Water quality and environmental health of lakes in Coimbatore, India: A comprehensive studyof the physicochemical characteristics

ABSTRACT

The deterioration of lake water quality is a major national issue, particularly in regions with industrial activity. This study assesses the water quality of five lakes in Coimbatore, India: Krishnampathi, Ukkadam, Kurichi, Sulur, and Singanallur, between December 2016 and April 2017. Twenty physicochemical parameters were analysed following standard procedures outlined by the American Public Health Association. Twelve heavy metal elements concentration in the lakes was analysed using inductively coupled plasma-mass spectroscopy. The results of this study revealed that the values of 17 physicochemical parameters fell beyond the WHO recommended pollution levels in all the study sites, except Sodium, Nitrate, and Sulphate. While, the concentration of 10 heavy metal elements determined were within acceptable limits of WHO-recommended standards for drinking water across all lakes, except Fe and Pb. *F*-test revealed that the concentration of all the physicochemical parameters varied significantly across all the study sites, except for pH (P = .749). Statistical analysis such as principal component analysis was adopted, and the results were discussed on the multivariate relationships of the physiochemical parameters and heavy metal concentrations of the five study sites. Overall, the findings highlight the urgent need for continuous monitoring and comprehensive management strategies to mitigate the deteriorating water quality in the lakes of Coimbatore district, emphasizing the critical importance of addressing the multitude of factors contributing to this environmental challenge.

Keywords: Water quality; physicochemical parameters; heavy metals; lakes; wetland degradation

1. INTRODUCTION

Water is crucial to all life on Earth. It serves vital functions in several biological processes, including hydration, metabolism, and ecological support. The fact that over 70% of the Earth's surface is covered in water shows its importance in sustaining life [1]. Water is essential for agriculture, industry, and environmental equilibrium. Protecting and conserving this valuable resource is critical for the well-being of current and future generations. To prevent disease and maintain a high quality of life, the availability of clean water is of paramount importance. Water is the most important but most limited resource in India. India only has about 4% of the world's water resources, yet houses about 16% of the world's people. The water resources of the nation are severely strained by this glaring mismatch. Ensuring reliable sources of potable water in India poses a substantial and complex task. This problem is made worse by the growing demand for water as well as other environmental stresses [2]. The agricultural practices, industrialization, and urbanization all add to the depletion of water supplies.

Numerous factors pose a threat to India's water supply, such as runoff from agriculture and industry, contamination from untreated sewage, and over-extraction of groundwater resources. These problems seriously jeopardize the public's health in addition to affecting the supply of safe drinking water. The deterioration of reservoirs and lakes also exacerbates the water situation [2]. Lakes in cities and rural areas are especially susceptible to environmental deterioration as a result of population growth, pollution, and climate change [3]. Freshwater resources are becoming increasingly scarce because of the pollution and disregard that have befallen many of these water bodies. India's water problems call for an all-encompassing strategy that includes public awareness, infrastructure development, regulation, and conservation. To guarantee that everyone has access to clean water and preserve the environment for future generations, investments must be made in water treatment facilities, sustainable agriculture, and improved water management techniques.

Surface water is an essential resource for home, agricultural, and industrial uses and is vital to the supply of water in many Indian regions. Roughly, 90% of irrigated land depends on surface water for irrigation in regions like Tamil Nadu, where it is a major economic activity. However, varieties of pollution sources are progressively compromising the quality of surface water. One of the main causes of the deterioration of surface water quality is the discharge of sewage and industrial waste [4]. These pollutants change the physical and chemical characteristics of the water as well as its microbiological makeup by introducing a variety of contaminants, including pathogens, nutrients, heavy metals, and organic compounds. Lead, mercury, and cadmium are examples of heavy metals that are particularly harmful pollutants in industrial regions [5]. Over time, these materials may build up in water bodies, endangering both human health and aquatic ecosystems. Surface water contamination is not limited to sewage and industrial waste; agricultural activities also contribute to this problem. Common causes of agricultural runoff include pesticides, fertilizers, and animal manure [6]. These runoffs can contaminate water bodies with diseases, nutrients, and chemical residues. The problem is made worse by improper compost disposal and poor septic tank effluent treatment.

The management of water quality and public health are severely challenged by the combined effects of the pollutants. Waterborne illnesses, ecological imbalances, and financial losses can result from contaminated surface water, particularly in areas where communities rely largely on surface water sources for irrigation and drinking. To effectively address surface water contamination, comprehensive strategies must be implemented, including strengthening monitoring and enforcement mechanisms, promoting sustainable land use practices, enforcing pollution control measures in the industrial and agricultural sectors, and improving wastewater treatment infrastructure. Maintaining surface water quality and guaranteeing its sustainable use for current and future generations requires cooperation between government agencies, businesses, communities, and environmental organizations.

The Coimbatore harbors several lakes that serve as critical water sources for the local inhabitants and support diverse ecosystems. However, rapid urbanization, industrialization, and population growth have exerted pressure on these water bodies, leading to concerns about water quality and environmental health. Water quality data for aquatic environments plays a crucial role in the management and conservation of surface water resources, including lakes, reservoirs, and rivers [7]. The main objective of this study is to systematically assess the physicochemical parameters, and heavy metal concentrations in five lakes (namely Krishnampathy, Ukkadam, Kurichi, Sulur, and Singanallur lakes) of Coimbatore, India.

2. MATERIAL AND METHODS

2.1 Study Area

Coimbatore, often referred to as the "Manchester of South India," stands as the second largest city in Tamil Nadu, India (Fig. 1). It serves as a hub of industrialization and urbanization, with a significant impact on the region's surface water environment. The city faces environmental challenges stemming from industrial activities, leading to pollution of both surface and subsurface water sources. This pollution primarily arises from a multitude of industries including textiles, automobiles, home appliances, and various small-scale enterprises.

The discharge of effluents from these industries severely disrupts the quality of surface water in the area. Consequently, the Coimbatore was chosen as the focal point of this study, aimed at analyzing the physicochemicalcharacteristics of five different lake waters. By examining these characteristics, we hope to gain insight into the extent of environmental degradation and identify strategies for mitigating the adverse effects of industrial pollution on Coimbatore's water resources. The geographical coordinate details of the five lakes (Fig. 1) are provided in Table 1.

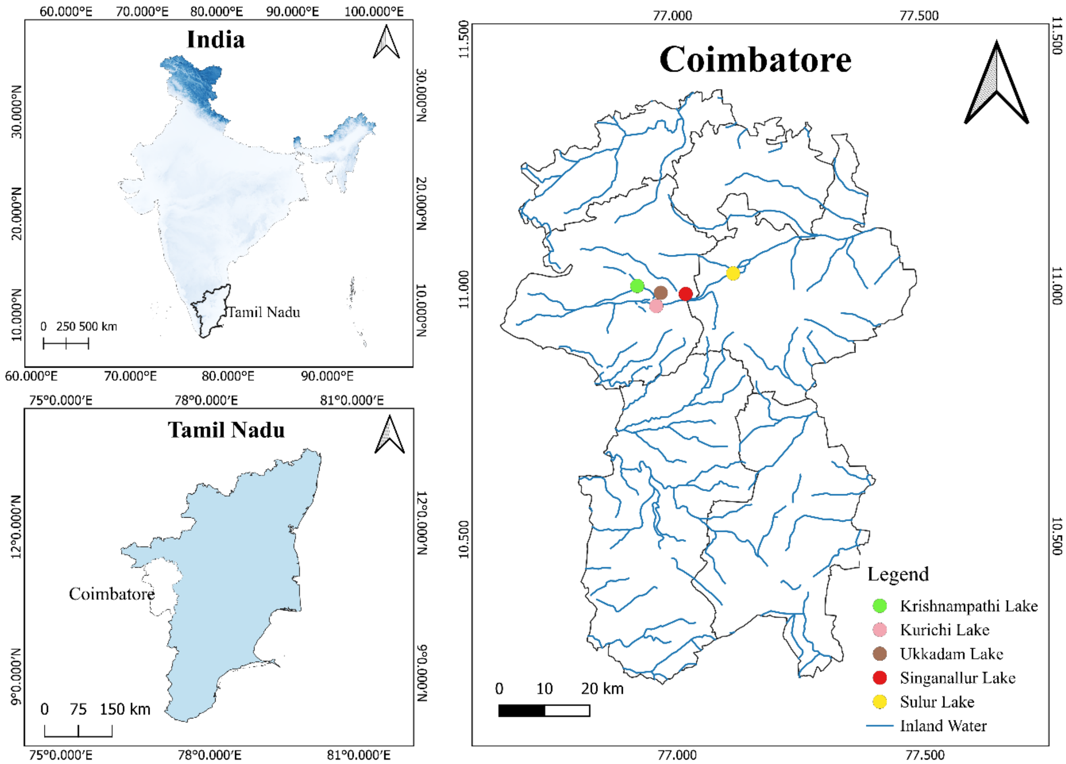

Fig. 1. Location of the five study sites in Coimbatore, Tamil Nadu, India

Table 1. Geographical coordinates of the five selected lakes in Coimbatore

Site	Lakes	Latitude	Longitude
1	Krishnampathy	11º 00'21"	76° 55'30"
2	Ukkadam	10º 58' 57"	76° 57'20"
3	Kurichi	10º 58'01"	76° 57' 48"
4	Sulur	11º 01' 43"	77° 06' 56"
5	Singanallur	10º 59' 25"	77° 01' 21"

2.2Climate data

According to climate data covering the period from 1991 to 2021, the study area experienced an average annual rainfall of 952 mm. Notably, the majority of this rainfall, accounting for 77% of the total, occurred during the months from June to November (as depicted in Fig. 2). For the same period, the average monthly temperature was recorded at 25°C (as illustrated in Fig. 3). The minimum and maximum temperatures were observed during January (18°C) and April (35°C), respectively. These climate parameters provide valuable insights into the environmental conditions of the study area, facilitating a better understanding of the dynamics affecting the water resources and ecosystems in Coimbatore.

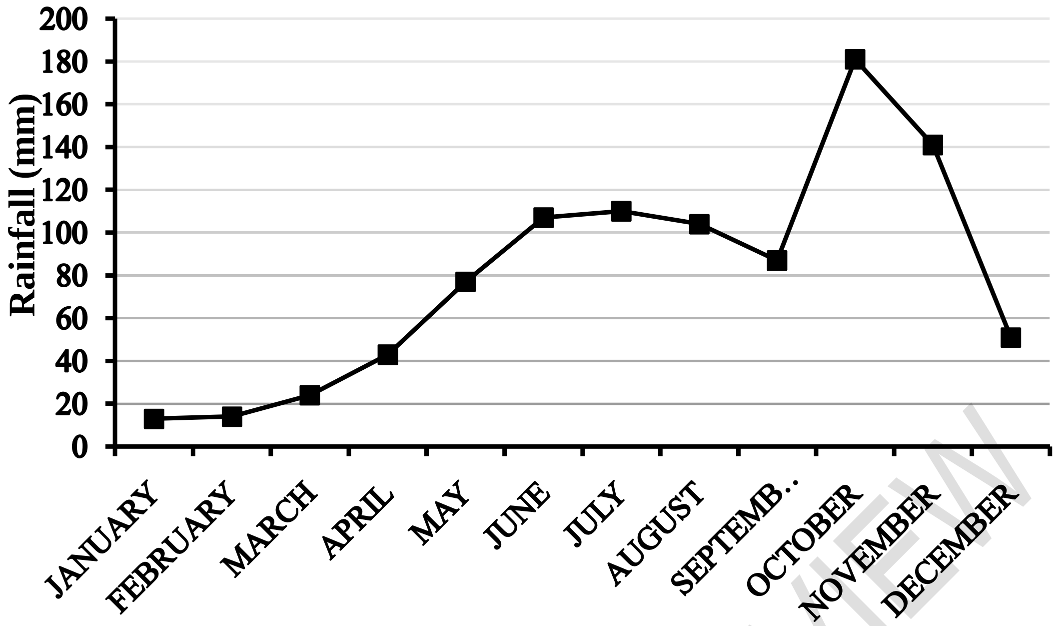

Fig. 2.Monthly rainfall pattern for the study area

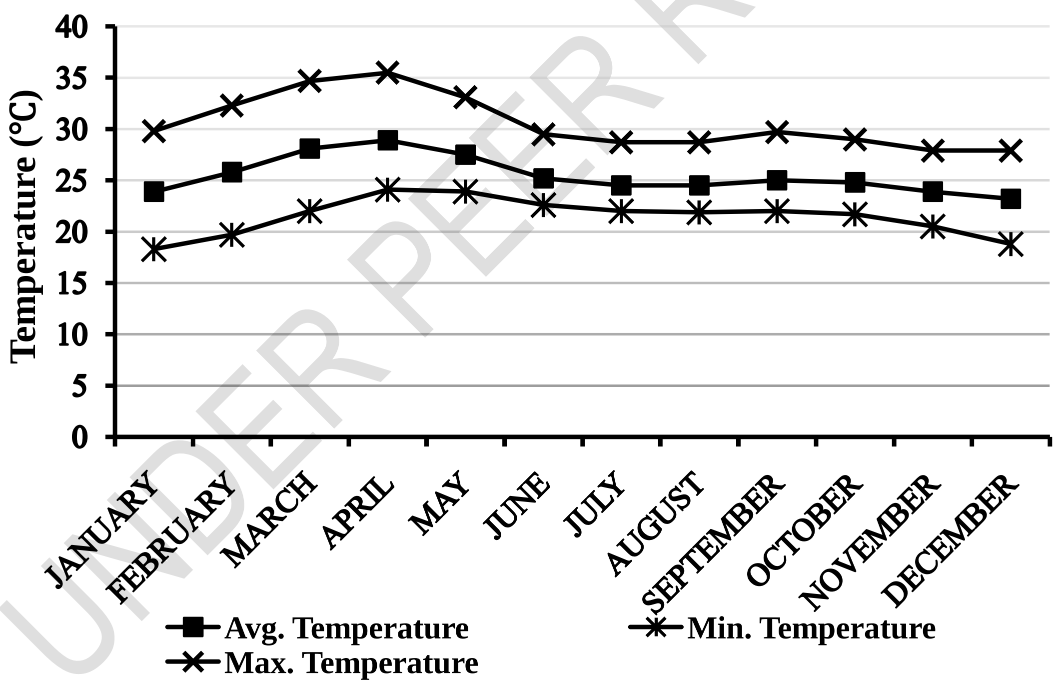

Fig. 3.Monthly temperature pattern for the study area

2.3Sample Collection and Analysis

Surface water samples were collected from the five study sites following approved procedures outlined by the American Public Health Association [8], during the period from December 2016 to April 2017 by morning between 8 AM and 11 AM. Samples were collected in pre-cleaned plastic bottles and labelled. The collectedwater samples were taken to the laboratory and filtered through Whatmann No.1 filter paper and kept in refrigerator at 4°C with addition of HNO_3 in order to preserve samples until analysis. The temperature, pH, electrical conductivity (EC) and turbidity were measured using a thermometer, digital pH meter, conductivity meter, and turbidimeter, respectively. Various physicochemical parameters viz., total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total alkalinity (TA), chloride (Cl^-), sulphate (SO_4^{2-}), nitrates (NO_3^{1-}), were analyzed using the standard methods. Hardness concentrations were determined by using the EDTA titration method. Phosphate (PO_4^{3-}) was determined by molybdate method. Sodium (Na^+) and potassium (K^+) content was analyzed by using flame photometer.

Elemental analysis was conducted to assess the presence of heavy metals, such as Aluminium (Al), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), Copper (Cu), Zinc (Zn), Arsenic (As), Selinium (Se), Molybdenum (Mo), Cadmium (Cd) and Lead (Pb), using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, NeX Ion 300 X, Perkin Elmer, USA).

2.4Statistical Analysis

Analysis of Variance (ANOVA, F-test) was performed to check for significant variation in the values of all the physicochemical parameters across the five study sites by using SPSS (ver. 21). Principal component analysis (PCA) was carried out to study the multivariate relationships for the physiochemical parameters as well as for the heavy metals across the study sites by using Origin 2021.Also, correlation matrix for the heavy metals were performed by Origin 2021.

3. RESULTS AND DISCUSSION

3.1Physicochemical parameters

The present study revealed significant deviations from World Health Organization (WHO) recommended thresholds for multiple physicochemical parameters across the five study sites (Table 2), posing risks to water quality and environmental health. The temperature fluctuations in Coimbatore's lakes, ranging from 28.6°C (Site 1) to 30.8°C (Site 2), emphasize the urgent need to evaluate the wider ecological impacts. Understanding how lakes respond to climate change is crucial for effectively managing and conserving their ecosystems, as predicted temperature increases and prolonged stratification periods can have serious ecological and environmental consequences [9].F-test revealed that there existed a significant variation in the values of all the physicochemical parameters across the five study sites, except for pH (Table 2), reflecting the varied pollution status of the lakes.

Table 2. Physicochemical parameters of the surface water in the study sites

Parameters	WHO	Site 1	Site 2	Site 3	Site 4	Site 5	*F*value	*P*value
Temp (˚C)	-	$28.60^{c}\pm0.26$	$30.80^{a}\pm0.46$	$29.50^{b}\pm0.26$	$30.30^{a}\pm0.35$	$30.40^{a}\pm0.35$	19.441	.000
pH	6.5-8.5	$7.26^{b}\pm0.72$	$7.14^{cd}\pm0.03$	$7.42^{a}\pm0.04$	$7.08^{d}\pm0.05$	$7.22^{bc}\pm0.04$	0.482	.749
EC (µS/cm)	1500	$1893^{c}\pm40.85$	$2126^{a}\pm31.75$	$2030^{b}\pm14.42$	$1880^{c}\pm18.13$	$1823^{d}\pm9.64$	69.926	.000
Turb (NTU)	5	$11.00^{b}\pm1.73$	$18.00^{a}\pm1.73$	$10.00^{b}\pm2.65$	$9.00^{b}\pm1.73$	$12.00^{b}\pm1.73$	9.871	.002
DO (mg/L)	5	$4.20^{bc}\pm0.36$	$5.40^{a}\pm0.44$	$3.90^{c}\pm0.26$	$4.80^{ab}\pm0.46$	$4.40^{bc}\pm0.26$	7.567	.004
BOD (mg/L)	-	$30.00^{ab}\pm2.64$	$22.00^{c}\pm3.46$	$34.00^{ab}\pm3.46$	$28.00^{bc}\pm3.61$	$36.00^{a}\pm5.29$	6.920	.004
COD (mg/L)	-	$124.00^{bc}\pm8.72$	$96.00^{d}\pm7.21$	$130.00^{b}\pm10.39$	$114.00^{c}\pm7.21$	$146.00^{a}\pm7.21$	15.267	.000
TS (mg/L)	-	$1656.00^{b}\pm56.71$	$1753.00^{a}\pm35.76$	$1680.00^{b}\pm19.70$	$1562.00^{c}\pm21.63$	$1518.00^{c}\pm11.13$	21.897	.000
TDS(mg/L)	500	$1174.00^{b}\pm47.62$	$1308.00^{a}\pm31.05$	$1208.00^{b}\pm16.37$	$1117.00^{c}\pm18.68$	$1101.00^{c}\pm9.54$	26.082	.000
TSS (mg/L)	-	$482.00^{a}\pm9.17$	$445.00^{b}\pm7.55$	$472.00^{a}\pm8.72$	$445.00^{b}\pm8.19$	$417.00^{c}\pm3.61$	33.090	.000
TA (mg/L)	200	$220.00^{bc}\pm7.21$	$286.00^{a}\pm5.29$	$208.00^{c}\pm9.17$	$225.00^{b}\pm8.54$	$226.00^{b}\pm4.36$	54.434	.000
Cl (mg/L)	250	$398.00^{c}\pm9.17$	$546.00^{a}\pm13.85$	$446.00^{b}\pm6.93$	$407.00^{c}\pm6.08$	$347.00^{d}\pm5.57$	211.903	.000
TH (mg/L)	300	$480.00^{b}\pm26.46$	$365.00^{d}\pm13.23$	$382.00^{d}\pm5.29$	$420.00^{c}\pm6.93$	$540.00^{a}\pm18.02$	61.590	.000
Ca H (mg/L)	200	$310.00^{b}\pm21.79$	$230.00^{c}\pm18.03$	$249.00^{c}\pm6.56$	$320.00^{b}\pm8.72$	$350.00^{a}\pm8.66$	38.350	.000
Mg H (mg/L)	100	$170.00^{a}\pm8.66$	$135.00^{b}\pm8.66$	$133.00^{b}\pm3.61$	$100.00^{c}\pm5.29$	$190.00^{a}\pm13.23$	50.376	.000
Na (mg/L)	250	$162.00^{c}\pm5.29$	$242.00^{a}\pm9.17$	$208.00^{b}\pm7.21$	$154.00^{c}\pm6.56$	$152.00^{c}\pm4.58$	104.364	.000
NO_3 (mg/L)	45	$35.00^{bc}\pm3.61$	$45.00^{a}\pm3.60$	$36.00^{b}\pm3.61$	$34.00^{bc}\pm3.61$	$29.00^{c}\pm2.65$	8.556	.003
PO_4 (mg/L)	0.1	$0.65^{c}\pm0.05$	$0.81^{b}\pm0.04$	$0.98^{a}\pm0.03$	$0.75^{b}\pm0.07$	$0.92^{a}\pm0.07$	17.605	.000
K (mg/L)	12	$17.00^{bc}\pm2.65$	$23.00^{a}\pm2.65$	$13.00^{cd}\pm1.73$	$12.00^{d}\pm2.65$	$19.00^{ab}\pm2.65$	9.748	.002
SO_4 (mg/L)	250	$6.00^{c}\pm1.73$	$11.00^{b}\pm1.73$	$17.00^{a}\pm2.65$	$12.00^{b}\pm1.73$	$14.00^{ab}\pm1.73$	13.030	.001

**Data are presented in mean ± S.D. (n=3). Mean values followed by different superscript (suffix)aresignificantly different at the 0.05 level for each parameter. Temp-Temperature, Turb- Turbidity, refer text for full form of parameters.*

Turbidity refers to the cloudiness or haziness of a fluid caused by minuscule particles that are often too small to identify with the naked eye. Turbidity is an optical property characterized by the absorption and scattering of light in water. It is a crucial variable as it directly impacts the amount of sunlight that penetrates the water body [10]. In the current study, turbidity (NTU) exceeded the WHO regulatory limit of 5 NTU in all the lakes. The turbidity values at the sampling sites ranged from low in Site 4 (9 NTU) to higher in Site 2 (18 NTU). Higher turbidity levels are attributed to the presence of humic compounds derived from decomposing organic matter and runoff [11].

The pH of a water body is crucial for regulating the bioavailability of nutrients and poisons because it affects the solubility and chemical form of these compounds [12]. It serves as an indicator of the concentration of hydrogen ions, delineating their acidity or alkalinity [13]. The pH level of the water system profoundly influences the majority of biological and chemical interactions. The pH of the water at all sample sites was found to be within the permitted level, slightly alkaline, and falling within the WHO-recommended range [14]. Site 3 exhibited the highest pH among the five lakes, measuring at 7.42, whereas Site 4 recorded the lowest pH at 7.08.

The observed pH range is beneficial to photosynthetic organisms such as phytoplankton and aquatic plants, which play an essential part in the aquatic food chain. These species need specific amounts of pH for efficient photosynthesis, which in the end sustains higher trophic levels such as fish and other species [15]. The lakes' primary productivity overall well-being and biodiversity are supported by the slightly alkaline pH levels. The pH levels differ throughout the sites, indicating the necessity for an extensive understanding of the unique chemical and biological interactions in each lake. The wide range may suggest different sources of inputs into each lake, like runoff, pollution, water column and sediment buffering capacities, or natural geological characteristics, which can change the water chemistry in particular areas [16].

The electrical conductivity (EC) of water, indicative of its ability to carry electrical current is determined by factors such as ion concentration, ionic mobility, and temperature. In the current study, the EC values exceeded the maximum allowable limit of 1500 µS/cm for drinking purposes as prescribed by the WHO. Among the selected lakes, Site 2 exhibited the highest EC value at 2126 µS/cm, while Site 5 recorded the lowest EC value at 1823 µS/cm. Elevated EC values in the lakes can be attributed to agricultural activities and the discharge of numerous ionic substances, including Na^+, Cl^-, and SO_4^{-2}, released from textile industries [17].

Total Dissolved Solids (TDS) encompass all the mobile charged ions, including minerals, salts, or metals, that have been dissolved within a specified volume of water [18]. All the lakes exceeded the WHO's most desirable limit of 500 mg/L for TDS. The concentrations varied with Site 2 exhibiting the highest level at 1308 mg/L, while Site 5 recorded the lowest at 1101 mg/L. Exceeding the permitted limits of TDS in water can pose health risks to individuals, potentially leading to renal and cardiac issues. Also, this may induce laxative effects and contribute to constipation [18]. Total suspended solids (TSS) was recorded higher in Site 1 (482 mg/L) and lower in Site 5 (417 mg/L). Suspended solids comprising both inorganic and organic particles carried by water runoff from the land, contribute to the turbidity or cloudiness of a water body. These particles pose a threat as they can obstruct fish gills, leading to mortality or developmental delays. Moreover, suspended solids reduce light penetration, thereby impacting the ability of algae to produce nutrients and oxygen [18]. Total solids (TS) in a lake refer to the sum of all dissolved and suspended solid particles present in the water. These solids can include organic matter, inorganic matter, and various dissolvedcontaminants. In this study, TS was observed higher in Site 2 at 1753 mg/L, whereas it was lower in Site 5 (1518 mg/L).

Alkalinity reflects water's capacity to resist pH changes towards increased acidity. All the five lakes exceeded the WHO's most desirable limit of 200 mg/L for total alkalinity. Specifically, alkalinity levels ranged from a high of 286 mg/L (Site 2) to a low of 208 mg/L (Site 3). The elevated alkalinity content observed in lake water can be attributed to reason that carbonates originating from domestic sewage and open defecation practices. The study conducted by Priya et al. [19] further corroborates the notion that heightened pollution intensity in the vicinity of lakes correlates with increased alkalinity levels [19]. The Chloride (Cl^-) content in all lakes surpassed the WHO's most desirable limit of 250 mg/L. It was highest in Site 2 (546 mg/L), while Site 5 recorded the lowest concentration (347 mg/L). High chloride levels in lake water can pose risks to individuals with heart and renal illnesses. Increased Cl^- concentrations can contribute to the formation of kidney stones and hypertension in humans [20]. Untreated effluents from industrial areas are believed to be the primary sources of Cl^- pollution near the industrial region [21].

Carbonates, bicarbonates, sulphates, calcium, and magnesium chlorides are the primary contributors to water hardness, impeding both the boiling temperature and the formation of soap lather. In the present study, the hardness content in water of all lakes exceeded the WHO's most desirable limit of 300 mg/L. Site 5 reported higher hardness levels at 540 mg/L, while Site 2 exhibited lower hardness at 365 mg/L. Elevated hardness levels exceeding 300 mg/L may lead to cardiovascular and renal issues. Increased hardness levels can change the availability of nutrients and metals, which could disrupt aquatic life ecologically. Some species are very responsive to fluctuations in water hardness, which may affect their physiological functions, such as osmoregulation, leading to consequences for biodiversity and ecological stability [22].

Calcium hardness refers to the concentration of dissolved calcium ions in water. All the lakes exceeded the WHO recommended maximum permissible levels of 200 mg/L for calcium in drinking water. Site 5 recorded the highest calcium content (350 mg/L), while Site 2 had the lowest at 230 mg/L. Calcium hardness is a crucial factor that affects the health of aquatic organisms [23]. It plays an essential role in shell and exoskeleton formation, reproduction, ion regulation, and the ability to cope with environmental stressors. Fluctuations in calcium levels can negatively affect the growth, metabolism, and overall well-being of aquatic life, particularly calcifying species like mollusks and crustaceans. Maintaining adequate and stable calcium levels is critical for maintaining a healthy aquatic ecosystem.

Except Site 4 all other lakes exceeded the WHO's limit of 100 mg/L for magnesium. Site 5 recorded the highest content at 190 mg/L, and Site 4 showed the lowest content at 100 mg/L. Magnesium hardness has a similar impact on aquatic organisms as calcium does. It affects their shell development, ion balance, and reproductive abilities. Both insufficient and excessive levels of magnesium can interfere with physiological processes in species such as mollusks and crustaceans. Maintaining appropriate magnesium levels is crucial to sustain biodiversity and prevent harmful effects on the health of aquatic ecosystems. Magnesium, similar to calcium, is crucial in aquatic environments as it affects the physiological functions of aquatic creatures such as shell development in molluscs, ion balance, and reproductive functions in different species [24]. High magnesium levels found in many locations may interfere with important biological processes, causing harmful impacts on species and the general well-being of aquatic ecosystems.

Sodium becomes the primary cation in water through the weathering process of alkali feldspar within rocks. We found that all the five lakes were within the WHO's recommended upper acceptable limit of 250 mg/L. With a concentration of 242 mg/L, Site 2 exhibited the highest salt content, while Site 5 showed the lowest value (152 mg/L). Sodium is essential for water use in both agricultural and household needs and its presence can be detrimental to individuals with circulatory, renal, or cardiac disorders. Excessive intake of sodium ions may lead to renal problems, nausea, vomiting, and muscle twitching [20]. High concentration of nitrates contaminate the water bodies, such as lakes, rivers, and groundwater. Nitrate levels exceeding 45 mg/L can lead to methemoglobinemia or blue baby syndrome in infants [25]. However, in the present study, the nitrate level did not exceed the WHO's acceptable limit of 45 mg/L for all the lakes. Site 2 recorded the maximum nitrate level (45 mg/L), and the minimum was observed at Site 5 (29 mg/L). High phosphate in lakes can lead to eutrophication in lakes, fueling the growth of algae and causing harmful algal blooms. These blooms deplete oxygen levels in the water, harming aquatic life and disrupting the ecological balance of the lake. In this study, the concentration of phosphate exceeded the WHO's acceptable limit of 0.1 mg/L for all the lakes. It ranged from a low of 0.65 mg/L (Site 1) to a high of 0.98 mg/L (Site 3). The major sources of phosphate include animal waste and agricultural runoff responsible for the majority of nutrient loadings, with phosphates primarily originating from the decomposition of organic matter, leaching of phosphorus-rich bedrock, and human waste [26].

Potassium in freshwater originates from rocks and tends to be more prevalent in contaminated water due to its higher resistance to weathering and the formation of clay minerals, making it less abundant compared to sodium. Except for Site 4, the potassium content in all the lakes exceeded the WHO's permitted limit of 12 mg/L. This can be attributed to potassium's poor solubility, leading to concentrations significantly lower than sodium. The elevated levels detected, varying from 12 mg/L at Site 4 to 23 mg/L at Site 2, indicate an increase from the usual levels, potentially due to pollution and the resistance of potassium to weathering and clay mineral formation processes [27]. High potassium levels can also suggest other pollution sources such as agricultural runoff or wastewater discharges, which could introduce more toxins into aquatic habitats [28].

Elevated sulphate concentrations can lead to the formation of sulphuric acid through bacterial action, resulting in acidification of the lake water, which negatively impacts aquatic organisms and ecosystems. In the present study, all the lakes have sulphate levels below the WHO-permitted limit of 250 mg/L with a range from 6 mg/L (Site 1) to 17 mg/L (Site 3). The results indicate a low threat of acidification from sulphuric production of acid triggered by bacterial activity due to high sulphate levels in freshwater habitats [29].

Dissolved oxygen (DO) is one of the most crucial components for the survival of an aquatic organism [30]. In the present study, except Site 2 (5.4 mg/L) the DO value was within the WHO-limit of 5 mg/L (Table 2). Biochemical oxygen demand (BOD) refers to the quantity of oxygen required by microorganisms to stabilize naturally decomposing materials for a specified period and under specific temperature conditions. The BOD test is used for assessing the oxygen-demanding strength of waste water [19]. In this study, the levels of BOD varied from a low of 22 mg/L at Site 2 to a high of 36 mg/L (Site 5). High COD levels indicate the presence of organic compounds that require oxygen for degradation, leading to oxygen depletion in the lake and threatening the survival of aquatic organisms. In the present study, the level of COD was higher in Site 5 at 146 mg/L and lower in Site 2 at 96 mg/L. The variations in Chemical Oxygen Demand (COD) levels between the lakes sampled, indicate different amounts of organic compounds in these ecosystems. Elevated COD levels suggest the existence of organic pollutants that, when broken down, use up dissolved oxygen, potentially causing oxygen depletion and endangering aquatic organisms' survival [31]. These results emphasise the necessity of monitoring and controlling COD levels to protect the well-being and diversity of freshwater environments.

3.2Heavy Metal Concentrations

The health impacts of heavy metal pollution in lake water can be detrimental to people around the area. Numerous health issues can arise from exposure to high concentrations of heavy metals, including lead, mercury, cadmium, and arsenic, from contaminated water sources. Due to their proven toxicity and propensity to bioaccumulate in the food chain, these metals are dangerous to human populations as well as aquatic habitats. The elemental concentration in the surface water of five lakes (Table 3), compared with WHO guidelines, reveals that no metal elements exceeded the WHO recommended standards for drinking water, except for iron (Fe) and lead (Pb) indicating potential sources of contamination from industrial effluents and urban runoff in the present study sites of Coimbatore.

Table 3. Concentration of the heavy metals of the five study sites

Heavy metal	WHO-limit	Site 1	Site 2	Site 3	Site 4	Site 5
Al (mg/L)	0.1	0.008	0.002	0.001	0.001	0.003
Cr (mg/L)	0.05	0.004	0.003	0.004	0.004	0.008
Mn(mg/L)	0.4	0.001	0.003	0.001	0.001	0.004
Fe (mg/L)	0.3	0.361	0.407	0.343	0.397	0.371
Ni (mg/L)	0.07	0.003	0.002	0.004	0.002	0.002
Cu (mg/L)	2	0.006	0.004	0.002	0.004	0.005
Zn (mg/L)	3	0.004	0.003	0.001	0.001	0.008
As (mg/L)	0.01	0.007	0.004	0.005	0.006	0.005
Se (mg/L)	0.01	0.006	0.00	0.003	0.003	0.003
Mo (mg/L)	0.07	0.001	0.002	0.002	0.001	0.001
Cd (mg/L)	0.003	0.00	0.00	0.00	0.00	0.001
Pb (mg/L)	0.01	0.002	0.015	0.001	0.001	0.00

The concentration of Fe ranged from 0.343 mg/L (Site 3) to 0.407 mg/L at Site 2. The occurrence of Fe in nearly all lakes exceeded the WHO recommendations of 0.300 mg/L. This could be attributed to the direct recharge of hospital and agricultural wastes in and around these lake areas. High iron concentrations in aquatic ecosystems can result in significant changes in community composition, potentially reducing diversity. Additionally, excess iron can bind with surplus phosphorus, prompting shifts from eutrophic environments to macrophyte-dominated mesotrophic or oligotrophic systems with increased biodiversity [32]. High levels of iron can cause changes in the water's chemistry, which can alter the pH levels, nutrient availability, and the overall quality of the water. This impact on the abundance and diversity of aquatic organisms, especially primary producers such as phytoplankton.

In the present study, the concentration of Pb in Site 2 (0.015 mg/L) slightly exceeded the WHO prescribed limit of 0.010 mg/L. This could be due to the receipt of effluent from the metal and automobile industries. According to Kumar et al. [26], the primary cause of increased Pb pollution in aquatic habitats is the long-term accumulation of Pb from motor vehicle emissions, resulting in rising concentrations of Pb in freshwater ecosystems. An increase in lead concentration in lake water can be harmful to both aquatic ecosystems and human health, often resulting from human activities such as industrial discharge, mining, and urban runoff. The presence of high concentrations of lead in lake water can be extremely harmful to aquatic organisms such as fish, invertebrates, and algae. When these organisms are exposed to lead, it accumulates in their tissues, leading to physiological disruptions, impaired growth, and reproductive abnormalities. In addition to this, lead contamination can also cause disruptions in food webs and ecosystem dynamics, which can have cascading effects on biodiversity and ecosystem function. Consumption of contaminated fish and water can pose significant health risks due to lead, causing neurological and developmental disorders in children and cardiovascular and renal effects in adults located around Site 2. The impacts of increased lead concentrations underscore the importance of implementing pollution control measures and monitoring programs to safeguard water quality and protect both aquatic ecosystems and public health around Site 2.

Table 4 shows the correlation matrix of the twelve heavy metal element concentrations of the study sites. Cr and Cd had a strong positive correlation with correlation coefficient of 0.98. While, Fe and Ni had a strong negative correlation (-0.86). The reason for these relations can be attributed that Cr and Cd might share common sources of input into the lake, such as industrial runoff or agricultural activities. Similarly, Fe and Ni may have contrasting sources or behaviors in the lake environment, leading to their negative correlation.

Table 4. Correlation matrix of the twelve heavy metal element concentrations of the study sites

	Al	Cr	Mn	Fe	Ni	Cu	Zn	As	Se	Mo	Cd	Pb
Al	-											
Cr	0.04	-										
Mn	-0.12	0.63	-									
Fe	-0.27	-0.25	0.32	-								
Ni	0.10	-0.26	-0.59	-0.86	-							
Cu	0.81	0.29	0.24	0.20	-0.49	-						
Zn	0.39	0.84	0.80	-0.05	-0.41	0.62	-					
As	0.68	-0.02	-0.62	-0.33	0.20	0.53	-0.06	-				
Se	0.73	0.18	-0.50	-0.62	0.40	0.48	0.12	0.93	-			
Mo	-0.47	-0.52	0.00	-0.03	0.41	-0.74	-0.44	-0.72	-0.65	-		
Cd	0.00	0.98	0.79	-0.10	-0.38	0.30	0.89	-0.20	0.00	-0.41	-	
Pb	-0.12	-0.54	0.31	0.65	-0.33	-0.05	-0.13	-0.61	-0.73	0.61	-0.34	-

3.3 Principal Component Analysis (PCA)

In our comprehensive study on the water quality and environmental health of lakes in Coimbatore, India, we employed Principal Component Analysis (PCA) as a powerful tool to unravel the underlying structure of the complex multivariate dataset. PCA enabled us to explore the relationships among various physicochemical parameters and heavy metal concentrations across the five study sites, shedding light on the intricate patterns within the dataset.

The PCA graph (Fig. 4) serves as a visual representation of the distribution of data points in a reduced-dimensional space. Each point on the plot corresponds to an individual sample, while the axes represent the principal components that capture the most variance in the data. Notably, distinct clusters emerge in the PCA plot, indicating inherent patterns within the dataset. The first two principal components, PC1 and PC2, collectively explain a significant portion of the total variance, with PC1 contributing 54% and PC2 contributing 20% to the overall variance. Moreover, the presence of outliers in the plot suggests potential data anomalies or unique observations that warrant further investigation.

Through PCA analysis, we gained valuable insights into the relationships among physicochemical parameters and heavy metal concentrations at the five study sites. Data points close to each other on the biplot are indicative of similar variable values, highlighting the similarities or differences among the study sites. Based on the set of physicochemical parameters, PCA grouped the five study sites into distinct clusters: Site 1 and Site 3 formed one group, while Site 4 and Site 5 comprised another group, with Site 2 standing out as a separate entity.

Further, PCA analysis of heavy metal concentrations revealed additional insights into the multivariate relationships among the study sites (Fig. 5). The clustering of specific heavy metals, such as Fe and Pb at Site 2, and Al, Se, and As at Site 1, underscores the unique environmental characteristics of each site. Similarly, the grouping of Site 4 and Site 5 based on Ni concentration highlights similarities in heavy metal profiles between these locations.

Overall, PCA analysis provides a comprehensive understanding of the interrelationships among physicochemical parameters and heavy metal concentrations across the study sites, offering valuable insights into the environmental health of lakes in Coimbatore, India.

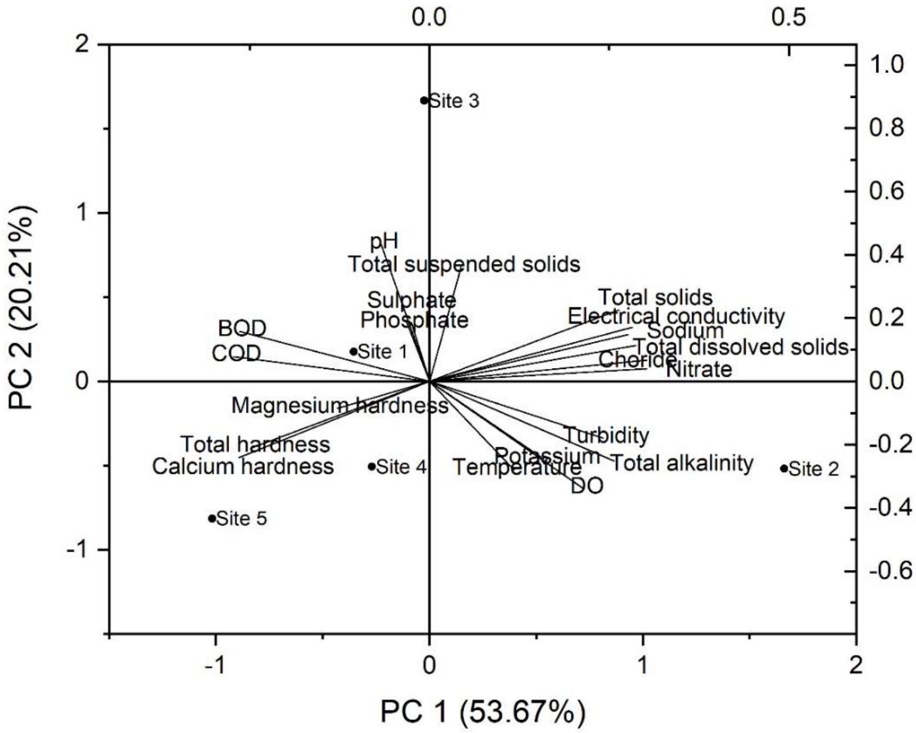

Fig. 4. **Principal component analysis revealing the multivariate relationships of the physiochemical parameters of the study sites**

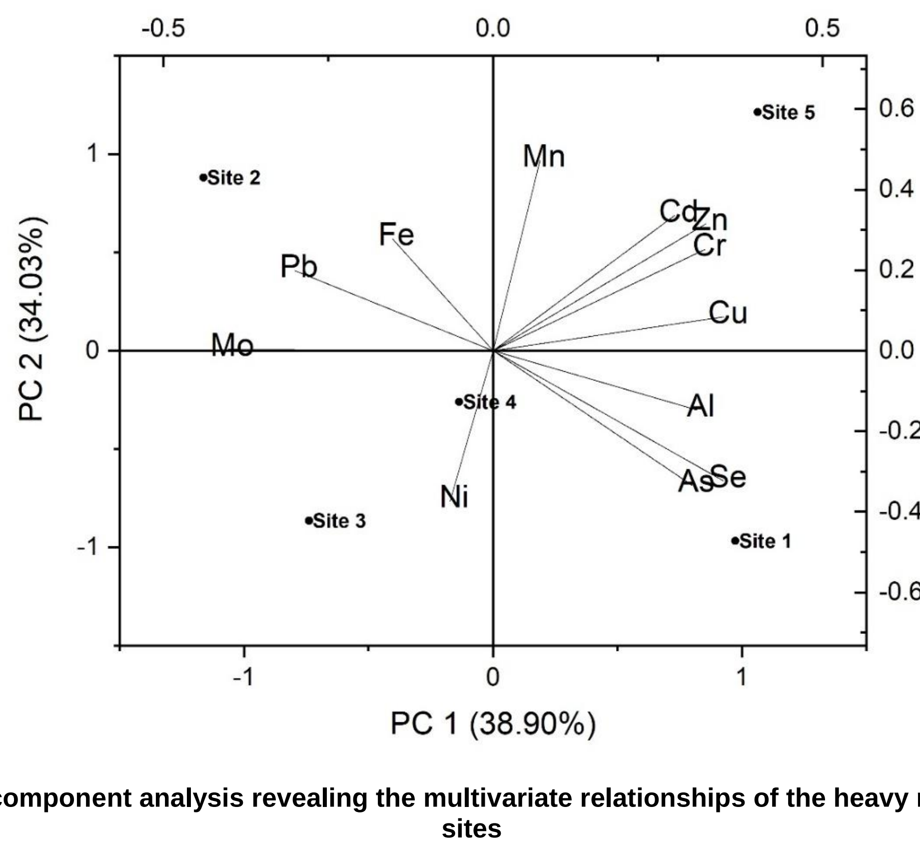

Fig. 5. **Principal component analysis revealing the multivariate relationships of the heavy metals of the study sites**

4. CONCLUSION

This study provides valuable insights into the deteriorating water quality status of lakes in the Coimbatore district and highlights the importance of concerted efforts to address pollution and promote environmental sustainability. We conclude that among the five study sites, Site 2 exceeded the WHO recommended limits for most of the physiochemical parameters, and Fe and Pb with regard to the heavy metal concentrations, demanding special consideration for pollution mitigation strategy. By implementing evidence-based interventions and fostering stakeholder collaboration, we can work towards restoring and maintaining the health and vitality of these vital water bodies for current and future generations. The findings underscore the urgent need for remedial action to mitigate pollution and safeguard water resources in the Coimbatore district. Effective wastewater treatment practices, improved sewage infrastructure, stringent regulations on industrial discharge, and community engagement in waste management and environmental conservation efforts are essential to address these challenges comprehensively. Additionally, long-term monitoring and proactive management strategies are crucial for restoring and preserving the ecological integrity of the lakes.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Dr. L. Arul Pragasan, Assistant Professor, the corresponding author contributed byconceptualization, statistical analysis, supervision and writing of the manuscript. Ms. T. Gomathi,Post Graduate student contributed by sample collection, laboratory analysis and data collection. All authors read and approved the final manuscript.

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