosphorus exists in various forms such as organic and inorganic phosphorus, the inorganic phosphorus is made of orthophosphates, polyphosphates, which are usually found in natural and engineered systems (Uddin *et al.*, 2018). The organic phosphorus compounds are very diverse in nature, which includes phospholipids, nucleotides, and phosphoproteins (Ebuele, 2016; Brenden *et al.*, 2018). Agricultural runoff, domestic wastewater, soil erosion, shoreline activities and internal sediment release are sources of nutrients to reservoirs in Nigeria. The pressures may differ from one sampling point to another and from one month to another due to the changes in nutrient behaviour caused by inflow, rainfall, dry season concentration and biological uptake (Akin-Oriola, 2003; Usman *et al.*, 2025). A number of studies conducted on reservoirs in Nigeria have reported nutrient enrichment, phytoplankton response and seasonal water quality variation (Ayoade & Aderogba, 2020; Fabian *et al.*, 2023; Usman *et al.*, 2025). Phosphorus is vital in the growth and productivity of living organisms like algae and plants (Smith & Schindler, 2009; Han *et al.*, 2017). Nevertheless, Excess phosphorus in reservoirs encourages overgrowth of algae, especially the cyanobacteria (blue-green algae). Some cyanobacteria like *Microcystis* and *Anabaena* may form harmful toxins called cyanotoxins in water amphibians (Dodd and Sharpley, 2016; Paerl *et al.*, 2020). The cyanotoxins are harmful to a wide range of aquatic organisms, causing liver damage, neurological effects, and even fish, invertebrates, and other aquatic organisms dying after consuming the water, as well as harmful to domestic animals and human poisoning by consuming the water (Paerl *et al.*, 2020).

While Alau Reservoir has been studied with respect to general physico-chemical quality, raw water suitability, socio-economic pressure and pollution indicators, there is limited evidence that phosphorus compound enrichment is a direct driver of eutrophication risk. Previous research typically measures only phosphate and assesses water quality primarily by permissible-use criteria. They fail to adequately separate orthophosphate, organic phosphorus, phosphate and total phosphorus, and do not correlate these phosphorus fractions with chlorophyll-a, dissolved oxygen and turbidity. This leaves the question of whether the reservoir is undergoing isolated nutrient elevation or a coordinated phosphorus-driven eutrophication process. The aim of this study is to assess the phosphorus fractions and their relationships with the eutrophication response variables in the Alau Reservoir.

## 1. MATERIALS AND METHOD

### 2.1 Study Area

Alau village is located at latitude 11°5' N and longitude 13° 20' E in the Konduga local government area of Borno State, 19 km southeast of Maiduguri in the Sahel savanna region of Nigeria. The River Ngadda, on which the Alau dam was constructed between 1984 and 1986 by the Chad Basin Development Authority (CBDA), is a major tributary of Lake Chad (CBDA, 1998). The River Ngadda originates from the confluence of the River Yedzram and River Gombole at the Sambisa Forest. The Alau reservoir has an estimated catchment area of 9,804.44 km<sup>2</sup> at 329 m above sea level, as shown in Figure 1 (a). It has a maximum depth of 9 m and an estimated surface area of 60 km<sup>2</sup>. The reservoir serves as the primary source of surface water supply for Maiduguri Metropolis and to irrigates over 8,000 hectares of farmland within the catchment area (CBDA, 1998). The climate is Sahelian with three distinct seasons: the cool-dry season (October to March), the hot season (April to June), and the rainy season (July to September). The annual rainfall ranges from 560 to 600 mm. The cold (dry harmattan) season runs from November to March, when temperatures fall to about 20°C, and a dry, dusty wind blows from the Sahara Desert (CBDA, 2018). The area is fragile and highly susceptible to drought, with relative humidity of 16.25% in the dry seasons and 71.15% in the rainy seasons as shown in Figure 1 (b). Scattered settlements across the catchment area, ranging from small rural villages to larger towns. These settlements serve as centers for agricultural activities and residential areas for the local population. Agriculture is the main economic activity in Alau village and its environs. Much of the catchment area is dedicated to agriculture, with fields of crops such as maize, millet, sorghum, rice, and

vegetables. Farmers in the area practice both rainfed and irrigated agriculture, using water from the Alau reservoir for irrigation during the dry season. Livestock rearing, including cattle, sheep, and goats, is also prevalent in the region, and fishing activities also take place in the Alau reservoir (CBDA, 2018).

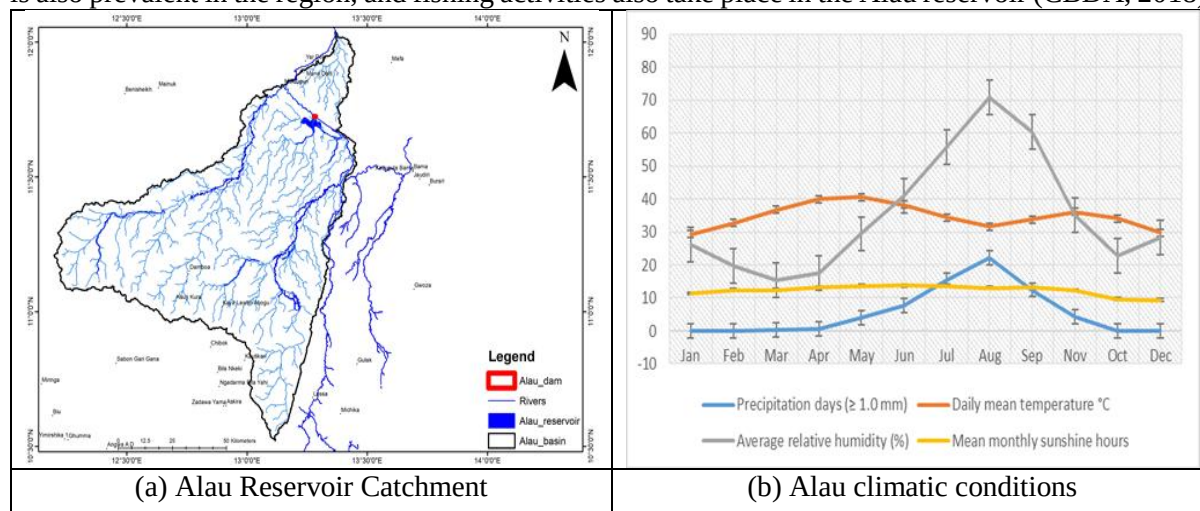


Figure 1: Alau Reservoir Catchment and its Climatic Conditions

## 2.2 Water Sampling and Analysis

Two sampling points were identified in the Alau reservoir based on the accessibility due to insecurity. The Water samples were collected following the standard procedures and protocols of the United States Environmental Protection Agency Laboratory Services and Applied Science Division (USEPA, 2021). The water samples were taken offshore at a depth of 1 m from the surface of the reservoir at two sampling points, SWA1 (13.2852190 E, 11.7229650 N) and SWA2 (13.2831770 E, 11.7181360 N), which are 270 m apart. The sampling was conducted during six selected months (May, June, July, August, September and December 2023) to reflect the seasonal variation. May represented the late dry-season, June-September represented the rainy season, while December represented the post-rainy dry-season condition. Samples were immediately taken to the laboratory for analysis. The water analysis was conducted following American Public Health Association (APHA, 2017) at the Chemistry Analytical Laboratory, Yobe State University, Damaturu, Nigeria. The parameters measured include turbidity, pH, dissolved oxygen (DO), chlorophyll a (CHL-a), orthophosphate (orth-P), organic phosphorus (Org-P) phosphate (P) and total phosphorus (TP). The water temperature, turbidity, pH and DO were measured in situ using TDS & EC meter (E51M0), pH meter, turbidity meter (WG7-B) and DO meter (DO-510) respectively. The CHL-a, orth-P, Org-P, P and TP were measured by the LaMotte colorimeter (SMART3).

## 2.3 Data analysis

Data were analyzed using Microsoft Excel. The overall distribution of the concentration of phosphorus fractions, DO, pH, chlorophyll-a and turbidity in the reservoir was summarized using descriptive statistics; mean and standard deviation. The trends of phosphorus concentration under different scenarios were assessed using Principal Component Analysis (PCA).

## 3. RESULTS AND DISCUSSION

### 3.1 Analysis of Physio-chemical characteristics of the water samples

The Table 1 presents the descriptive statistical analysis of the two sampling sites (SWA1 & SWA2) for the phosphorus fractions and eutrophication response variables in the Alau Reservoir.

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Table 1: Physio-chemical properties of the water samples

| Variable         | SWA1   |        |        |         | SWA2    |         |        |         | USEPA         |
|------------------|--------|--------|--------|---------|---------|---------|--------|---------|---------------|
|                  | Min.   | Max.   | Mean   | Std/dvn | Min.    | Max.    | Mean   | Std/dvn |               |
| Orth-P<br>(mg/L) | 0.0036 | 0.0049 | 0.0043 | 0.0005  | 0.00492 | 0.00661 | 0.0059 | 0.0007  | 0.5-2         |
| Org-P<br>(mg/L)  | 0.12   | 0.19   | 0.1633 | 0.0258  | 0.21    | 0.25    | 0.2308 | 0.0186  | <10           |
| P (mg/L)         | 0.735  | 1.104  | 0.9159 | 0.1312  | 0.913   | 1.097   | 0.9948 | 0.0647  | 0.1           |
| TP (mg/L)        | 0.917  | 1.192  | 1.0442 | 0.1065  | 1.112   | 1.266   | 1.1735 | 0.0662  | 0.5-1.5       |
| pH               | 6.23   | 6.78   | 6.5850 | 0.2249  | 6.24    | 6.92    | 6.6833 | 0.2682  | 6.5-8.5       |
| DO<br>(mg/L)     | 4.03   | 6.85   | 5.0567 | 0.9967  | 4.02    | 6.35    | 4.9433 | 0.8369  | 5-8           |
| Chl-a<br>(µg/L)  | 0.27   | 0.382  | 0.3220 | 0.0393  | 0.37    | 0.47    | 0.4233 | 0.0398  | 1.9-<br>12.35 |
| Turb<br>(NTU)    | 6.23   | 7.82   | 7.0383 | 0.5800  | 6.41    | 7.8     | 7.0683 | 0.5826  | 5-30          |

Orth-P – Orthophosphate, Org-P - Organic phosphorus, P – Phosphate, TP - Total phosphorus, DO - Dissolved oxygen, Chl\_a – Chlorophylla, Turb. – Turbidity

The mean concentration of phosphate at SWA1 was 0.9159 mg/L, and total phosphorus was 1.044 mg/L. At SWA2, the mean concentration of phosphate was 0.995 mg/L, and total phosphorus was 1.174 mg/L. The values indicate that the phosphorus load in SWA2 was greater than in SWA1. The high total phosphorus concentrations reflect a high nutrient pool, which can support current and future algal growth, as total phosphorus encompasses all forms of dissolved, particulate, organic and inorganic phosphorus. The phosphate values are also worthy of consideration as phosphate is closely associated with the availability of nutrients for aquatic primary producers. The mean concentrations of orthophosphate were low at both sampling points, 0.004 mg/L at SWA1 and 0.006 mg/L at SWA2. These values are small on their own, but do not diminish the eutrophication concern due to the high phosphorus pool. The mean concentration of organic phosphorus was also higher at SWA2 (0.231 mg/L) than at SWA1 (0.163 mg/L). Sources of organic phosphorus include decomposing plant material, animal wastes, domestic inputs, soil particles and sediment-associated organic matter. It can subsequently be mineralised to inorganic phosphorus by microorganisms. Therefore, the organic phosphorus result indicates that there is a greater pool of phosphorus in SWA2 that can continue to support eutrophication even after the immediate dissolved forms are consumed by algae. The findings are similar to previous Nigerian reservoir studies that have classified trophic status based on phosphorus enrichment and chlorophyll-a response. Ayoade and Aderogba (2020) reported that the total phosphorus and chlorophyll-a values were above the criteria for eutrophication.

The dissolved oxygen results also indicate concern for ecological stress, with a mean dissolved oxygen concentration of 5.057 mg/L at SWA1 and 4.943 mg/L at SWA2. Higher mean phosphorus and higher chlorophyll-a are associated with the lower oxygen value at SWA2. Algal biomass can increase following the addition of phosphorus in nutrient-rich reservoirs, and the subsequent decomposition of the biomass can deplete oxygen. The minimum values of approximately 4.0 mg/L at both sampling locations indicate that oxygen stress may occur, particularly during warm, stagnant or organically enriched periods. This is consistent with the overall limnological knowledge that nutrient enrichment can lead to increased algal biomass, which can then lead to decreased oxygen due to respiration and decomposition (Wurtsbaugh *et al.*, 2019.). The mean chlorophyll-a value was 0.322 µg/L at SWA1 and 0.423 µg/L at SWA2. The sampling point with the highest phosphorus enrichment, however, still had a higher mean chlorophyll-a concentration than SWA1, and the algal-biomass signal was stronger. The same findings were reported by Ahmed and Ibrahim (2024) who found that the abundance of phytoplankton in Lake Alau was influenced by nutrient concentration, physicochemical factors and season. The turbidity was found to be similar at both points with mean value of 7.038 at SWA1 and 7.068 at SWA2, indicating similar conditions of suspended material or light attenuation.

### 3.2 PCA Eigenvalues of phosphorus in Alau reservoir

The first two components explained 77.57% and 87.29% of the total variance at SWA1 and SWA2, respectively, indicating that they adequately summarized the relationships among phosphorus fractions and water-quality variables as presented in Table 2.

Table 1: PCA Eigenvalues of phosphorus fractions in Alau reservoir

| SWA1            | F1     | F2     | F3     | F4     | F5      |
|-----------------|--------|--------|--------|--------|---------|
| Eigenvalue      | 3.454  | 2.752  | 1.585  | 0.190  | 0.019   |
| Variability (%) | 43.177 | 34.395 | 19.817 | 2.372  | 0.239   |
| Cumulative %    | 43.177 | 77.572 | 97.389 | 99.761 | 100.000 |
| SWA2            |        |        |        |        |         |
| Eigenvalue      | 4.858  | 2.125  | 0.716  | 0.200  | 0.101   |
| Variability (%) | 60.726 | 26.562 | 8.951  | 2.497  | 1.265   |
| Cumulative %    | 60.726 | 87.288 | 96.239 | 98.735 | 100.000 |

The first principal component (F1) at SWA1 accounted for 43.18% of the variance and the second principal component (F2) accounted for 34.40% of the variance, for a total of 77.57%. This suggests that several environmental processes affect phosphorus fractions and eutrophication variables, not just one. The third component (19.82%) also had an eigenvalue greater than 1, the Kaiser criterion, indicating the presence of another, but less influential, ecological process as indicated in Table 2. The results are consistent with those of Jolliffe & Cadima (2016) who found that PCA is most useful when the first two principal components account for over 70% of the total variance, enabling the environmental gradients to be interpreted. At SWA2 much higher first component (60.73%) and F2 (26.56%) for a total of 87.29% cumulative variance. The higher percentage accounted for by F1 suggests that water quality at SWA2 is more strongly influenced by a single nutrient-enrichment gradient, suggesting greater coupling between the availability of phosphorus and biological response than at SWA1. Likewise, Wurtsbaugh *et al.* (2019) noted that eutrophication of reservoirs often have a dominant nutrient component, with phosphorus, algal biomass and oxygen dynamics being connected. The descriptive statistics indicated that the concentration of organic phosphorus, soluble phosphorus and total phosphorus were higher at SWA2 than at SWA1, which is consistent with the higher cumulative variance at SWA2.

### 3.3 PCA Factor Loadings for phosphorus fractions in Alau reservoir

The PCA factor loading patterns at SWA1 and SWA2 reveal that nutrient dynamics in Alau are driven by seasonal hydrology as presented in Table 3.

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Table 3: PCA Factor Loading for phosphorus fractions in Alau Reservoir

| SWA1  | F1     | F2     | F3     | F4     | F5     |
|-------|--------|--------|--------|--------|--------|
| OTH-P | -0.479 | -0.522 | 0.697  | 0.110  | 0.019  |
| Org-P | -0.615 | -0.454 | 0.642  | 0.052  | -0.028 |
| P     | 0.768  | 0.267  | 0.550  | -0.190 | 0.007  |
| TP    | 0.819  | 0.176  | 0.544  | -0.040 | -0.010 |
| pH    | 0.620  | 0.727  | 0.159  | 0.246  | -0.035 |
| DO    | -0.480 | 0.850  | 0.111  | 0.185  | 0.036  |
| Chl-a | 0.774  | -0.607 | -0.069 | 0.134  | 0.101  |
| Turb. | -0.610 | 0.743  | 0.216  | -0.157 | 0.072  |
| SWA2  |        |        |        |        |        |
| OTH-P | 0.597  | -0.735 | 0.283  | 0.036  | -0.149 |
| Org-P | 0.937  | -0.296 | 0.170  | -0.006 | 0.073  |
| P     | 0.797  | 0.417  | 0.426  | -0.051 | -0.077 |
| TP    | 0.514  | 0.799  | 0.272  | 0.150  | 0.024  |
| pH    | -0.670 | 0.699  | 0.094  | -0.210 | -0.096 |
| DO    | -0.783 | -0.266 | 0.520  | -0.089 | 0.194  |
| Chl-a | 0.900  | 0.344  | -0.223 | 0.061  | 0.136  |
| Turb. | -0.923 | 0.083  | 0.149  | 0.343  | -0.038 |

The highest positive loadings for F1 were total phosphorus (0.819), chlorophyll-a (0.774) and phosphate (0.768), which suggests that F1 is the gradient of phosphorus enrichment and algal productivity. The biological expression of nutrient enrichment was also observed as the concentration of phosphorus increased, so did the concentration of chlorophyll-a. On the other hand, organic phosphorus (-0.615), turbidity (-0.610) and orthophosphate (-0.479) were negatively loaded on F1, indicating that these variables are associated with a different environmental process, which may be associated with the decomposition of organic matter and transport of sediment-associated phosphorus as indicated in Table 3. This separation suggests that there are several biogeochemical forms of phosphorus in SWA1, each having a different transport mechanism. Similarly, Ayoade & Aderogba (2020) reported a positive relationship between total phosphorus and chlorophyll-a in a tropical reservoir in Nigeria, which is consistent with eutrophic interpretation. Dissolved oxygen (0.850), turbidity (0.743) and pH (0.727) dominated the second component (F2). This component is not nutrient enrichment, but physical–chemical regulation. The negative loading of chlorophyll-a (-0.607) may indicate that algal biomass increases when dissolved oxygen levels are low due to respiration and decomposition, while high dissolved oxygen and turbidity may be associated with inflow-induced mixing during rainy periods. These observations are similar to those reported by Paerl *et al.* (2020) that phosphorus enrichment leads to algal growth, and that subsequent decomposition leads to increased biological oxygen demand and decreased dissolved oxygen.

The PCA at SWA2 revealed a much clearer eutrophication pattern as the first component was dominated by organic phosphorus (0.937), chlorophyll-a (0.900) and phosphate (0.797), while turbidity (-0.923) and dissolved oxygen (-0.783) showed strong negative loadings. This means that F1 is an active eutrophication gradient, where the more phosphorus enriched the more algal biomass and the less dissolved oxygen. The highest loading was for organic phosphorus (0.937), indicating that it is an important reserve nutrient pool that can support eutrophication following mineralization. This is consistent with the results of Han *et al.* (2017) who found that organic phosphorus in sediments and suspended particles is a significant source of long-term phosphorus availability in reservoirs. The negative correlation between turbidity and chlorophyll-a indicates that the clearer the water, the more likely algae will grow due to better light penetration. The same was found by Fabian *et al.* (2023) in Lake Alau, where a decrease in suspended sediments during the season was correlated with an increase in phytoplankton. Total phosphorus (0.799) and pH (0.699) were the main factors in the second component (F2). This component is probably a reflection of the chemical environment affecting the

availability of phosphorus. Increased pH can also increase the release of phosphorus from sediments and can also be associated with high photosynthetic activity due to the removal of carbon dioxide, which is well documented in eutrophic lakes (Smith & Schindler, 2009). Overall, SWA2 shows a higher ecological connection between phosphorus compounds and eutrophication indicators than SWA1, which is consistent with the fact that it is the more environmentally sensitive part of Alau Reservoir.

### 3.4 Interactions between Phosphorus fractions and eutrophication variables

The correlation circles for SWA1 and SWA2 illustrate the relationships between orthophosphate, organic phosphorus, phosphate, total phosphorus, pH, dissolved oxygen, chlorophyll-a and turbidity on the first two principal component axes as shown in Figure 2. The principal component analysis correlation circle show variables in the same direction as positively associated, in opposite directions are negatively associated, and lying at almost right angles have weak relationships. The length of each vector is also important, as the first two axes are strongly represented by variables near the outer circle.

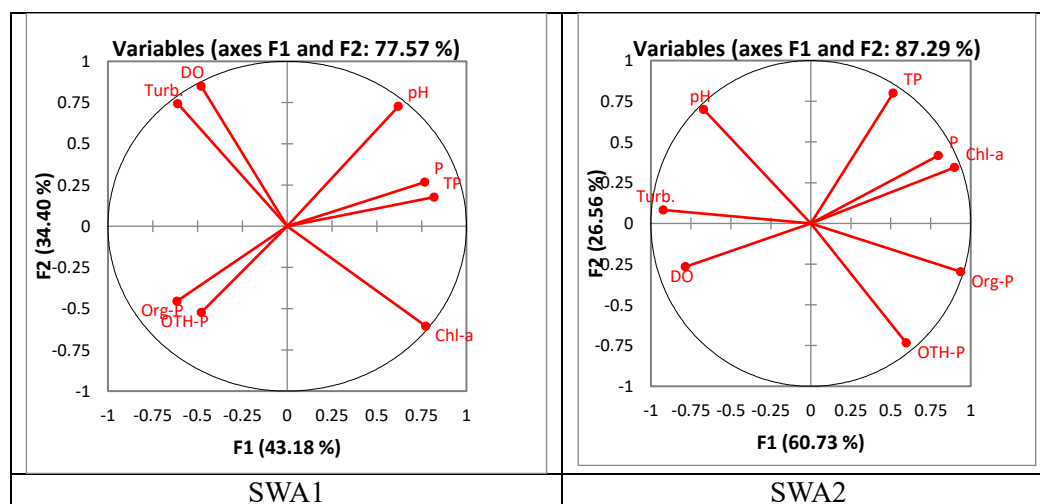


Figure 2: Correlation circles for phosphorus fractions and eutrophication variables

At SWA1, the first two axes explain 77.57% of the total variation, with F1 account for 43.18% and F2 is 34.40%. This implies that the correlation circle provides a good summary of the primary physicochemical and eutrophication relationships at this sampling location. The strongest positive association is seen in SWA1, where phosphate and total phosphorus are grouped together on the positive side of F1. This suggests that phosphate is a significant component of the total phosphorus pool at SWA1. The first two axes account for 87.29% of the total variation in SWA2, with F1 and F2 explaining 60.73% and 26.56% respectively. This is more than the SWA1 plot can explain, and the SWA2 correlation circle provides an even better summary of the measured water quality variables. The high proportion of F1 also indicates that a more powerful common environmental gradient influences SWA2. Orthophosphate and organic phosphorus constitute another group at SWA1, both vectors are directed towards the lower left side of the circle, away from the other vectors, phosphate, total phosphorus, pH and chlorophyll-a. The correlation matrix shows a very strong positive correlation between them, which is reflected in their proximity. This clustering indicates that orthophosphate and organic phosphorus could have a similar source or transformation pathway at SWA1. They can be associated with organic matter decomposition, soil run-off, domestic inputs, sediment interaction or microbial mineralisation. Their direction of flow is opposite to that of phosphate and total phosphorus, however, and they do not follow the same pattern as the larger group. This indicates that the phosphorus system at SWA1 is not homogeneous. The various phosphorus fractions may originate from various sources or react differently to physical and chemical conditions in the reservoir. The results are consistent with Ayoade & Aderogba (2020) who reported positive correlation between total phosphorus and chlorophyll-a in a tropical reservoir in Nigeria, which is consistent with eutrophic interpretation.

Organic phosphorus and orthophosphate are also positive at SWA2, but they are pointing down. They are directed towards the phosphorus-enrichment side of the system, but are not the same as total

phosphorus and phosphate in their F2 behaviour. Organic phosphorus is near the right side of the circle, indicating that it is well represented by the first two components. This suggests that organic phosphorus plays an important role in the SWA2 nutrient structure. Organic phosphorus can be mineralised by microorganisms to more available inorganic forms, and can therefore serve as a nutrient pool that can continue to contribute to eutrophication. At SWA1, the position of chlorophyll-a is moderately positively related to total phosphorus and phosphate. This implies that there is some biological expression of the phosphorus enrichment at SWA1, albeit not a direct one. This is ecologically sound because algal growth is not solely dependent on phosphorus. Other factors that affect chlorophyll-a concentration include light penetration, water residence time, water mixing, grazing, and nitrogen availability and turbidity. The phosphorus concentration thus suggests high eutrophication potential, and the chlorophyll-a concentration suggests that the biological response may be partly influenced by other environmental factors. The most important pattern at SWA2 is the group of phosphate, total phosphorus and chlorophyll-a on the right side of the correlation circle. Phosphate and chlorophyll-a are grouped tightly together, and total phosphorus is in the same general direction. This indicates that the enrichment of phosphorus at SWA2 is more closely linked to algal biomass than at SWA1. In the same way, Dadin Kowa Reservoir was recently studied by Usman *et al.* (2025) and it was found that the enrichment of N and P in the reservoirs in Nigeria can be seasonal and site-specific, thus supporting the use of SWA1 and SWA2 separately rather than as a single water body. It implies that the enrichment of phosphorus at SWA2 is not only chemical but also biological, as evidenced by the increase in chlorophyll-a. Since eutrophication is a process of nutrient loading and algal production, studies of reservoir trophic state typically include nutrient enrichment as well as biological response variables like chlorophyll-a and transparency.

The dissolved oxygen at SWA2 is a very important position that shows a negative correlation between dissolved oxygen and the eutrophication related variables. This pattern indicates that as chlorophyll-a and phosphorus levels increase, oxygen levels decrease at SWA2. This is one of the most significant indicators of eutrophication stress as algal growth and decomposition of organic matter can lead to increased oxygen demand and decreased dissolved oxygen. The chlorophyll-a and the dissolved oxygen-turbidity group are the strongest ecological contrast at SWA1. Dissolved oxygen and turbidity are grouped together in the upper left quadrant of the circle, and chlorophyll-a is grouped together in the lower right quadrant of the circle. The relationship between chlorophyll-a and dissolved oxygen is strongly negative, as is the relationship between chlorophyll-a and turbidity. The negative correlation with turbidity indicates that suspended materials could limit light penetration and algal growth at some times. Therefore, SWA1 seems to be highly available for phosphorus, but the strength of this nutrient enrichment to generate algal biomass may be controlled by turbidity and oxygen conditions (Fabian *et al.*, 2023).

The location of pH near phosphate and total phosphorus also provides a valuable chemical interpretation at SWA1. The pH values are generally in the same direction as the phosphate and total phosphorus values, particularly in the positive direction of the F1 axis. This pattern agrees with the positive correlations between pH and phosphate, and between pH and total phosphorus. It indicates that the higher the concentration of phosphorus at SWA1, the higher the pH. This can be a sign of increased photosynthetic activity in nutrient-rich waters, as algal photosynthesis consumes carbon dioxide from the water and can increase the pH. But pH is not on the same vector as phosphate and total phosphorus, and should not be considered as the same process. It is more correctly viewed as a supportive chemical state associated with nutrient behaviour and potential algal activity. The pH and turbidity vectors at SWA2 are opposite to the direction of phosphate and chlorophyll-a. The pH is in the upper left quadrant and turbidity is closer to the negative F1 axis. This indicates that pH and turbidity are negatively associated with the nutrient and chlorophyll-a group at SWA2. The negative correlation between turbidity and chlorophyll-a indicates that algal growth may be promoted by clearer water conditions, and algal growth may be inhibited by more turbid water conditions due to reduced light penetration. Turbidity can also be an indicator of suspended sediment and runoff inputs, however. It can decrease algal growth at one time and carry particle-bound phosphorus into the reservoir at another time. The pH pattern also indicates that the various fractions of phosphorus may react differently to the chemical conditions (Jolliffe & Cadima, 2016).

### 3.5 Temporal variations of the Phosphorus fractions and eutrophication variables

The principal component analysis biplots for SWA1 and SWA2 represent the measured water quality variables and the sampling months as shown in Figure 3. In this type of biplot, a month near the direction of a variable is typically correlated with relatively high values of that variable. A month on the other side of a variable is correlated with relatively lower values. A month near the centre indicates more average conditions, and a month far from the centre indicates stronger departure from the average water quality condition.

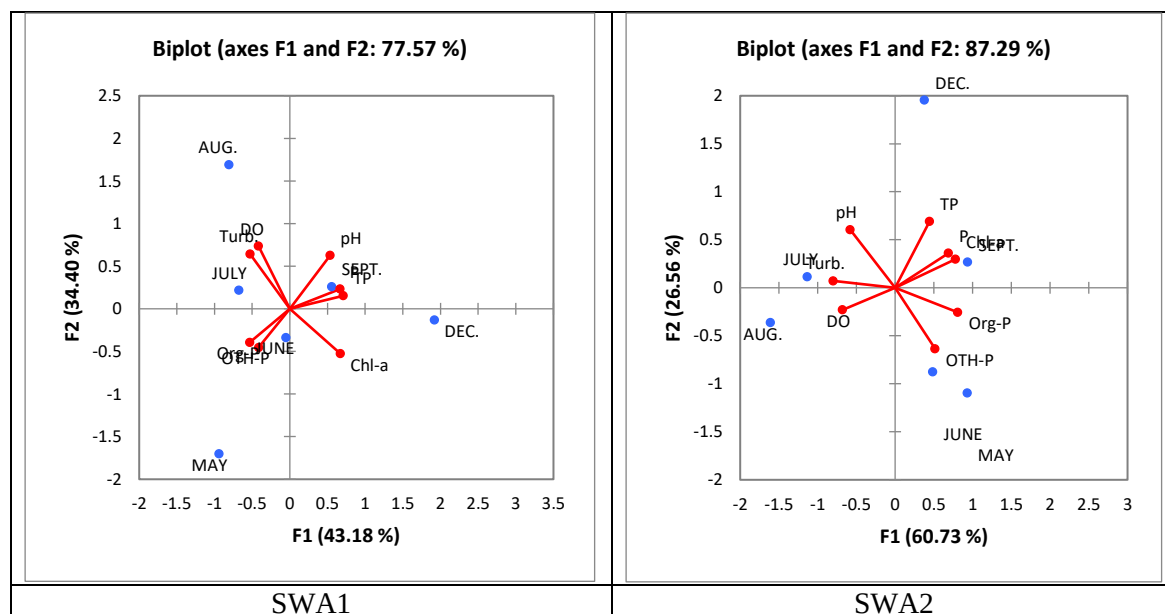


Figure 3: Biplots for phosphorus fractions and eutrophication variables

The positions of dissolved oxygen and turbidity at SWA1 biplot show a different environmental condition. August is located close to dissolved oxygen and turbidity, while July is also on the left side near turbidity as shown in Figure 3. This suggests that these months were more strongly associated with oxygenated and turbid conditions at SWA1. This pattern can be indicative of inflow, mixing or suspended particle transport. Light penetration may be affected by turbidity, which may be a partial reason for the negative relationship between chlorophyll-a and turbidity. Simply put, as water becomes more turbid, light may be less available for algal photosynthesis, even in the presence of phosphorus. This is why the formation of algal blooms is not always observed at each sampling time when phosphorus enrichment occurs. General trophic assessment is based on the combination of total phosphorus, chlorophyll-a and measures related to transparency, since eutrophication is a combination of nutrient pressure and biological response, not just nutrient concentration (USEPA, 2021). May is in the lower left corner of the SWA1 biplot, near orthophosphate and organic phosphorus. This indicates that May was more closely related to the orthophosphate and organic phosphorus fractions than to the larger group of phosphate-total phosphorus. The position of May is important because organic phosphorus can act as a reserve nutrient fraction. It can later be transformed into more accessible inorganic forms by microbial decomposition. The clustering of orthophosphate and organic phosphorus in this section of the biplot thus indicates that SWA1 may be supplied with phosphorus from organic matter inputs, decomposition of aquatic organic matter, or from organic particles or sediment associated processes from runoff. The biplot indicates that the phosphorus system at SWA1 is not monodirectional with respect to phosphate and total phosphorus, suggesting that there is more than one source or transformation pathway for phosphorus (Fabian *et al.*, 2023).

September and December are on the positive side of F1 at SWA1, and are more related to the phosphorus enrichment side of the biplot. September is close to phosphate, total phosphorus and pH, and December is far to the right and slightly below the F1 axis. This indicates that these months are more strongly associated with nutrient-rich conditions than May, July or August. September is close to the phosphate and total phosphorus, indicating a time when phosphorus loading increased. The F1 position for December is also very positive, indicating a strong departure from the average position, but

it is also separated from the main phosphorus arrows, so it may not be explained by phosphorus alone. The month-to-month variation is important in eutrophication assessment because water quality in reservoirs can vary with inflow, runoff, dilution, evaporation, sediment disturbance, and biological uptake. June is near the centre of the SWA1 biplot, indicating that it is a more average month than the others. June was not strongly dominated by any one water quality factor, as it does not correlate well with any variable. This is helpful because it indicates that the eutrophication condition in SWA1 is not consistent throughout the month. Rather, the sampling point alternates between an organic phosphorus condition, a turbidity-oxygen condition and a phosphate-total phosphorus condition. This is consistent with the previous PCA eigenvalue interpretation, which indicated that SWA1 had three meaningful components. The water quality structure at SWA1 is therefore more mixed, and the interaction between phosphorus enrichment and physical and chemical controls is more complex (Usman *et al.*, 2025).

September is near to phosphate and chlorophyll-a, the most obvious indicators of eutrophication risk, at SWA2 biplot. It suggests that September was associated with higher phosphate and higher algal biomass at SWA2 as shown in Figure 3. Phosphate is a direct nutrient for algal growth and chlorophyll-a is a measure of algal biomass, so their close association suggests an active nutrient-biological response. This is in line with the studies conducted on reservoirs in Nigeria, which indicated that the trophic state of the reservoirs was assessed using the total phosphorus, chlorophyll-a and Secchi disc transparency, which were found to be higher than the criteria used to interpret eutrophic condition, and the abundance of green algae and blue-green algae confirmed this (Ayoade & Aderogba, 2020). The SWA2 biplot thus indicates that the enrichment of phosphorus at this sampling site is not only a chemical problem, but also associated with algal productivity. The December is positioned high on F2 at SWA2 and close to the direction of total phosphorus. This indicates that December was highly correlated with total phosphorus enrichment, but not as closely correlated with chlorophyll-a as September. This is important because total phosphorus is composed of dissolved, particulate, organic and inorganic phosphorus. A high total phosphorus association can thus be a sign of a high nutrient pool that can be utilized for subsequent algal growth, even if all of the phosphorus is not available to algae at the time of sampling. The December position may thus be a nutrient-storage or nutrient-loading situation, and September a more direct phosphorus-chlorophyll response. The monthly biplot results are consistent with the findings of (Usman *et al.* (2025) which indicated that nutrient enrichment and eutrophication risk in Dadin Kowa Reservoir was different among sampling points and seasons, and hydrological conditions influenced the nitrogen and phosphorus dynamics.

The SWA2 biplot shows the May and June in the lower right corner, near orthophosphate and organic phosphorus. This suggests that these months were more related to these phosphorus fractions. Organic phosphorus is particularly important because it may originate from organic wastes, decaying biomass, aquatic vegetation, animal inputs or sediment-associated materials. It may later be a source of eutrophication following mineralisation. Orthophosphate, however, is a more readily available form for algal uptake. The presence of May and June therefore indicates that SWA2 had a large reservoir of phosphorus forms that could support eutrophication beyond the one sampling period. This is consistent with the descriptive statistics, which showed that SWA2 had a higher mean organic phosphorus and orthophosphate than SWA1. July and August are located on the left side of the SWA2 biplot, near turbidity, dissolved oxygen and in part pH. This indicates that these months were more related to physical disturbance and oxygenated conditions than to chlorophyll-a and phosphorus enrichment. The July data is closest to turbidity, the August data is farther left and below the F1 axis, closer to the oxygen side of the plot. Although the reservoir is generally considered to be a phosphorus-rich system, the turbidity data indicates that periods of higher turbidity may have resulted in less light available for algal growth, and thus less algal biomass. The direction of dissolved oxygen is also against chlorophyll-a and phosphate, which further supports the interpretation that oxygen decreases with increasing algal biomass and nutrient enrichment. This is a typical eutrophication process as the demand for oxygen rises due to algal respiration and organic matter decomposition (Usman *et al.*, 2025).

#### 4. CONCLUSION

This study showed that the reservoir is highly enriched with phosphorus, and that the total phosphorus and phosphate levels suggest a high eutrophication potential. The temporal assessment revealed that the nutrient enrichment was not consistent across the sampling months, suggesting that seasonal processes affect nutrient dynamics in the reservoir. The principal component analysis showed that the water quality variation was significantly influenced by nutrient related processes at SWA1 and SWA2. The higher nutrient-biological relationship found at SWA2 suggests that this sampling site is more susceptible to eutrophication development. The dissolved oxygen levels were below acceptable guideline range as observed at SWA2 indicates increasing oxygen stress due to organic matter decomposition and biological activity. The PCA biplot analysis indicated that December was strongly correlated with total phosphorus enrichment, and September was more strongly correlated with phosphate and chlorophyll-a, indicating periods of greater biological response and eutrophication pressure. The correlation between phosphorus compounds and chlorophyll-a, and the negative correlation between chlorophyll-a and dissolved oxygen, suggest that nutrient enrichment has started to affect the ecological conditions in the reservoir. The Alau Reservoir is vulnerable to eutrophication because of high levels of phosphorus and seasonal changes in nutrient levels. The results indicate the need to shift from general water quality assessment to continuous nutrient monitoring programs that account for the various fractions of phosphorus, algal response and oxygen dynamics. Proper management of nutrient sources entering the reservoir is required to ensure the ecological health of the reservoir and its suitability for domestic, agricultural and fishery uses.

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