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

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ABSTRACT

Phosphorus (P) is primarily released from sediments through the reduction of iron (Fe^{3+}) oxides under anoxic conditions, leading to the dissolution of Fe-bound phosphorus and an increase in dissolved phosphorus in lake water. This study aimed to quantify the major sedimentary phosphorus fractions and assess 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 identified as the dominant fractions in both lakes. Principal component analysis (PCA) was employed to explore the relationship between P fractions and sediment characteristics. Pollution levels, determined using the Single Pollution Index (SPI), were 2.07 for Krishnampathy and 2.14 for Singanallur, indicating serious pollution in both lakes. Surface water phosphorus concentrations were relatively lower, while the distribution of HCl-P and Fe-P was influenced by environmental and geochemical factors. The results suggest that both lakes are at risk of eutrophication. Identifying sedimentary P sources and evaluating ecological risks are crucial for effective restoration and management of these polluted water bodies.

1. INTRODUCTION

Phosphorus (P) is the most critical factor influencing primary productivity in aquatic environments. It is present in lake sediments and the water column, where it continuously undergoes transformation and cycling (Xie et al. 2019). Climate change and human activities exacerbate water scarcity, with the United Nations estimating a 40% shortfall in freshwater availability by 2030 if current trends persist (UN-Water 2023). Lakes and wetlands, vital freshwater sources, are increasingly threatened by eutrophication driven by phosphorus from agricultural runoff and urban pollution, leading to biodiversity loss and ecosystem disturbances (Sharpley et al. 2013, Zhang et al. 2016, Wu & Wang 2017).

Lakes are crucial freshwater ecosystems that offer vital services such as water storage, supporting biodiversity, climate regulation, and recreational activities. Nevertheless, they remain susceptible to nutrient overloads and sediment variations (Mitsch & Gosselink 2015, Rutledge & Chow-Fraser 2019). More than 70% of surface water is contaminated, mainly from agricultural and industrial runoff (CWC 2023). The government has prioritized the restoration of lakes and wetlands as part of sustainable water management efforts, acknowledging their significance in climate regulation and biodiversity preservation (MoEFCC 2023). Freshwater systems, including rivers and wetlands, play a key role in climate regulation, nutrient cycling, and ensuring economic and food security. They face threats from pollution, overextraction, and climate change, underscoring the importance of sustainable management practices (Falkenmark & Rockström 2004, Dingman 2015, Yuan et al. 2019, Camargo et al. 2025).

Sediments form through natural processes and are crucial in aquatic ecosystems by affecting the transport and concentration of pollutants in water bodies (Joshi et al. 2015, Dang et al. 2017, Wang et al. 2021). During deposition, sediments store phosphorus, which can be released under specific physicochemical conditions such as oxygen depletion, pH fluctuations, and changes in oxidation. As they accumulate in lakes and riverbeds, sediments can release pollutants that impact water quality even when external sources are controlled (Dhanakumar et al. 2015, Helfenstein et al. 2018). Additionally, sediments serve as historical records of environmental changes, offering insights into past climate conditions, ecosystem dynamics, and human activities—key for understanding climate change, detecting pollutants, and evaluating land use changes (Hupfer et al. 2019, Heinrich et al. 2021). Lakes, as dynamic ecosystems, play a vital role in global nutrient cycles, especially phosphorus. Eutrophication, primarily caused by untreated sewage, agricultural runoff, and other human activities, leads to elevated phosphorus levels (Parsons et al. 2017, Dhanakumar & Mohanraj 2019). This phenomenon affects roughly 30-40% of the world's freshwater lakes and reservoirs, resulting in biodiversity loss, habitat degradation, declines in fisheries, reduced food security, and economic challenges (Carpenter et al. 1988, Scheffer et al. 2001). Eutrophication also promotes harmful algal blooms, which pose significant health risks and economic costs (Dodds 2002, Paerl & Otten 2013, Wilfert et al. 2018).

Phosphorus diffusion between sediments and surrounding water is a crucial process that regulates internal nutrient cycling. Nutrient enrichment impacts phytoplankton communities, disturbs food webs, and decreases ecosystem resilience (Smith et al. 1999, Walpersdorf et al. 2013). Excess nutrients, particularly nitrogen and phosphorus stemming from agricultural practices, exacerbate eutrophication, leading to harmful algal blooms and ecological disruptions (Anderson et al. 2002, Galloway et al. 2003, Dhanakumar & Mohanraj 2013). Phosphorus present in lake sediments exists in various organic and inorganic forms, each influencing its bioavailability and mobility (Kraal et al. 2017). Sediments act as both a sink and a source of phosphorus, contributing to internal loading that sustains eutrophic conditions even when external inputs decrease (Lijklema et al. 1993, Søndergaard et al. 1996, Rippey et al. 2021). Biogeochemical processes, including redox shifts and pH fluctuations, affect phosphorus release, while climatic factors like temperature and hydrological changes further modulate its behavior (Lepori & Roberts 2015, Saar et al. 2022). For this research, understanding these interactions is vital for designing strategies to mitigate eutrophication and enhance water quality (Wang et al. 2018a, 2018b). Eutrophication remains a significant challenge in lake management worldwide, mainly driven by human activities such as agricultural runoff and urbanization, which elevate phosphorus inputs in water bodies, leading to algal blooms tied to nutrient enrichment, particularly when iron- and manganese-bound phosphorus (Fe-P and NaOH-P) is released into the water column during anoxic conditions in bottom waters (Paerl & Otten 2013, Huang et al. 2020, Lepori & Robert 2015).

Chemical fractionation involves a sequence 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 acts 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 caused by eutrophication, while sediment-bound phosphorus is regarded as a long-term sink for phosphorus (Gérard 2016). HCl-P signifies phosphorus bound to organic matter, which can be liberated through microbial activity. Changes in redox conditions can mobilize phosphorus from its long-term storage form, bound to metal oxides (Li et al. 2015, Barik et al. 2019). Total phosphorus (TP), encompassing both organic and inorganic forms, is used to assess the overall phosphorus content in sediments and their impact on nutrient levels in the water column (Turner et al. 2005, Reddy et al. 2022). Effective lake management and restoration require a comprehensive understanding of these processes, as phosphorus dynamics and water quality are heavily influenced by both internal loading from sediments and external loading from catchment run-off. This study aims to investigate the relationships between various phosphorus fractions and the physico-chemical properties of lake sediments.

2. MATERIALS AND METHODS

2.1. Description of Study Area

Coimbatore is the leading industrial hub in South India. It is situated between 10°55' and 11°10' N latitude and 77°50' and 76°50' E longitude at an elevation of approximately 470 m above sea level. Located along the Noyyal River and encircled by the Western Ghats, the region features around 28 wetlands predominantly fed by the Noyyal River. Sediment samples were collected from two wetlands: Krishnampathy Lake and Singanallur Lake. Krishnampathy Lake, located in the western part of Coimbatore, spans 61 acres and is part of a series of lakes connected to the Noyyal River. Singanallur Lake, situated in Singanallur, covers 1.153 km² with an average depth of 4.25 m. It is divided into two sections: the southern half receives rainwater, while the northern half manages urban and industrial waste (Fig.1).

2.2. Sediment Sampling and Analysis

During the post-monsoon season of 2023, ten sediment samples were collected from each of the Krishnampathy and Singanallur lakes. The top sediment layer, approximately 5 cm thick and situated beneath about 20 cm of water, was gathered using a spade, placed in pre-washed polyethene bags and bottles, and promptly transported to the laboratory. In the lab, the samples were shade-dried at room temperature, ground, and sieved through a 2 mm mesh. The sieved samples were then oven-dried overnight at 108°C to eliminate moisture. A 1:5 sediment-to-water suspension was prepared for pH and electrical conductivity (EC) measurements using potentiometry. Alkalinity was determined via titration with 0.02 N sulfuric acid employing phenolphthalein as an indicator (APHA 2320 B), and chloride concentration was assessed by argentometric titration in the sediment samples, reported as $mg.L^{-1}$ of extract solution following aqueous extraction—these do not reflect bulk sediment chloride content (APHA 4500-Cl-B 2017). Calcium and magnesium levels were analyzed through complexometric titration using the Versanate (EDTA) method. Total organic carbon (TOC) was estimated using the Walkley and Black (1934) method, while total nitrogen (TN) was measured following the procedure described by Jackson et al. (2005).

The alkaline permanganate method was employed to quantify ammoniacal nitrogen. Available phosphorus was extracted using Olsen's method with a sodium bicarbonate solution at pH 8.5, and it was measured spectrophotometrically via the ascorbic acid method. Total phosphorus was determined by molybdenum blue colorimetry after perchloric acid digestion (Grimshaw 1987). Total potassium was measured using a flame photometer after extraction with hydrochloric acid, while available potassium was extracted with neutral ammonium acetate. The cation exchange capacity (CEC) was assessed using the ammonium acetate method as described by Raman and Sathiyanarayanan (2009).

2.3. Multivariate Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 20.0 (IBM Corp., Armonk, NY, USA). The study employed multivariate statistical techniques, including descriptive statistics and Principal Component Analysis (PCA).

2.4. Sequential Extraction Method

Different forms of phosphorus, including readily available, organic, and mineral-bound phosphorus, can be more effectively evaluated concerning soil fertility and environmental concerns such as eutrophication. The sequential extraction method is a laboratory procedure that isolates various phosphorus (P) fractions in sediments using different chemical reagents. This technique, first introduced by Psenner et al. (1984) and subsequently refined by Hupfer

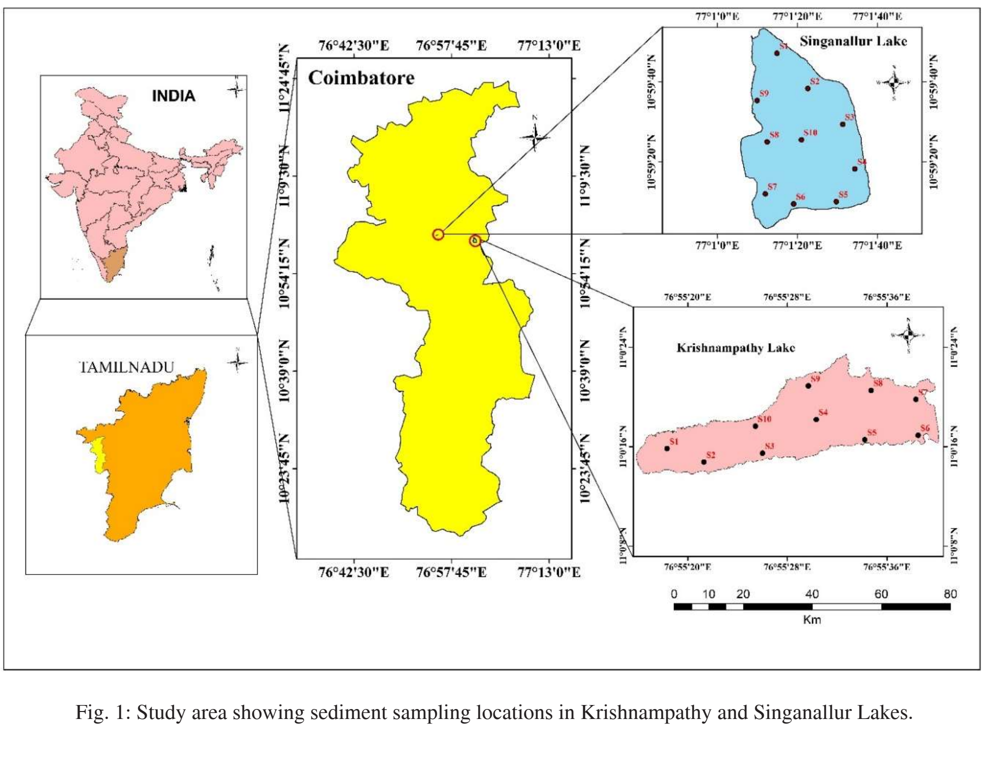

Fig. 1: Study area showing sediment sampling locations in Krishnampathy and Singanallur Lakes.

et al. (1995), improves the extraction process to achieve more accurate phosphorus fractionation. To perform the analysis, 1 gram (1 g) of dry sediment was weighed and placed into a conical flask. Then, 25 mL of 1 M NH4Cl was added, and the mixture was shaken for 2 h. The solution was transferred to a centrifuge tube and centrifuged at 8,000 RPM for 10 minutes. A 10 mL aliquot of the supernatant was collected, to which 2 mL of chloromolybdic acid and a few drops of chlorostannous reductant were added. After 10 minutes, a blue coloration developed, which was then measured spectrophotometrically at 690 nm. This procedure was repeated for subsequent extractants, with slight variations: shaking for 2 h with 1 M NH4Cl, 1 hour with 0.11 M $NaHCO_3/Na_2S_2O_4$, and 16 h with 0.1 M NaOH and 0.5 M HCl.

2.5. Pollution Assessment

The ecological risk was assessed using a single pollution index based on total phosphorus levels. This index calculates the pollution level within the research area through equation (1). Such an approach allows for quantifying the ecological impact of phosphorus contamination and identifying potential environmental hazards.

$$S_{TP} = \frac{C_{TP}}{C_S} \quad \ldots(1)$$

STP represents the single pollution index, CTP refers to a specific concentration of Total Phosphorus (TP), and CS denotes the standard phosphorus concentration aligned with safe nutrient limits as specified in sediment quality guidelines (SQGs) (Younis et al. 2022). The recommended maximum TP concentration is 600 $\mu g.g^{-1}$, which could pose ecological risks (Barik et al. 2016). Based on the STP index value, Table 1 categorizes risks into four distinct levels.

3. RESULTS AND DISCUSSION

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 values are characteristic of freshwater systems with carbonate buffering, and they considerably impact microbial activity, metal distribution, and nutrient solubility within sediments (Sayeed et al. 2015). Salinity and ionic concentration, assessed via electrical conductivity (EC), vary from 330 to 800 $\mu S.cm^{-1}$. The sediment alkalinity, ranging from 54.00 to 176.00 $mg.g^{-1}$ as $CaCO_3$, reflects the lake's buffering capacity, primarily due to bicarbonate and carbonate ions. The relatively high alkalinity supports the alkaline pH and indicates a well-buffered aquatic environment. Elevated chloride (Cl) levels, with an average of 168.29 $mg.L^{-1}$ (Table 2), could influence sediment chemistry by modifying ionic interactions and promoting nutrient release from sediment particles. This may also suggest anthropogenic influences such as domestic wastewater or agricultural runoff.

Calcium (Ca) and Magnesium (Mg) are vital bivalent cations, with mean concentrations of 2.46 and 1.34 $mg.L^{-1}$, respectively. The Total Organic Carbon (TOC) varied considerably from 0.3 to 2.43%, averaging 1.45%, indicating a moderate presence of organic matter in the sediment samples. TOC significantly influences microbial activity, sediment quality, and the attachment and movement of nutrients and contaminants. The relatively high organic carbon level points to active detrital input, likely originating from algal production, aquatic plants, and terrestrial runoff (Meyers & Ishiwatari 1993).

Available phosphorus (AP), a crucial macronutrient, exhibits significant variability with concentrations ranging from 311.86 to 791.50 $mg.kg^{-1}$. Its elevated levels are influenced by external sources such as domestic wastewater discharge and agricultural fertilizer application, as well as internal loading processes where phosphorus is released

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)

Table 2: Descriptive statistics of sediment characteristics in Krishnampathy Lake.

Parameters	Min	Max	Mean
pH	7.40	8.10	7.81
Electrical conductivity [$\mu S.cm^{-1}$]	330	800	525
Alkalinity [$mg.g^{-1}$ as $CaCO_3$]	54.00	176.00	93.15
Chloride extract concentration [$mg.L^{-1}$]	16	502.52	168.29
Calcium in sediment extract [$mg.L^{-1}$]	1.61	4.26	2.46
Magnesium in sediment extract [$mg.L^{-1}$]	0.97	1.81	1.34
Total organic carbon [%]	0.30	2.43	1.45
Available Phosphorus [$mg.kg^{-1}$]	311.86	791.50	690
Total Phosphorus [$mg.kg^{-1}$]	1125	1417.5	1274.65
Total potassium [$mg.kg^{-1}$]	3500	5100	4200
Available potassium [$mg.kg^{-1}$]	2101.12	2505.44	2275.53
Ammoniacal Nitrogen [$mg.kg^{-1}$]	0.80	4.20	2.99
Total Kjeldhal Nitrogen [$mg.kg^{-1}$]	2.80	4.48	3.58
Cation exchange capacity [$cmoL^{+}.kg^{-1}$]	1.64	6.83	3.99

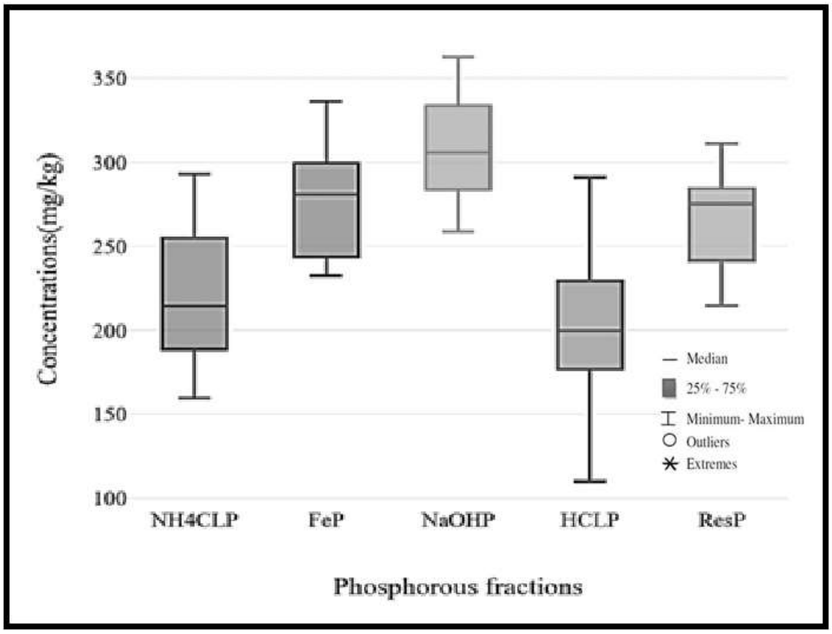

Fig. 2: Phosphorus fractionation concentration mg.kg^{-1} in Krishnampathy Lake.

from sediments under anoxic conditions (Song et al. 2017). Phosphorus predominantly exists in readily available or loosely bound forms rather than in stable, mineralized states, as reflected by the relatively low average total phosphorus (TP) level of 1,274.65 mg.kg^{-1}, with observed values between 1,125 and 1,417.5 mg.kg^{-1}.

The average total potassium (TK) content in the sediments was 4200 mg.kg^{-1}, while the available potassium (AK) varied from 2101.12 to 2505.44 mg.kg^{-1}. The mean concentrations of ammoniacal nitrogen (AN) and Total Kjeldahl Nitrogen (TKN) were recorded as 2.99 and 3.58 mg.kg^{-1}, respectively, indicating the presence of both inorganic and organic nitrogen forms within the sediments. The sediment cation exchange capacity (CEC) ranged from 1.64 to 6.83 cmoL^{+}.kg^{-1}, suggesting a low to moderate potential for nutrient retention. Lower CEC values, often associated with sandy textures, reduced clay content, and limited organic matter, may hinder the sediment's ability to retain essential exchangeable cations such as K^{+}, Ca^{2+}, and Mg^{2+}. Variations in CEC also likely reflect differences in clay mineral composition, organic matter content, and redox-sensitive metal oxides present in the sediments. The analysis of phosphorus fractionation in the sediments offers valuable insights into nutrient mobility and the risk of eutrophication. The distribution of various phosphorus fractions (NH_4Cl-P, Fe-P, NaOH-P, HCl-P, and Res-P) in sediment samples from Krishnampathy Lake is depicted in the box plot shown in Fig. 2.

The NH_4Cl-P, representing readily available phosphorus, ranged from 159.5 to 293.00 mg.kg^{-1}. The highest value suggests the existence of localized hotspots with the potential to release substantial amounts of phosphorus into the upper water layers. This indicates that Krishnampathy Lake remains susceptible to eutrophication, even if external nutrient inputs are managed. The average NH_4Cl-P concentration of 221.13 mg.kg^{-1}, which is widely distributed, reflects variations within this fraction. According to Nishigaki et al. (2018), the lack of dissolved oxygen in water under static or stratified conditions specifically enhances internal nutrient loading. A significant portion of phosphorus is associated with iron oxides, as evidenced by iron-bound phosphorus, which remains potentially bioavailable—especially in reducing conditions where Fe^{3+} reduces to Fe^{2+}, leading to phosphate release into the water column (Xiang et al. 2011). The

Table 3: Mass balance of phosphorus fractions in Krishnampathy Lake sediments.

Parameter	Mean [mg.kg^{-1}]
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%**

distribution of phosphorus fractions in Krishnampathy Lake sediments is summarized in Table 3.

Fe-P concentrations ranged from 232.5 to 336.25 mg.kg^{-1}, with an average of 278.68 mg.kg^{-1}, indicating 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+} facilitates the dissolution of these oxides, leading to the release of bound phosphorus into the overlying water. The relatively high Fe–P levels suggest a significant 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^{-1}. This moderately bioavailable fraction can be mobilized through microbial activity, thereby contributing to sustained internal phosphorus loading. HCl–P associated with carbonate and apatite minerals ranged from 110 to 291 mg.kg^{-1}. 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, predominantly comprising mineral-bound and refractory organic forms, ranged from 214.72 to 311.25 mg.kg^{-1}. This indicates a dominance of immobile phosphorus with limited immediate ecological impact. Although mostly non-labile, extended acidification, diagenetic processes, or microbial degradation could gradually increase its mobilization over extended timescales (Cavalcante et al. 2018, Mina Kiani et al. 2023).

TP was observed at a minimum of 1125 mg.kg^{-1} and a maximum of 1417.5 mg.kg^{-1}, with an average of 1274.65 mg.kg^{-1}. 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 attributed 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.

3.1.2. Singanallur Lake

The sediment pH of Singanallur Lake varies from 7.81 to 8.43, with an average of 8.12, indicating slightly alkaline conditions typical of freshwater systems. Such conditions generally promote the precipitation of certain metal ions and phosphorus compounds, influencing nutrient cycling and availability within the sediment (Wu et al. 2014). The freshwater quality of the lake is confirmed by an electrical conductivity with a mean value of 461 µS.cm^{-1}. Alkalinity ranges from 21.00 to 73.50 mg.g^{-1} as $CaCO_3$. The average chloride (Cl^-) concentration in sediments is 320.77 mg.L^{-1}, suggesting significant external inputs rather than retention, as chloride is a highly mobile and conservative ion (Li et al. 2012). The mean concentrations of calcium (Ca) and magnesium (Mg) are 59.48 mg.L^{-1} and 3.20 mg.L^{-1}, respectively. Sediments contain a moderate amount of organic carbon, ranging from 0.34 to 2.58%. The average available phosphorus (AP) is 741.01 mg.kg^{-1},

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^{-1}]	260	750	461
Alkalinity [mg.g^{-1} as $CaCO_3$]	21.00	73.50	49.35
Chloride extract concentration [mg.L^{-1}]	187.11	503.27	320.77
Calcium in sediment extract [mg.L^{-1}]	31.18	100.17	59.48
Magnesium in sediment extract [mg.L^{-1}]	1.07	7.51	3.20
Total organic carbon [%]	0.34	2.58	1.66
Available Phosphorus [mg.kg^{-1}]	294.78	1118.2	741.01
Total Phosphorus [mg.kg^{-1}]	1125	1582.5	1287.25
Total potassium [mg.kg^{-1}]	3800	5700	5000
Available potassium [mg.kg^{-1}]	1800.12	2576.84	2052.54
Ammoniacal Nitrogen [mg.kg^{-1}]	3.92	24.64	11.87
Total Kjeldhal Nitrogen [mg.kg^{-1}]	11.57	31.14	21.16
Cation exchange capacity [cmoL$^+$.kg^{-1}]	1.82	6.22	3.04

while the total phosphorus (TP) averages 1287.25 $mg.kg^{-1}$, with a range of 1125 to 1582.5 $mg.kg^{-1}$ (Table 4). Total potassium (TK) has a mean of 5000 $mg.kg^{-1}$, with values between 3800 and 5700 $mg.kg^{-1}$. Available potassium (AK) levels vary from 1800.12 to 2576.84 $mg.kg^{-1}$, averaging 2052.54 $mg.kg^{-1}$. Ammoniacal nitrogen (AN) ranges from 3.92 to 24.64 $mg.kg^{-1}$, with a mean of 11.87 $mg.kg^{-1}$. Total Kjeldahl nitrogen (TKN) ranges from 11.57 to 31.14 $mg.kg^{-1}$. The cation exchange capacity (CEC) distribution is notably high, with an average of 3.04 $cmoL^{+}.kg^{-1}$ and minimal variation, indicating consistent sediment nutrient retention capacity. The distribution of various phosphorus fractions (NH_4Cl-P, Fe-P, NaOH-P, HCl-P, and Residual-P) in Singanallur Lake sediments is illustrated in the box plot in Fig. 3.

The NH_4Cl-P fraction represents loosely sorbed, exchangeable phosphorus that is highly bioavailable and easily exchanged with the water column. Its average concentration of 204.48 $mg.kg^{-1}$ indicates a significant risk of eutrophication, particularly under low-oxygen conditions (Mahmood et al. 2020). Elevated levels of this phosphorus form suggest a strong potential for resuspension, which can rapidly promote algal blooms, especially in warm, stagnant waters typical of urban lakes. The Fe-P fraction has a minimum observed concentration of 255.75 $mg.kg^{-1}$. It is sensitive to redox fluctuations and can contribute to internal phosphorus loading by releasing phosphorus into the water column during anoxic conditions (Xu et al. 2014).

The NaOH-P fraction exhibited the highest average concentration at 341.18 $mg.kg^{-1}$ and is primarily associated with organic matter and aluminum compounds. It is moderately bioavailable and somewhat sensitive to environmental factors such as pH, redox potential, oxygen levels, and microbial activity. Its release is driven by biogeochemical changes within the sediment (Jiang et al. 2006). The HCl-P fraction, reaching a maximum of 287.50 $mg.kg^{-1}$, tends to be more stable and less bioavailable. The residual phosphorus fraction, averaging 269.62 $mg.kg^{-1}$, contains refractory organic and mineral-bound forms that are largely unavailable for biological uptake and reflects long-term phosphorus sequestration. A significant portion of phosphorus exists in potentially mobile forms—NH_4Cl-P, Fe-P, and NaOH-P—indicating their sensitivity to environmental changes (Bańkowska-Sobczak et al. 2020). Although this residual fraction does not directly contribute to eutrophication, it signifies historical nutrient accumulation and the geochemical evolution of the sediment.

Table 5: Mass balance of phosphorus fractions in Singanallur Lake sediments.

Parameter	Mean [$mg.kg^{-1}$]
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%**

NaOH-P exhibits the highest mean concentration, signifying a high availability of phosphorus with minimal variation. In contrast, Fe-P's higher median value and

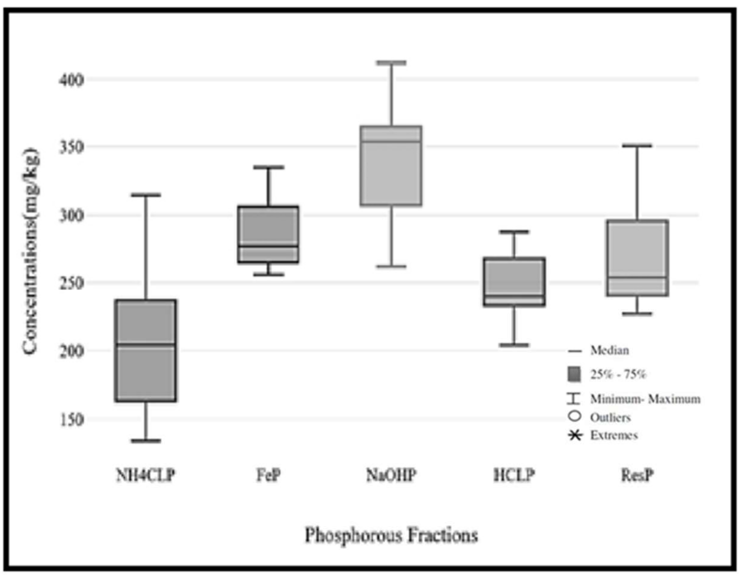

Fig. 3: Phosphorus fractionation concentration $mg.kg^{-1}$ in Singanallur Lake.

wider distribution indicate greater variability in phosphorus content associated with iron minerals. The lowest mean concentration observed in NH_4Cl-P suggests limited amounts of exchangeable phosphorus. The variability of phosphorus related to carbonate is demonstrated by the broader spread and lower mean of HCl-P. Residual phosphorus (Res-P) shows a wide range and an average value, implying that a substantial portion of phosphorus is retained in residual forms across samples with differing concentrations.

Previous studies indicated that sediment phosphorus was predominantly found in the NaOH-P fraction, with total phosphorus (TP) concentrations between 1125 and 1582.5 $mg.kg^{-1}$. Similar findings were reported in Krishnampathy Lake (Søndergaard et al. 2003). Singanallur Lake experiences a greater influx of nutrients than Krishnampathy Lake, suggesting a more significant influence from human activities, including non-point sources like construction debris and household solid waste. The phosphorus fractions' mass balance in Singanallur Lake sediments is detailed in Table 5.

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. CONCLUSIONS

Lake management strategies must be tailored to each site due to the differing ecological and environmental impacts. The management plan for Krishnampathy Lake should prioritize stabilizing Fe-bound phosphorus through reducing internal nutrient loading and limiting organic matter deposition. In contrast, addressing Singanallur Lake's issues involves minimizing external nutrient inputs by improving stormwater management, enhancing wastewater treatment, and promoting greater community involvement. Both urban lakes require targeted restoration efforts and ongoing sediment monitoring to combat eutrophication, restore ecological balance, and preserve water quality.

A comparative evaluation of Singanallur and Krishnampathy Lakes highlights distinct sedimentary and biogeochemical regimes that influence nutrient dynamics. These regimes affect ecosystem functions through the distribution of phosphorus and sediment characteristics. Both lakes exhibit significant phosphorus contamination, especially in NaOH-P and Fe-P fractions, which can degrade water quality under anoxic conditions. Singanallur sediments show higher correlations among total phosphorus, ammoniacal nitrogen, and available phosphorus, but weaker inter-fractional coherence, indicating active internal nutrient recycling. The littoral zones experience greater nutrient mobility due to frequent disturbances and surface inputs, whereas benthic zones maintain more stable, redox-driven phosphorus dynamics, emphasizing the differences between shallow and deep sediment processes. Sediment Pollution Index values categorize both lakes as seriously polluted, with Singanallur affected by external inputs and internal recycling, while Krishnampathy is mainly regulated by Fe–Ca interactions.

Nitrogen cycling and sediment dynamics highlight the importance of site-specific management approaches. Restoration should focus on internal loading pathways by minimizing organic matter and ammoniacal inputs to reduce phosphorus remobilization in Singanallur, and on maintaining oxic bottom conditions to stabilize Fe-bound phosphorus in Krishnampathy. This research offers a scientific foundation for developing targeted eutrophication control strategies based on sediment geochemistry. Implementing these measures will strengthen the resilience of urban freshwater systems, support ecological stability, and protect biological integrity. Without proactive intervention, nutrient enrichment risks accelerating harmful algal blooms, thereby jeopardizing ecosystem health and resilience.

5. ACKNOWLEDGMENTS

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