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Original Research

Geochemical Fractionation and Internal Loading of Phosphorus in Urban Lake Sediments in Coimbatore, Tamil Nadu, India

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Abstract: Phosphorus (P) is released from sediments primarily through the reduction of iron (Fe^{3+}) oxides under anoxic conditions, which dissolves Fe-bound phosphorus and increases dissolved P in lake water. This study aimed to quantify the major sedimentary phosphorus fractions and evaluate their ecological risks in Krishnampathy and Singanallur lakes in urban Coimbatore during the post-monsoon season. The sequential extraction method was used to analyze loosely sorbed exchangeable P (NH_4Cl-P), redox-sensitive P (Fe-P), metal oxide-bound P (NaOH-P), calcium-bound P (HCl-P), residual P (Res-P), and total phosphorus (TP). Fe-P and NaOH-P were found to be the dominant fractions in both lakes. Principal component analysis (PCA) was performed as an exploratory tool to examine the relationship between P fractions and sediment characteristics. Pollution levels were assessed using the Single Pollution Index (SPI), with values of 2.07 for Krishnampathy and 2.14 for Singanallur, indicating serious pollution in both lakes. Surface water phosphorus concentrations were comparatively lower, while the distribution of HCl-P and Fe-P was influenced by environmental and geochemical factors. The findings indicate that both lakes are at risk of eutrophication. Identifying sedimentary P sources and assessing ecological risks are essential for effective restoration and management of these polluted water bodies.

1. INTRODUCTION

The most important variable in controlling primary productivity in aquatic environments is phosphorus (P). Phosphorus appears in the bottom sediments and water column of lakes, where it is constantly changing and transforming (Xie et al., 2019). Climate change and humans worsen water scarcity, with the United Nations projecting a 40% shortfall in freshwater availability by 2030 if current trends continue (UN-Water, 2023). Lakes and wetlands, essential freshwater sources, are under growing threat from eutrophication caused by phosphorus enrichment from agriculture and urban runoff, resulting in biodiversity loss and ecosystem disruption (Sharpley et al., 2013; Zhang et al., 2016; Wu and Wang, 2017; Maykoll et al., 2019).

Lakes are vital freshwater ecosystems that provide essential services, including water storage, biodiversity support, climate regulation, and recreation. However, they are vulnerable to nutrient loading and sediment changes (Mitsch and Gosselink, 2015; Rutledge and Chow-Fraser, 2019). Over 70% of surface water is polluted, primarily due to agricultural and industrial runoff (CWC, 2023). The government has prioritized rejuvenating lakes and wetlands as part of sustainable water management, recognizing their role in climate regulation and biodiversity conservation (MoEFCC, 2023). Freshwater systems, including rivers and wetlands, help regulate climate, cycle nutrients, and support economic and food security. They are threatened by pollution, overextraction, and climate change, highlighting the need for sustainable management (Falkenmark and Rockström, 2004; Dingman, 2015; Yuan et al., 2019; Camargo et al,2025).

Sediments are formed through natural processes and play a vital role in aquatic ecosystems by influencing pollutant transport and concentration in water bodies (Joshi et al., 2015; Dang et al., 2017; Wang et al., 2021). Phosphorus is stored in sediments during deposition and released at specific physicochemical conditions, including oxygen depletion, pH variations, and oxidation change. Accumulating in lakes and riverbeds, sediments can release pollutants, affecting water quality even after external sources are controlled (Dhanakumar et al., 2015; Helfenstein et al., 2018; Zhaokui et al., 2020). They also serve as records of environmental history, providing insights into past climatic conditions, ecosystem dynamics, and human activities, which are essential for understanding climate change effects, detecting pollutants, and assessing land use changes (Hupfer et al., 2019; Heinrich et al., 2021). Lakes, as dynamic ecosystems, are pivotal in global nutrient cycles, especially phosphorus. Eutrophication is a major ecological concern caused by untreated sewage, agricultural runoff, and other human activities, leading to increased phosphorus levels (Parsons et al., 2017; Dhanakumar and Mohanraj, 2019). This process affects about 30-40% of the world's freshwater lakes and reservoirs (UNEP, 2016). Its impacts include biodiversity loss, habitat degradation, declines in fisheries, reduced food security, and economic challenges (Carpenter et al., 1988; Scheffer et al., 2001). Furthermore, eutrophication promotes harmful algal blooms, which pose significant health risks and economic costs (Dodds, 2002; Paerland Otten, 2013; Wilfert et al., 2018).

Phosphorus diffusion between sediments and the water surrounding them is an essential process controlling internal nutrient flow. Nutrient enrichment alters phytoplankton composition, disrupts food webs, and reduces ecosystem resilience (Smith et al., 1999; Walpersdorf et al., 2013). Excess nutrients, especially nitrogen and phosphorus from agricultural practices, worsen eutrophication, causing harmful algal blooms and ecological imbalances (Anderson et al., 2002; Galloway et al., 2003; Dhanakumar and Mohanraj, 2013). Phosphorus in lake sediments exists in various organic and inorganic fractions, each affecting its bioavailability and mobility (Kraal et al., 2017; Xiancang et al., 2023). Sediments serve as both a sink and a source of phosphorus, contributing to internal loading that maintains eutrophic conditions even after external inputs decline (Lijklema et al., 1993; Sondergaard et al., 1996; Rippey et al., 2021). Biogeochemical processes such as redox changes and pH variations influence phosphorus release, while climatic factors like temperature and hydrological changes further affect its dynamics (Roberts, 2015; Saar et al., 2022). For this study, understanding these interactions is essential for developing effective strategies to mitigate eutrophication and improve water quality (Wang et al., 2019). Eutrophication is a major challenge in lake management worldwide, primarily driven by human activities like agricultural runoff and urbanization, which increase phosphorus loading in aquatic systems, causing algal blooms due to nutrient enrichment, which increases when iron- and manganese-bound phosphorus (Fe-P and NaOH-P) are released back into the water column when bottom waters are anoxic (Paerl and Otten, 2013; Huang et al., 2019; Lepori and Huang, 2019)

Chemical fractionation involves a series of extraction steps that depend on how different solid phases react to various extractant solutions (Voegelin et al., 2013). Among the phosphorus fractions, NH_4Cl-P serves as a short-term indicator of phosphorus availability for aquatic organisms (Ajmal et al., 2018). NaOH-P is released into the water column under anaerobic conditions induced by eutrophication, whereas sediment-bound phosphorus is considered a long-term sink for phosphorus (Gérard, 2016). HCl-P indicates phosphorus bound to organic matter, which can be released through microbial activity. Changes in redox conditions can mobilize phosphorus from its long-term storage pool, bound to metal oxides (Li et al., 2015; Barik et al., 2016). TP, encompassing both organic and inorganic fractions, is used to evaluate the overall phosphorus levels in sediments and their influence on nutrient levels in the water column (Turner et al., 2003; Reddy et al., 2008). The effective lake management and restoration methods require a thorough understanding of these processes, as phosphorus dynamics and water quality are greatly influenced by both internal loading from sediments and external loading from catchment run-off. This study aims to examine the relationships between various Phosphorus (P) fractions and the physico-chemical properties of lake sediments.

2. MATERIALS AND METHODS

2.1. Description of study area

Coimbatore is the most important industrial town in South India. It lies between 10°55' and 11°10' N latitude and 77°50' and 76°50' E longitude at about 470 meters above sea level. It is located along the Noyyal River and is surrounded by the Western Ghats, with around 28 wetlands fed mainly by the Noyyal River. Sediment samples were taken from two wetlands, Krishnampathy Lake and Singanallur Lake. Krishnampathy Lake, situated in the western part of Coimbatore, covers 61 acres and is part of a series of lakes connected to the Noyyal River. Singanallur Lake, located in Singanallur, spans 1.153 km^2 with an average depth of 4.25 meters. It is divided into two halves: the southern half receives rainwater, while the northern half handles urban and industrial waste (Figure 1).

2.2. Sediment sampling and analysis

A total of ten sediment samples were collected from each of the Krishnampathy and Singanallur lakes during the post-monsoon season of 2023. The top sediment layer, approximately 5 cm thick and located beneath a water depth of about 20 cm, was collected using a spade, packed in pre-washed polyethene bags and bottles, and promptly transported to the laboratory. The sediment samples were shade-dried at room temperature, ground, and sieved through a 2 mm mesh. The sieved samples were then oven-dried at 108°C overnight to remove moisture content. A 1:5 sediment-to-water suspension was used to measure pH, electrical conductivity (EC) using potentiometry, alkalinity using titration with 0.02 N sulfuric acid using phenolphthalein as an indicator (APHA 2320 B) and chloride concentration was determined by argentometric in sediment samples, which are reported as mg/L of extract solution following aqueous extraction, and do not represent bulk sediment chloride content (APHA 4500-Cl-B, 2017). Calcium and magnesium were analyzed by complexometric titration using the Versanate (EDTA) method. The Walkley and Black (1934) method was used to estimate total organic carbon (TOC), and the total nitrogen (TN) method was employed by Jackson et al. (1958).

The alkaline permanganate method was used to measure the amount of Ammonical nitrogen. Olsen's method with sodium bicarbonate solution (pH 8.5) was used to extract the available phosphorus, and the ascorbic acid method was used to measure it spectrophotometrically. In contrast, total phosphorus was determined by the molybdenum blue colorimetry method following perchloric acid digestion (Grimshaw, 1987). A flame photometer was used to determine total potassium, extracted using hydrochloric acid, and the available potassium extracted with neutral ammonium acetate. The cation exchange capacity (CEC) was analyzed using the ammonium acetate method by Raman and Sathiyanarayanan (2009).

2.3. Multivariate Statistical Analysis

Sediment was identified using the SPSS 20 version (IBM Corp, Released, IBM SPSS Statistics for Windows, Version 22.0, NY; IBM Corp). Multivariate statistical techniques, including descriptive statistics and Principal component analysis.

2.4. Sequential extraction method

Phosphorus in various forms, including readily available, organic, and mineral-bound phosphorus, can be more easily assessed in terms of soil fertility and environmental risks, such as eutrophication. The sequential extraction method is a laboratory technique that separates various phosphorus (P) fractions in sediment using different chemical reagents. This method, initially developed by Psenner et al. (1984) and later modified by Hupfer et al. (1995), enhances the extraction process to increase phosphorus fractionation accuracy. One gram (1g) of dry sediment was weighed and placed in a conical flask. 25 ml of 1 M NH_4Cl was added, and the mixture was shaken for 2 hours. The solution was then transferred to a centrifuge tube and centrifuged at 8000 RPM for 10 minutes. 10 ml of the supernatant was collected, to which 2 mL of chloromolybdic boric acid and a few drops of chlorostannous reductant were added. After 10 minutes, a blue colour developed, which was then analyzed spectrophotometrically at 690 nm. The same procedure was followed for all subsequent extractants, with variations in shaking time of 1M NH_4Cl for 2 hours, 0.11M $Na\text{-}HCO_3/Na_2S_2O_4$ for 1 hour, 0.1M NaOH and 0.5M HCl for 16 hours.

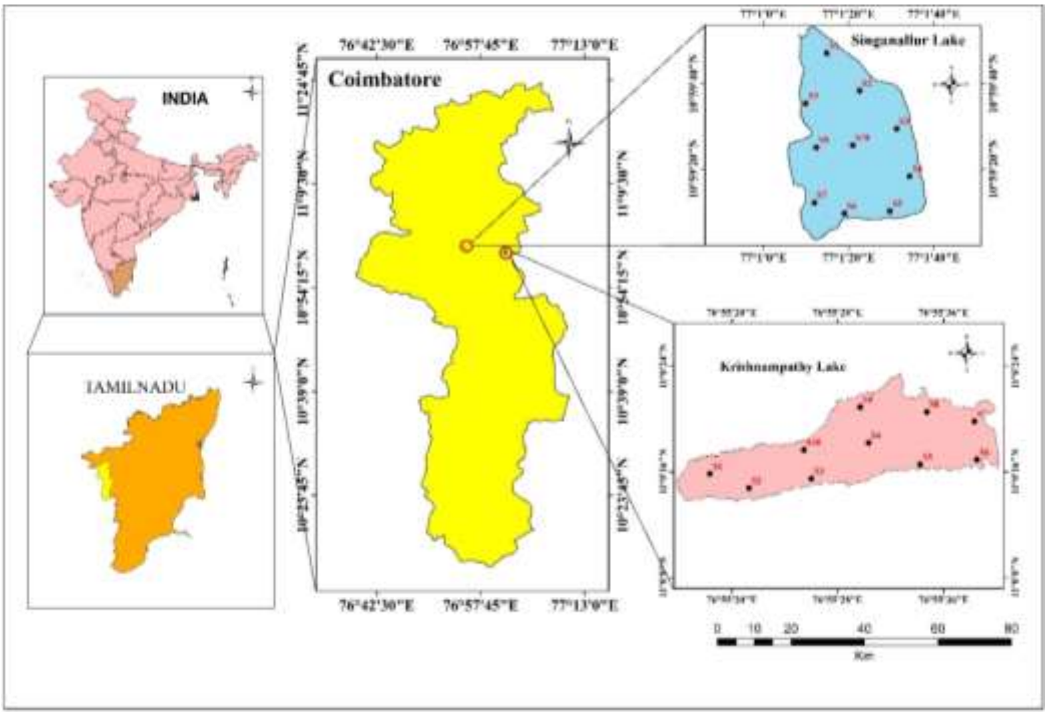

Figure 1: Study area showing sediment sampling locations in Krishnampathy and Singanallur Lakes

2.5. Pollution Assessment

The single pollution index, which is based on total phosphorus levels, was used to conduct an ecological risk assessment. It determines the pollution level in the research area using an equation (1). This method helps quantify the ecological impact of phosphorus contamination to identify potential environmental hazards.

$$S_{TP} = \frac{C_{TP}}{C_S} \qquad \text{--} \ (1)$$

Where S_{TP} stands for single pollution index, C_{TP} for a determined concentration of Total phosphorus (TP), and C_S for the standard P concentration concerning safe nutrient limits as outlined in sediment quality guidelines (SQGs) (Younis et al., 2022). The recommended standard concentration of TP is 600 µg/g, which poses potential ecological risks (Barik et al., 2016). According to the STP index value, Table 1 shows the breakdown of risks into four levels.

Table 1: Criteria and factors to evaluate the ecological risk

Risk level	Value	Pollution assessment
Level I	$S_{TP} < 0.5$	*Clean*
Level II	$0.5 \leq S_{TP} < 1$	*Slightly polluted*
Level III	$1 \leq S_{TP} < 1.5$	*Moderately polluted*
Level IV	$1.5 \leq S_{TP}$	*Seriously polluted*

(Source: Barik et al., 2016; Younis et al., 2022)

3. RESULTS AND DISCUSSIONS

3.1. Descriptive statistics of Krishnampathy and Singanallur Lakes Sediments

3.1.1 Krishnampathy Lake

Sediment pH ranges from 7.40 to 8.10, with an average of 7.81. These pH values are typical of freshwater environments with carbonate buffering, and they significantly influence microbial activity, metal distribution, and nutrient solubility in sediments (Sayeed et al., 2015). Salinity and ionic concentration were measured using electrical conductivity (EC), which varied from 330 to 800 µS/cm. Alkalinity in sediments ranges between 54.00 and 176.00 mg/g as $CaCO_3$, indicating the buffering capacity of the lake system, primarily due to bicarbonate and carbonate ions. The relatively high alkalinity supports the alkaline pH and suggests a well-buffered aquatic environment. Elevated chloride (Cl) concentrations, with a mean of 168.29 mg/L (Table 2), may impact sediment chemistry by altering ionic interactions and affecting the release of nutrients from sediment particles. This might indicate anthropogenic inputs, such as domestic wastewater or agricultural runoff.

Calcium (Ca) and Magnesium (Mg) are two important bivalent cations, and mean concentrations of Ca and Mg were recorded as 2.46 and 1.34 mg/L, respectively. Total Organic Carbon (TOC) ranged widely from 0.3

to 2.43%, with a mean level of 1.45%. This indicates a moderate amount of organic matter present in the sediment samples. TOC plays a significant role in microbial activity, sediment quality, and the binding and mobility of nutrients and contaminants. A relatively high level of organic carbon suggests active detrital input, which may originate from algal production, aquatic vegetation, and terrestrial runoff (Meyers and Ishiwatari, 1993).

Available phosphorus (AP), a key macronutrient, shows significant enrichment with concentrations ranging from 311.86 to 791.50 mg/kg. The elevated presence of AP is affected by external sources, such as domestic wastewater discharge and the use of agricultural fertilizers, as well as internal loading mechanisms where phosphorus is released from sediments under anoxic conditions (Song et al., 2017). Phosphorus mainly exists in readily available or loosely bound forms rather than in stable, mineralized forms, as indicated by the relatively low average total phosphorus (TP) level of 1274.65 mg/kg, with values from 1125 to 1417.5 mg/kg.

Table 2: Descriptive statistics of sediment characteristics in Krishnampathy Lake

Parameters	Min	Max	Mean
pH	7.40	8.10	7.81
Electrical conductivity (μS/cm)	330	800	525
Alkalinity (mg/g as $CaCO_3$)	54.00	176.00	93.15
Chloride extract concentration (mg/L)	16	502.52	168.29
Calcium in sediment extract (mg/L)	1.61	4.26	2.46
Magnesium in sediment extract(mg/L)	0.97	1.81	1.34
Total organic carbon (%)	0.30	2.43	1.45
Available Phosphorus (mg/kg)	311.86	791.50	690
Total Phosphorus (mg/kg)	1125	1417.5	1274.65
Total potassium (mg/kg)	3500	5100	4200
Available potassium (mg/kg)	2101.12	2505.44	2275.53
Ammonical Nitrogen (mg/kg)	0.80	4.20	2.99
Total Kjeldhal Nitrogen (mg/kg)	2.80	4.48	3.58
Cation exchange capacity ($cmol^{+}/kg$)	1.64	6.83	3.99

The mean total potassium (TK) content in the sediments was 4200 mg/kg, while the available potassium (AK) ranged from 2101.12 to 2505.44 mg/kg. Mean concentration of ammonical nitrogen (AN) and Total Kjeldahl Nitrogen (TKN) were found as 2.99 and 3.58 mg/kg, respectively, indicating the presence of both inorganic and organic nitrogen forms in the sediments. Sediment cation exchange capacity (CEC) ranged from 1.64 to 6.83 $cmol^{+}/kg$, indicating a low to moderate capacity for nutrient retention. Lower CEC values, commonly associated with sandy textures, reduced clay content, and limited organic matter, may restrict the sediment's ability to retain essential exchangeable cations such as K^{+}, Ca^{2+}, and Mg^{2+}. Variations in CEC may also reflect differences in clay mineral composition, organic matter content, and redox-sensitive metal oxides within the sediments. The phosphorus fractionation analysis of the sediments provides significant information on the movement of nutrients and the potential for eutrophication. The distribution of the various phosphorus fractions

(NH_4Cl-P, Fe-P, NaOH-P, HCl-P, and Res-P) in sediment samples from Krishnampathy Lake is illustrated in the box plot presented in Figure 2.

The NH_4Cl-P, which is readily available phosphorus, ranged from 159.5 to 293.00 mg/kg. The maximum value indicates the presence of localized hotspots that may release significant amounts of phosphorus into the top water. It suggests that Krishnampathy Lake remains vulnerable to eutrophication, even if external nutrient sources are controlled. The average NH_4Cl-P value of 221.13 mg/kg, which is widespread, indicates variations in this fraction. According to Nishida et al. (2018), the absence of dissolved oxygen in water under static or stratified circumstances specifically contributes to internal nutritional loading. A large amount of phosphorus is associated with iron oxides, as shown by the iron-bound phosphorus, which is potentially bioavailable, especially in reducing conditions where Fe^{3+} converts to Fe^{2+}, causing phosphate release into the water column (Xiangcan et al., 2006). The mass balance of Phosphorus fractions in Krishnampathy Lake Sediments is observed in Table 3:

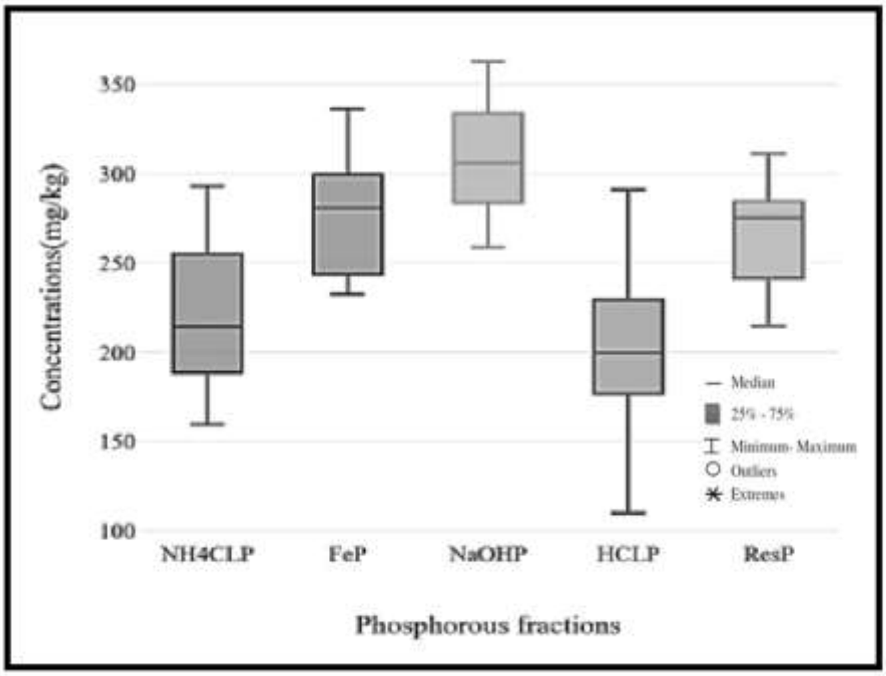

Figure 2. Phosphorus fractionation concentration mg/kg in Krishnampathy Lake

Table 3: Mass Balance of Phosphorus Fractions in Krishnampathy Lake Sediments

Fe-P concentrations ranged from 232.5 to 336.25 mg/kg, with a mean value of 278.68 mg/kg, representing phosphorus bound to iron and manganese oxides. Under reducing or anoxic conditions, the reduction of Fe^{3+} and Mn^{4+} to Fe^{2+} and Mn^{2+} promotes the dissolution of these oxides, resulting in the release of bound phosphorus into the overlying water. The relatively high Fe–P concentrations, therefore, indicate a strong potential for internal phosphorus loading during periods of low oxygen availability in bottom waters.

Phosphorus associated with humic substances and amorphous aluminum oxides (NaOH–P) exhibited a minimum concentration of 232.50 mg/kg. This moderately bioavailable fraction can be mobilized through microbial activity, thereby contributing to sustained internal phosphorus loading (Luyao et al., 2019). HCl–P associated with carbonate and apatite minerals ranged from 110 to 291 mg/kg. Although this fraction is generally considered stable and less bioavailable, sediment acidification can enhance its solubility and promote phosphorus release into the water column.

Residual phosphorus, primarily composed of mineral-bound and refractory organic forms, ranged from 214.72 to 311.25 mg/kg, indicating dominance of immobile phosphorus with limited immediate ecological relevance. While largely non-labile, prolonged acidification, diagenetic transformations, or microbial degradation may gradually increase its mobilization over long timescales (Cavalcante et al., 2018; Mina Kinani et al., 2023).

TP was observed at a minimum of 1125 mg/kg and a maximum of 1417.5 mg/kg, with an average of 1274.65 mg/kg. The relatively higher concentrations of NaOH-P and Fe-P suggest that iron and aluminum-bound phosphorus forms dominate, reflecting potential internal phosphorus loading under reducing conditions. The sediments of the study area location are not only nutrient storage areas, but also potential sources of phosphorus release, as they contain multiple phosphorus forms that can become mobilized under certain environmental conditions. Res-P reflects diverse phosphorus retention in residual forms. The results suggest that the two most common phosphorus fractions in the sediment are NaOH-P and Fe-P, possibly indicating a significant contribution from iron-bound and bioavailable phosphorus. Res-P and NH_4Cl-P are factored to contributions from recalcitrant and removable phosphorus sources, respectively. The decreased concentration of HCl-P suggests that phosphorus has minimal interaction with carbonate-bound components.

Parameter	**Mean (mg/kg)**
NH_4Cl–P	221.83
BD–P	278.28
NaOH–P	308.08
HCl–P	202.13
Residual–P	266.52
Sum of Fractions	**1276.84**
Measured TP (Mean)	**1274.65**
Recovery (%)	**100.17%**

3.1.2 Singanallur Lake

The sediment pH of Singanallur Lake ranges from 7.81 to 8.43, with an average of 8.12, indicating slightly alkaline conditions in freshwater systems, which generally promote the precipitation of certain metal ions and phosphorus compounds, thereby affecting nutrient cycling and availability within the sediment (Wu et al., 2014). The lake's freshwater quality, confirmed by electrical conductivity with a mean value of 461 µS/cm. The alkalinity ranges from 21.00 to 73.50 mg/g as CaCO3. The average chloride (Cl^-) concentration in sediments was 320.77 mg/L, reflecting significant external inputs rather than in situ retention, as chloride is a highly mobile and conservative ion (Li et al., 2012). The mean concentration of calcium (Ca) and Magnesium (Mg) was recorded as 59.48 mg/L and 3.20 mg/L, respectively. The sediments contain a moderate amount of organic carbon, recorded in the range from 0.34 to 2.58%. The mean available phosphorus (AP) is recorded as 741.01 mg/kg. The mean total phosphorus (TP) level is 1287.25 mg/kg, with a range of 1125 to 1582.5 mg/kg (Table 4).Total Potassium (TK) has a mean of 5000mg/kg, with values ranging from 3800 to 5700 mg/kg. Available potassium (AK) levels range from 1800.12 to 2576.84 mg/kg, with a mean of 2052.54 mg/kg. Ammonical Nitrogen (AN) levels range from 3.92 to 24.64 mg/kg, with a mean of 11.87 mg/kg. Total Kjeldahl Nitrogen (TKN) levels range from 11.57 to 31.14 mg/kg. The distribution of Cation Exchange Capacity (CEC) values is significantly high, with a mean of 3.04 cmol+/kg. The relatively narrow range indicates minimal variation in the sediment nutrient retention capacity. The distribution of the several phosphorus fractions (NH_4Cl-P, Fe-P, NaOH-P, HCl-P, and Res-P) in sediment samples of Singanallur Lake is shown in the box plot in Figure 3.

Table 4: Descriptive statistics of sediment characteristics in Singanallur Lake

Parameters	Minimum	Maximum	Mean
pH	7.81	8.43	8.12
Electrical conductivity (µS/cm)	260	750	461
Alkalinity (mg/g as $CaCO_3$)	21.00	73.50	49.35
Chloride extract concentration(mg/L)	187.11	503.27	320.77
Calcium in sediment extract (mg/L)	31.18	100.17	59.48
Magnesium in sediment extract (mg/L)	1.07	7.51	3.20
Total organic carbon (%)	0.34	2.58	1.66
Available Phosphorus (mg/kg)	294.78	1118.2	741.01
Total Phosphorus (mg/kg)	1125	1582.5	1287.25
Total potassium (mg/kg)	3800	5700	5000
Available potassium (mg/kg)	1800.12	2576.84	2052.54
Ammonical Nitrogen (mg/kg)	3.92	24.64	11.87
Total Kjeldhal Nitrogen (mg/kg)	11.57	31.14	21.16
Cation exchange capacity ($cmol^+/kg$)	1.82	6.22	3.04

The NH_4Cl-P is the loosely sorbed exchangeable phosphorus and a highly bioavailable form of phosphorus, easily exchangeable with the water column. The mean concentration of 204.48 mg/kg signifies a considerable risk of eutrophication, especially under low-oxygen conditions (Mahmood et al., 2020). Its elevated levels suggest a strong potential for phosphorus resuspension, which can quickly stimulate algal blooms, mainly in warm and stagnant waters typical of urban lakes. The Fe-P fraction has a minimum observed concentration of 255.75

mg/kg. It is sensitive to redox changes and can contribute to internal phosphorus loading by releasing phosphorus into the water column under anoxic conditions (Xu et al., 2014).

The NaOH-P fraction recorded the highest mean concentration, 341.18 mg/kg, and is mainly associated with organic matter and aluminum compounds, and is moderately bioavailable. It is moderately sensitive to environmental factors such as pH, redox potential, oxygen levels, and microbial activity, and its release is driven by biogeochemical changes in the sediment (Jiang et al., 2006). The HCl-P, with a maximum value of 287.50 mg/kg, is generally more stable and less bioavailable. The residual phosphorus fraction, with a mean of 269.62 mg/kg, consists of refractory organic and mineral-bound forms that are largely unavailable for biological uptake (Ying et al., 2019). This fraction reflects long-term phosphorus sequestration. A substantial proportion of phosphorus occurs in potentially mobile forms (NH_4Cl-P, Fe-P, and NaOH-P), indicating sensitivity to environmental changes (Bańkowska-Sobczak et al., 2020). While it does not directly contribute to eutrophication, it represents past nutrient accumulation and the geochemical evolution of the sediment.

NaOH-P has the highest mean concentration, indicating high phosphorus availability with little variation. Fe-P's higher median value and wider spread show greater variability in phosphorus linked to iron minerals. The lowest mean concentration of NH_4Cl-P indicates minimal amounts of exchangeable phosphorus. Phosphorus variability related to carbonate is reflected by the wider spread and lower mean of HCl-P. Res-P exhibits a broad range and an average mean value, indicating that a significant amount of phosphorus is preserved in residual forms in samples with varying concentrations.

In earlier studies, sediment phosphorus was found mainly in the NaOH-P fraction, with total phosphorus (TP) concentrations ranging between 1125 and 1582.5 mg/kg; similar results were observed in Krishnampathy Lake (Søndergaard et al., 2003). Singanallur Lake receives more nutrient inputs than Krishnampathy Lake, indicating a higher impact from human activities due to non-point sources such as building debris and domestic solid waste. The mass balance of phosphorus fractions in Singanallur Lake sediments is presented in Table 5.

Table 5: Mass Balance of Phosphorus Fractions in Singanallur Lake Sediments

Parameter	Mean (mg/kg)
NH_4Cl–P	204.48
BD–P	285.33
NaOH–P	341.19
HCl–P	246.70
Residual–P	269.62
Sum of Fractions	**1347.31**
Measured TP (Mean)	**1347.31**
Recovery (%)	**100.00%**

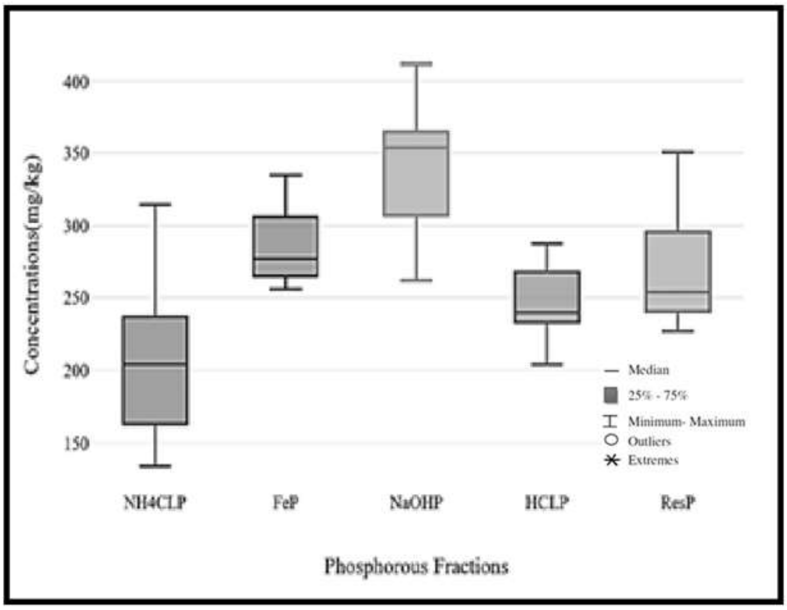

Figure 3: Phosphorus fractionation concentration mg/kg in Singanallur Lake

Ecological risk assessment using the single pollution index confirms significant pollution in both lakes, with STP values exceeding level IV (2.07 and 2.14, respectively), indicating high contamination and serious environmental concerns (Younis et al., 2022).

4. CONCLUSION

Lake management strategies must be site-specific because ecological and environmental impacts vary. The Krishnampathy Lake management plan should focus on stabilizing Fe-bound phosphorus by reducing internal loading and limiting organic matter deposition. For Singanallur Lake, minimizing external nutrient inputs requires improving stormwater management, enhancing wastewater treatment, and increasing community participation. Both urban lakes need targeted restoration initiatives and long-term sediment monitoring to mitigate eutrophication, restore ecological stability, and maintain freshwater quality.

Comparative assessment of Singanallur and Krishnampathy Lakes reveals distinct sedimentary and biogeochemical regimes governing nutrient dynamics. These regimes influence ecosystem functioning through phosphorus distribution and sediment properties. Both lakes show significant phosphorus contamination, particularly in NaOH-P and Fe-P fractions, which can impair water quality under anoxic conditions. Singanallur sediments display higher correlations among total phosphorus, ammoniacal nitrogen, and available phosphorus but weaker inter-fractional coherence, reflecting active internal nutrient recycling. Littoral zones exhibit greater nutrient mobility due to frequent disturbance and surface inputs, while benthic zones demonstrate more stable, redox-controlled phosphorus dynamics, highlighting differences between shallow and deep sediment processes. Sediment Pollution Index values classify both lakes as seriously polluted, with Singanallur enriched by external inputs and internal recycling, and Krishnampathy regulated mainly by Fe–Ca interactions.

Nitrogen cycling and sediment dynamics underscore the need for site-specific management. Restoration efforts should target internal loading pathways by reducing organic matter and ammoniacal inputs to limit phosphorus remobilization in Singanallur, and by maintaining oxic bottom conditions to stabilize Fe-bound phosphorus in Krishnampathy. This study provides a scientific basis for developing site-specific eutrophication control strategies grounded in sediment geochemistry. Such measures will enhance the resilience of urban freshwater systems, maintain ecological stability, and preserve biological integrity. Without proactive management, nutrient enrichment can accelerate harmful algal blooms, threatening ecosystem health and resilience.

5. SUPPLEMENTARY MATERIAL

5.1 Principal Component Analysis

In Krishnampathy and Singanallur Lake, sediment quality analysis was applied to principal component analysis (PCA) with Varimax rotation and Kaiser normalization of component scores. PCA was used to quickly understand the observed associations among cluster variables, expressed as patterns of variance and covariance between variables and within the data. According to Kaiser, only factors with eigenvalues greater than one should be used (Liu et al., 2003). The KMO measure of sampling adequacy for the Krishnampathy and Singanallur lake datasets is 0.9634.

The Component Plot in rotated space visualizes how different sediment quality parameters are grouped based on the principal components (PCs). Each point represents a variable such as pH, EC, TKN, TOC, etc. The results indicate that PCA can be used for both datasets. Three variables with eigenvalues greater than one were retained in the informative collection for the study area, collectively accounting for 96.37% of the total variation in the informational index.

5.1.1. Krishnampathy Lake

The principal component analysis (PCA) matrix reveals the relationships between the principal components (PC1, PC2, and PC3) and other sediment characteristics. The component loadings show how strongly and in which direction the parameters and major components are related. The first principal component (PC1) demonstrates that the sediment of Krishnampathy Lake exhibits a strong positive correlation with Fe-P (r = 0.912), NaOH-P (r = 0.907), HCl-P (r = 0.704), NH_4Cl-P (r = 0.657), and TP (r = 0.742), indicating the influence of phosphorus retention and organic matter. These high values suggest that phosphorus fractions play a significant role in PC1. Lake sediments act as a storage for phosphorus, which can be released when environmental conditions change, contributing to eutrophication. TK (-0.636), TKN (-0.482), and Res P (-0.545) have negative loadings.

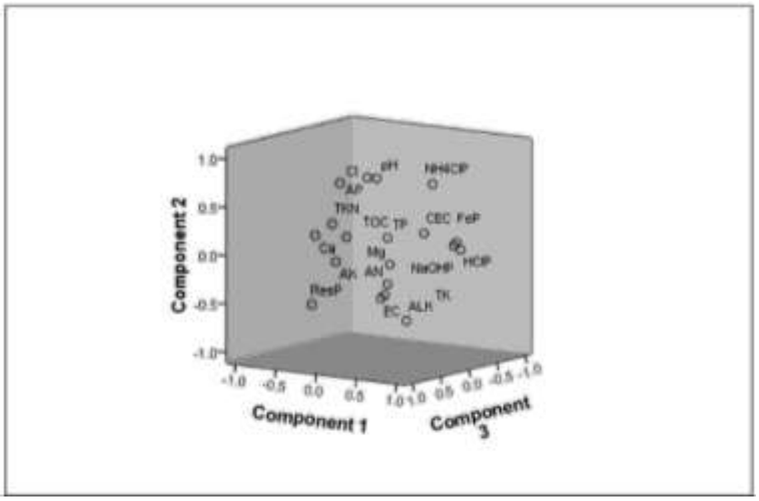

Figure S1. Principal Component Analysis - Krishnampathy Lake

The second major component (PC2) is the impact of salinity and ionic pollution on phosphorus fractionation. The loadings of AK (0.485), AP (0.460), TKN (0.407), Cl (0.837), and Ca (0.745) are all strongly positive. The anthropogenic influences and ionic content indicated by these parameters may be attributed to urban runoff, agricultural operations, or industrial waste. For this study, key indicators of pollution, such as sewage discharge, road runoff, or fertilizers used in agriculture, include Cl and Ca. The parameters ALK (-0.586) and HCl-P (-0.540) show substantial negative loadings. Based on these parameters, alkalinity and HCl-P relate to pollution sources. The formation of organic substances and the protective function of sediment in Krishnampathy Lake (Figure S1).

These measurements demonstrate how effectively sediments interact with organic components and retain nutrients. The highest negative loadings were AP (-0.628), NH4Cl-P (-0.610), and CEC (-0.630). This indicates a negative relationship between phosphorus percentages and nutrient retention due to variations in sediment composition and redox conditions. Based on their correlation with the sediment quality of Krishnampathy Lake, several phosphorus components (Fe-P, NaOH-P, and HCl-P) were identified in the sediment, and when released, these compounds may cause algal blooms. The highest levels of contaminants were caused by human activity.

5.1.2. Singanallur Lake

Principal Component Analysis (PCA) is a technique used to identify the main factors influencing sediment composition. PC1 shows nutrient accumulation and organic matter content (43.46%) in Singanallur Lake. Most of the processes involving AP (0.812), AK (0.856), AN (0.725), Ca (0.861), Fe-P (0.568), Mg (0.474), and TOC (0.389) are shown in Figure S2. The high levels of available phosphorus (AP), ammonical nitrogen (AN), and total organic carbon (TOC) suggest external nutrient inputs from organic matter decomposition, sewage, and agricultural runoff. Elevated Fe-P and Ca indicate phosphorus retention in sediments, implying potential release under anoxic conditions. AK (available potassium) and Mg contribute to sediments, affecting microbial activity and nutrient cycling. Sediments serve as nutrient sinks, but seasonal changes can release stored phosphorus and nitrogen, increasing eutrophication risks. High TOC signals organic pollution, possibly from wastewater discharge and decaying vegetation.

Ionic pollution with sediment chemistry is observed in PC 2 (52.14%). Parameters like TP (0.704), NaOH-P (0.699), pH (0.555), EC (0.567), Mg (0.509), AK (0.517), and CEC (0.468) are key contributors. High levels of NaOH-P and total phosphorus (TP) indicate that sediment chemistry affects phosphorus speciation. pH and electrical conductivity (EC) influence ionic mobility and metal solubility, which impact metal transport and nutrient retention. Sediment-water interactions are affected by CEC, reflecting the sediment's capacity to retain nutrients and contaminants. Environmental impacts such as saltwater intrusion, wastewater discharge, or industrial effluents influence sediment chemistry, especially with high ionic activity and EC. Fluctuations in pH can promote phosphorus release, potentially leading to internal nutrient loading in lakes.

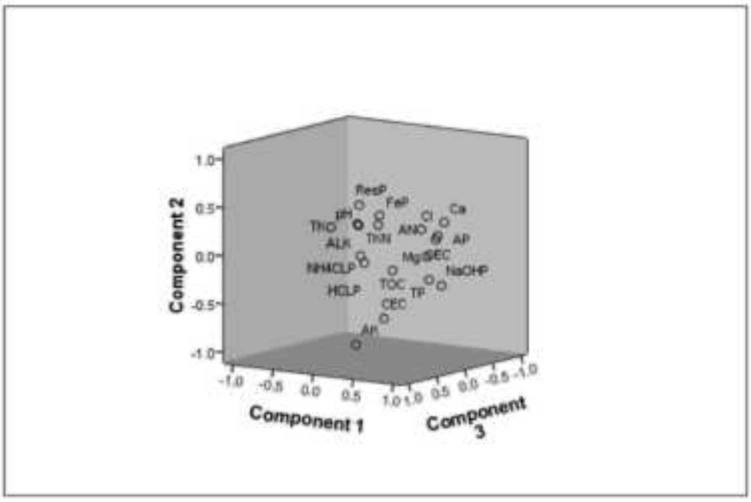

Figure S2: Principal Component Analysis - Singanallur Lake

Residual phosphorus and Sediment Stability (4.23%) are represented by PC 3. The main contributing parameters are within the ranges Res-P (0.210), HCl-P (0.517), TOC (0.511), and Cl (0.959). The high concentrations of chloride (Cl^-) indicate anthropogenic contamination, most likely from industrial discharges or wastewater inputs. Phosphorus attached to mineral fractions, which affect its long-term availability, is indicated by HCl-P and Res-P. The moderate levels of TOC indicate organic matter's role in phosphorus retention and release. Elevated Cl levels point to pollutants from industrial waste, sewage, and road runoff. Res-P signals long-term phosphorus storage that could be mobilized under changing redox conditions, thereby influencing eutrophication dynamics.

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7. CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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