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Seasonal Variations of Physicochemical Parameters and Microbial Pollution in The Brackish Water Lake Chilika, India and Their Impact on Human Health

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Abstract

Chilika Lake, located on East coast of Odisha (19. 8450° N, 85. 4788° E), India, experiences dynamic physicochemical variations due to inputs from rivulets as well as seawater influx, making it brackish, which supports a gargantuan load of flora and fauna. The current report explored variations in water quality across three seasons, summer, winter and rainy across 10 geographically distinct lake zones, using spatial mapping with QGIS (Quantum Geographic Information System) and ArcGIS (Arc Geographic Information System) and additionally through microbial profiling via VITEK-2, covering approximately 35 km of its coastline. Ten distinct locations within the lake, including Mangaljodi, Balugaon, Kalijai, Barkul, Rambha and Satapada yielded water samples to analyze the biological balance and water quality of Chilika. The following parameters were mainly examined: fluoride, sodium chloride, ammonium, hydrogen sulfide, heavy metals (Fe, Cu, Pb, Mn, Hg and Zn), sulfates, chlorides, nitrates, nitrites, pH, alkalinity and overall hardness. One-way ANOVA was used to identify significant seasonal variations ($p < 0.05$) in core indicators, such as nitrate, fluoride, ammonium and lead, highlighting anthropogenic inputs and storm-induced runoffs. The pH was >7, but the salinity levels varied at 1,000-2,000 ppm. Several Gram-positive bacterial isolates, *Staphylococcus xylosus* and *Staphylococcus gallinarum* suggested potential bacterial contaminations to humans and animals. The emergence of antibiotic resistance in the lake and the management of fisheries and tourism sustainably were crucial for the conduct of routine biogeochemical monitoring. Results illustrate how human pressures; pollution inputs and freshwater flow impact the aquatic health of Chilika.

Keywords: Bacterial Pollution, Brackish Ecosystem, Chilika Lake, Heavy Metals, Physicochemical Parameters.

Introduction

The Bay of Bengal can be accessed from Chilika Lake, which covers the districts of Puri, Khurda and Ganjam in Odisha. The dynamism of the lake ecosystem was marked by inconsistent gradients of salinity and other physicochemical characteristics for a long. Studies on flora and fauna, as well as on the physicochemical properties of Chilika were preliminary work known (1). Indeed, in considering the present water pollution levels at Chilika, it was intuitive to initiate this study. The large population of the state of Odisha has cumulative adverse effects on the ecosystem of Chilika Lake, through fish farming, natural fish-catching, tourism and local water transport etc. A water body regulates the adjoining land area and influences climatic conditions, supports flora and fauna, agriculture and pisciculture, while being linked to various natural life processes, including transportation and the economics of the zone. Lake Chilika is located in Eastern Odisha as a brackish-water dynamic lake that supports a group of seasonal migratory birds during winter. Indeed, the lake helps support commercial pisciculture and transports several village-islands located inside the lake.

Typically, characteristics of physical, chemical and biological compositions of the water dictate the status of a water body. Additionally, uses of agricultural chemicals, fertilizers and pesticides pollute the water and quick preparatory industrializations significantly add to soil and water contaminations equally. Eventually, a decline in the aquatic biodiversity and the physicochemical state of water occurs. The use of contaminated water by humans should lead to problems in public health with waterborne infections or destroy aesthetic values. Chilika is a rich source of marine fish for these and adjoining

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states, commercially.

Thus, it is crucial to examine the water quality of this Brackish water lake, after a few gaps in work in the face of some similar studies (2). Moreover, most freshwater bodies are getting contaminated, rendering the water less potable and aesthetically usable worldwide. A lake is essentially a sizable body of water surrounded by land that is home to numerous aquatic creatures.

This lake was included as a 'Ramsar site' in the Montreux records in 1993 (3). The size of the lagoon remains at 906 km^2 in the summer, while 1,165 km^2 during both monsoon and winter (4). Indeed, the central sector is the intermixing brackish zone receiving saline water from the Southeastern Bay of Bengal and fresh water from the Tributaries of the Mahanadi River at the Northern and Western sides of the lake. Rivulets of the Mahanadi River are Daya, Bhargavi, Nuna and Makara, providing freshwater on the Northern side; while Mandakini, Kansari, Salia and several other tiny streams provide freshwater on Western Chilika. Thus, three subsystems, the Mahanadi River tributaries and streams from the Western catchment release fresh water to the lake; through a direct connection to the Bay of Bengal at the 'Mugger Mukh Channel', seawater enters the lake during the high-tide time. A fisher community of approximately 140,000 people is supported at the islands inside the lake, with a catchment area of roughly 4,406 km^2 (5). Along with fisheries, various migratory birds are found in Chilika during winter, as an essential part of the total biota. Chilika has a sediment load that increases through the silt carried by rivers, rendering the lagoon richer in mineral nutrients and continually leading to natural eutrophication and the organic matter progressively causes the sediment load with concomitant increases of macrophytes, widely (6). Commercial practices like fishing and jetties contribute to petroleum pollutants to the water environment; an enormous number of boats passing through the lagoon for fishing and leisure activities severely tax the ecology. By default, being an estuarine environment, the inherent salinity variation in the lagoon induces several problems in the survival of both flora and fauna.

The presently seen environmental deterioration could have some additional adverse effects on Chilika since the Bay of Bengal experienced a considerably high number of tropical storms during the last decade. The current study assessed the quality of Chilika water with a special reference to physicochemical properties, during 2022-23. Special to this lake, periodic tropical storms have devastated the typical normal conditions, almost every year, for the last decade. Understanding its water quality is essential to its long-term survival as a vital habitat for local fishermen, migrating birds and aquatic biodiversity. Seasonal variations in precipitation, temperature and salinity have an impact on the distribution and behavior of the chemical constituents of the lake and the physicochemical properties of the water have a direct impact on biological productivity and ecological health. Through a comprehensive evaluation of these fluctuations over the three primary seasons, this study seeks to discover trends and possible environmental hazards. The dynamic water quality fluctuation of Chilika Lake has been highlighted by recent studies, especially the freshwater input and seawater exchange-induced changes in salinity and nutrients that are frequently made worse by cyclones and other extreme weather events (7, 8). A thorough spatiotemporal investigation shows that the lagoon's physicochemical properties, such as dissolved oxygen, salinity and nutrients, exhibit significant sectoral and seasonal variations (9). Additionally, exposure to heavy metals is causing increasing worry. Uncontrolled tourism, agricultural runoff and aquaculture effluents have all been connected to elevated levels of Pb, Cd and Hg in sediments and water (10-12). The importance of ongoing monitoring has been highlighted by studies that have shown cancer and environmental health problems that impact the local community. Geographic Information Systems (GIS) and remote sensing methods have been used to evaluate water quality indicators, habitat mapping and sedimentation patterns. Despite these advancements, less research has been done that integrates assessments of microbiological contamination in different zones with regional mapping. The microbial ecology investigations have discovered several bacterial assemblages as a result of the widespread use of metagenomics and community-level sequencing, despite the fact that these techniques provide significant ecological insights (13). The dangers that pathogenic and resistant microorganisms in Chilika pose to human and animal health are thus not entirely understood

(14, 15). While earlier research has examined hydrological dynamics, heavy metal pollution and microbial diversity in tandem, no integrated study has yet to effectively combine multi-zonal GIS mapping, seasonal physicochemical assessments and automated VITEK-2 profiling for microbial identification. The goal of this study is to bridge this gap by providing a comprehensive assessment of the lake's condition and its impact on public health, tourism and fisheries.

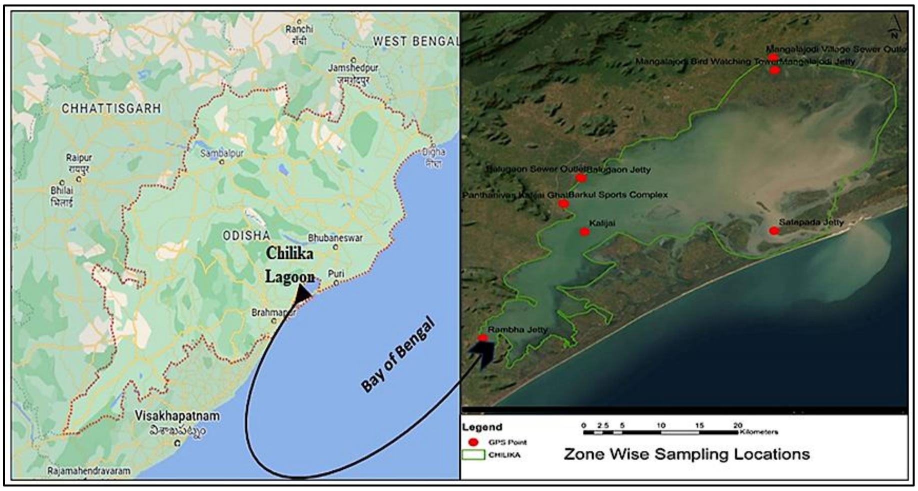

Figure 1: Locations of Sampling Sites at Chilika Lake

Table 1: Geographical Positions of 10 study Sites of Chilika Lake

Sample stations	S no.	Name	Longitude° E	Latitude° N
Northern sector	S1	Mangaljodi village sewer outlet	85.436149° E	19.913916° N
	S2	Mangaljodi bird-watching tower	85.438194° E	19.896122° N
	S3	Mangaljodi jetty	85.4382° E	19.8963° N
Central sector	S4	Balugoan sewer outlet	85.203814° E	19.742991° N
	S5	Balugoan jetty	85.211389° E	19.742749° N
	S6	Panthanivas Kalijai ghat	85.191477° E	19.706237° N
	S7	Barkul sports complex	85.191729° E	19.705987° N
	S8	Kalijai	85.216162° E	19.66551° N
Southern sector	S9	Rambha jetty	85.09759° E	19.51366° N
Outer sector	S10	Satapada jetty	85.437571° E	19.666998° N

*S: Site. During the pre-monsoon summer (March to June), monsoon (July to October) and winter (November to February) seasons of 2022 to 2023, water samples were collected three times as replicates from each site.

Materials and Methods

Ten locations, Sites (S) 1 to 10, were selected within the Northern, Central, Southern and Outer Channel Sectors of Chilika Lagoon, including jetties, sewage discharges, bird habitats and tourism attractions (Figure 1). Mangaljodi village sewer outlet, 2. Mangaljodi bird-watching tower and 3. Mangaljodi jetty in the northern sector. In the central sector, samples were taken at site 4. Balugaon sewer outlet, 5. Balugaon jetty, 6. Panthanivas Kalijai ghat, 7. Barkul Sports Complex and 8. Kalijai. In the southern sector 9. Rambha jetty and in the outer sector 10. Satapada jetty lending water samples (Table 1).

Sampling and Physicochemical Analysis

The physicochemical parameters of the cited sites, general- pH of water, total hardness (TH), total alkalinity (TA), sulfates, chlorides, nutrients- nitrates, nitrites, ammoniacal compounds, hydrogen sulfide and metals- iron, copper, lead, manganese, mercury, zinc, fluorides and sodium chloride were assessed. Measured values of parameters are expressed in parts per million (ppm), whereas pH is a dimensionless parameter.

GIS Mapping

The exact locations of 10 sampling were coordinated (latitude ° N, longitude ° E) by using a geographical information system (GIS) as shown in Table 1. Images were drawn using QGIS and ArcGIS was used to strain the layout (Figure 2) to ensure spatial accuracy of the study. The sampling locations ranged between 19.51366° N to 19.913916° N latitude and 85.09759° E to 85.438194° E longitude.

Isolation and Identification of Bacteria

An automated microbiological identification system, the VITEK 2 system version 9.902, was used in conjunction with the Gram Positive (GP) card (GP Bar Code: 2422251403265943). With lot numbers: 2422251403, the testing Instrument: 00001B1B3D33 [20607], McFarland: 0.60 [0.50-0.63], the approach was employed for the quick identification of bacteria within the analysis time of 7.78 hr. This technique allowed for the quick and efficient detection of bacteria isolated from water samples at high throughput. We were able to learn more about the microbial ecology of the lake by accurately identifying the bacterial species connected to pollution and associated diseases.

Statistical Analysis

A one-way ANOVA was performed to identify seasonal variations across all parameters using significant testing to find seasonal changes. A one-way analysis of variance (ANOVA) with a significance level of $p < 0.05$ was applied to all observed parameters. Prior to ANOVA, the Shapiro-Wilk test and Levene's test were used to demonstrate the homogeneity of variance and normality assumptions, respectively. SPSS version 22.0 was used for all statistical analyses. The mean ± standard deviations of the data are displayed. Relationships between the variables were examined using Pearson's correlation analysis; correlations were deemed statistically significant at $p < 0.05$.

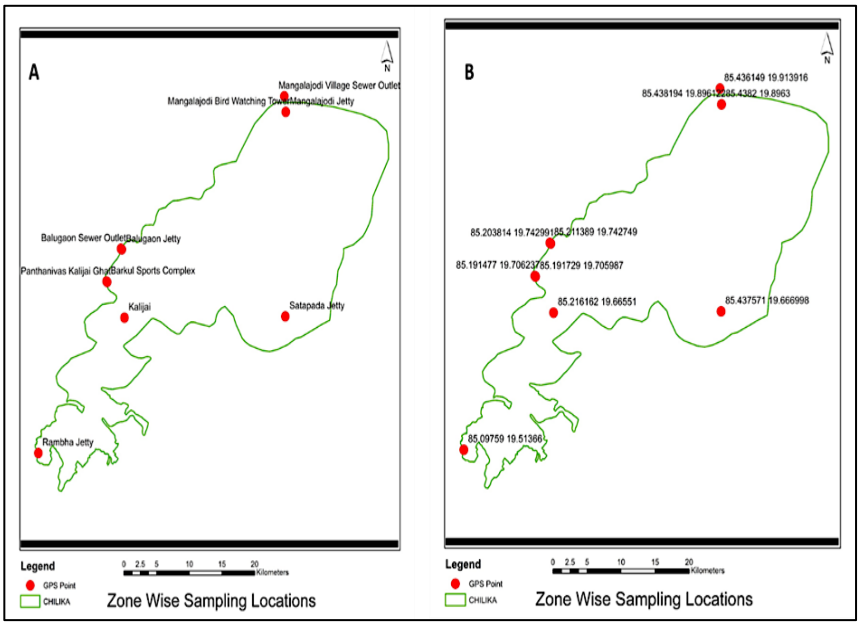

Figure 2: Zone Wise Sampling Locations – (A) Map of Chilika Lake Showing Names of The Sampling Sites, (B) Map of Chilika Lake Showing the Longitude and Latitude of Those Sites (GIS Mapping by Using Arcgis)

Table 2: Water Parameters of Chilika Lake in Summer

	SUMMER																
Parameters (ppm)	pH	TH	TA	SO_4	Cl^-g/l	NO_2	NO_3	NH_4	H_2S	Fe	Cu	Pb	Mn	Hg	Zn	F^-	NaCl
S1	8	425	400	200	3	1	10	0.25	0	0	0.1	0	0	0	5	4	2000
S2	8	425	400	200	3	0	0	0.25	0	0	0.2	5	0	0	5	0	2000
S3	8	425	400	200	3	0	10	0.25	0	0	0.2	5	0	0.002	5	4	2000
S4	8.5	425	300	200	3	0	0	0.25	0	0.3	0	5	0.05	0	5	0	2000
S5	8.5	425	440	400	5	1	10	0.25	0	0.3	0.1	15	0.05	0.002	0	4	2000
S6	8.5	425	400	400	5	1	10	0.5	0	0.3	0	5	0.05	0	0	4	1000
S7	8	425	400	400	5	1	10	0.5	0.5	0	0.1	5	0.05	0	5	0	1000
S8	8.5	425	400	400	5	1	10	0.5	0.5	0.3	0.4	15	0.1	0	0	4	2000
S9	8.5	425	400	200	1	0	0	0.25	0	0.3	0.2	5	0.05	0	5	4	2000
S10	8.5	425	400	400	5	1	0	0.25	0	0	0.1	5	0	0	5	4	2000

*pH: Potential of hydrogen (unitless measure of acidity/alkalinity); TH: Total Hardness (mg/L as $CaCO_3$); TA: Total Alkalinity (mg/L as $CaCO_3$); SO_4^{2-}:Sulphate (mg/L); Cl^-: Chloride (g/L); NO_2^-:Nitrite (mg/L); NO_3^-: Nitrate (mg/L); NH_4^+:Ammonium (mg/L); H_2S: Hydrogen sulphide (mg/L); Fe: Iron (mg/L); Cu: Copper (mg/L); Pb: Lead (mg/L); Mn: Manganese (mg/L); Hg: Mercury (mg/L); Zn: Zinc (mg/L); F^-: Fluoride (mg/L); NaCl: Sodium chloride (mg/L), Notation: S1–S10: Sites of Chilika Lake during the summer season

Notes: All parameters are expressed in mg/L (ppm) unless otherwise stated. Chloride (Cl^-) is expressed in g/L. Values represent measured concentrations at respective sampling sites..“0” indicates below the detectable limit or absence of the parameter.

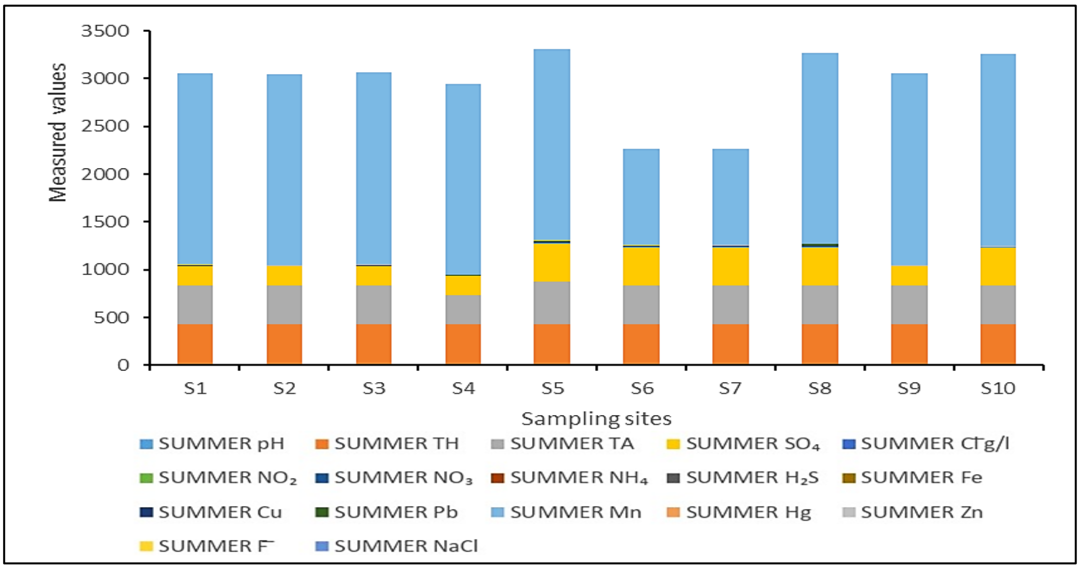

Figure 3: Spatial Variation of Physicochemical Parameters in Water Samples Collected from Different Sampling Sites (S1-S10) During the Summer Season

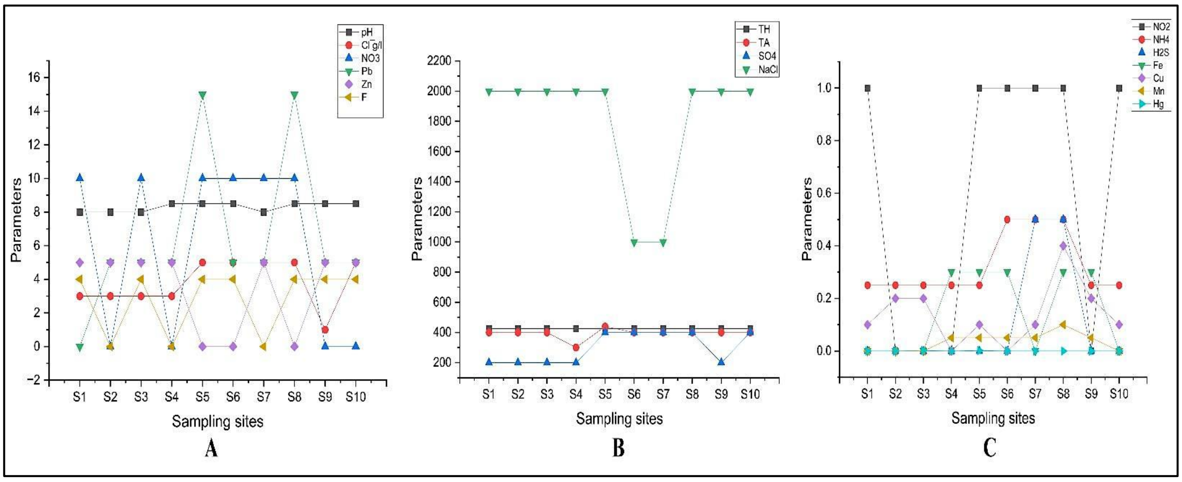

Figure 4: Variation of physicochemical parameters across sampling sites (S1–S10) during the summer season: (A) pH, Cl^-, NO_3^-, Pb, Zn and F^-, (B) TH (Total Hardness), TA (Total Alkalinity), SO_4^{2-} and NaCl, (C) NO_2^-, NH_4^+, H_2S, Fe, Cu, Mn and Hg

Results

Seasonal Changes in Physicochemical Parameters

pH

The pH of aquatic environments, which affects the formation of phytoplankton, is one of the key elements that regulate the quantity of carbon and nutrients present. Compared to seawater, the pH of coastal water varies considerably between locations as shown in Table 2 and Figure 3. The pH remained alkaline, 7.4 –10.3, throughout the survey and did not significantly differ among the studied sectors; however, there was a temporal shift (16). According to this study, the highest water pH values during the summer were identified in S4, S5, S6, S8, S9 and S10 (Figure 4), while the lowest values were found in S1, S2, S3 and S7. For the winter, lower pH levels were observed at S4 and S5. The water pH at the sample sites, S6, S9 and the outer channel (S10) remained alkaline throughout the year as shown in Tables 3 and 4.

The three sites with the highest pH, 7, during the wet season were S2, S3, S6, S8 and S10. In the winter the sites, S1, S2, S3, S6, S7, S8, S9 and S10 had the highest pH values. The water was alkaline because of the salt in the river and the ocean that drained into the lagoon. The water salinity could be too high, if the pH is alkaline range (17). Furthermore, the water in the lake was mostly alkaline during summer and winter, with pH levels between 7.0 and 8.5 at all stations. But in the rainy season, the pH dropped and the water became acidic, going as low as 6.0 at station S1. This change can harm aquatic animals and plants and also make harmful metals dissolve more easily in the water, increasing health risks.

Total Hardness (TH) and Total Alkalinity (TA)

The TH of the lake water was mostly the same at 425 ppm during most seasons. But during the rainy season, it became lower, between 210 to 220 ppm at many places. The TA, which helps to balance the pH of the water, dropped to 0–1 ppm during the winter and rainy seasons. Thus, the water had a very weak buffering capacity, making it easier for the pH to change suddenly, which can make the water unstable and unsafe for use.

Sodium Chloride (NaCl) and Chloride (Cl^-)

According to earlier research, the chloride content was higher in the winter than in other seasons (18). This study analyzed that the chloride content was higher in the summer and that S10, 10gm/l had the greatest chloride levels when it rained as shown in Table 2. The outer Channel has a higher chloride level compared to other areas with higher salinity. Chloride levels were highest at S6, S7, S8 and S10 among the sites in the summer and lowest at S9 as shown in Table 2 and Figure 3. S8 and S10 had larger levels during the winter, while S1, S2, S3 and S4 had the lowest values as shown in Table 3. The salinity of the lake water was high in most seasons, reaching up to 2,000 ppm of common salt (NaCl). Only at stations S6 and S8, during some times, the salt level was lower at 1,000 ppm. Drinking this salty water without treatment can be harmful to people. It can increase the risk of high blood pressure (hypertension) and kidney problems, especially in people who are already sensitive to salt. According to records, the lowest average NaCl level during observations in 2022–2023 was 1,000 ppm. The highest locations throughout the winter were associated with river/rivulet discharge and an average NaCl value of 2,000 ppm was noted. All sites except S4, S5, S6, S7 and S10 observed low NaCl levels during the rainy season. The lagoon inlet eventually became narrower due to natural siltation, which also changed tidal fluxes. Freshwater input reduced salinity from the previously measured value of [5.5 1.3] in the Northern and Central Sectors; according to the salinity readings [12.5 1.2 psu], the water was brackish. In the outside channel, the salinity was higher [20.7, 1.8 psu] (19). Seasonal and spatial salinity gradients were consistently present throughout the lagoon due to regular seasonal patterns, freshwater flowing via the Northern Sectors and saltwater flowing through the outer channel. Salinity substantially declined from 2013 to 2014, the time of the extreme occurrence (19). The summertime decreases in water volume in the lagoon led to a rise in water salinity. Due to the high temperatures during the summer, excessive water evaporation in the Chilika lagoon occurred, which increased the salinity of the water. In this investigation, the outside channel consistently had the greatest salinity levels. This can be the result of seawater getting into the lagoon. The salt level in the northern sector was low because of the influx of freshwater into the lagoon during the rainy and winter seasons through rivers and water channel systems. River water entering the lagoon may be the cause of the lower salinity level in the Northern sector. In the monsoon and winter, the salinity level of the water in Chilika Lagoon was lower.

Nitrate (NO_3^-), Nitrite (NO_2^-) and Ammonia (NH_4^+)

During the rainy season, the levels of nitrate and ammonium increased a lot. Nitrate (NO_3^-) reached up to 25 ppm at several stations like S1, S3 and S6 to S8. Too many of these nutrients in lake water can cause eutrophication, where algae grow too fast. This can lead to algal blooms, which use up the oxygen in the water, making it hard for fish and other animals to survive. Some algae also produce harmful toxins (cyanotoxins) that can affect human health if people come in contact with the water or eat contaminated fish. Prior observations showed that over the 2013 pre-monsoon, monsoon and post-monsoon seasons, the average NO_3^- concentrations steadily increased; this pattern persisted in 2014. The effects of NO_3^- adding processes brought on by tropical cyclones were blamed for the peak NO_3^- concentration during the post-monsoon season. The larger influence of freshwater enriched with nitrogenous nutrients from the nearby catchment was linked to the higher NO_3^- NO_3^- concentrations in the Northern sectors (20). The Southern sectors region had lower NO_3 observations, which showed that influxes from nutrient-rich rivers had not yet reached this area (16). Sites S1, S2, S3, S5, S6, S7 and S8 in the summer and S1, S2, S3, S5, S6, S7 and S8 in the winter, respectively, were the sites with higher nitrate levels. Compared to other seasons, the rainy season had the highest levels of nitrate, peaking in S1, S3, S6, S7 and S8, as well as S2, S4, S5, S9 and S10. Over the year, 2022-23 (Figures 5 and 6), the nitrate concentration in the water fluctuated. According to the current analysis, the nitrate content was highest during the wet season. In the northern sector, a greater nitrate level was caused by the presence of large rivers and agricultural drainage (21).

Table 3: Water Parameters of Chilika Lake in Winter

	WINTER																
Parameters (ppm)	pH	TH	TA	SO_4	Cl^-g/l	NO_2^-	NO_3^-	NH_4^+	H_2S	Fe	Cu	Pb	Mn	Hg	Zn	F^-	NaCl
S1	7.5	425	0	200	1	1	10	0.25	0	0	0	0	0	0	0	0	2000
S2	7.5	425	0	200	1	1	10	0.25	0	0	0	5	0	0	0	0	2000
S3	7.5	425	0	0	1	0	10	0.25	0	0	0.2	0	0	0.002	0	4	2000
S4	7	425	1	200	1	0	0	0.25	0.5	0.3	0	5	0	0	0	0	2000
S5	7	425	0	200	3	1	10	0.25	0.5	0	0	5	0	0	5	0	2000
S6	7.5	425	0	200	3	1	10	0.5	0	0.3	0	0	0	0.002	0	4	2000
S7	7.5	425	0	200	3	1	10	0.5	0.5	0.3	0.2	5	0.05	0	0	0	2000
S8	7.5	425	0	200	5	1	10	0.25	0.5	0	0.2	0	0	0.002	0	0	1000
S9	7.5	425	0	200	3	1	0	0.25	0	0	0.1	5	0.1	0	0	0	2000
S10	7.5	425	0	200	5	1	0	0.5	0.5	0	0	15	0	0	0	4	2000

*pH: Potential of hydrogen (unitless measure of acidity/alkalinity); TH: Total Hardness (mg/L as $CaCO_3$); TA: Total Alkalinity (mg/L as $CaCO_3$); SO_4^{2-}:Sulphate (mg/L); Cl^-: Chloride (g/L); NO_2^-:Nitrite (mg/L); NO_3^-: Nitrate (mg/L); NH_4^+:Ammonium (mg/L); H_2S: Hydrogen sulphide (mg/L); Fe: Iron (mg/L); Cu: Copper (mg/L); Pb: Lead (mg/L); Mn: Manganese (mg/L); Hg: Mercury (mg/L); Zn: Zinc (mg/L); F^-: Fluoride (mg/L); NaCl: Sodium chloride (mg/L), Notation: S1–S10: Sites of Chilika Lake during the winter season

Notes: All parameters are expressed in mg/L (ppm) unless otherwise stated. Chloride (Cl^-) is expressed in g/L. Values represent measured concentrations at respective sampling sites. "0" indicates below the detectable limit or absence of the parameter.

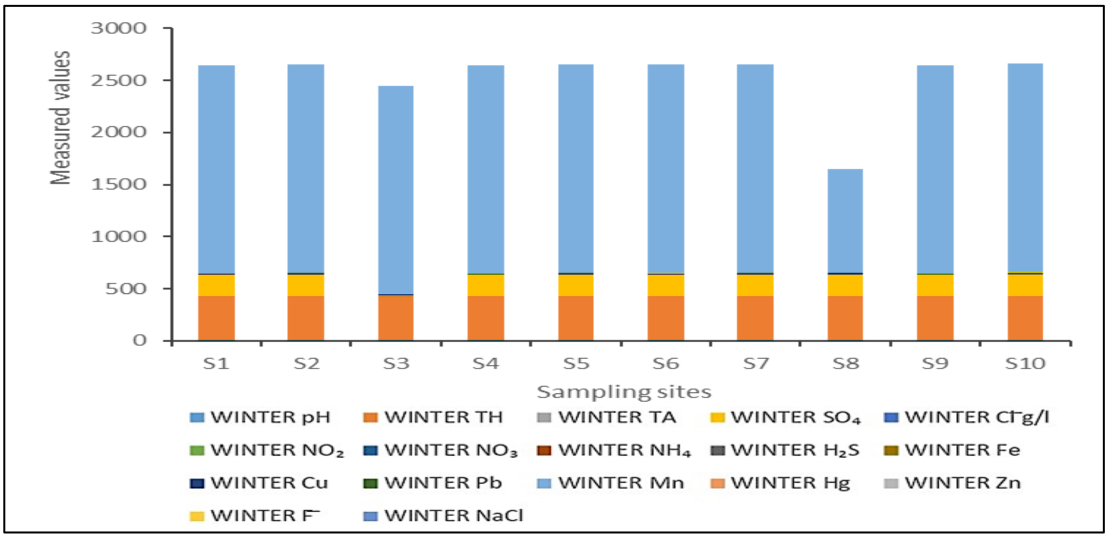

Figure 5: Spatial Variation of Physicochemical Parameters in Water Samples Collected from Different Sampling Sites (S1-S10) During the Winter Season

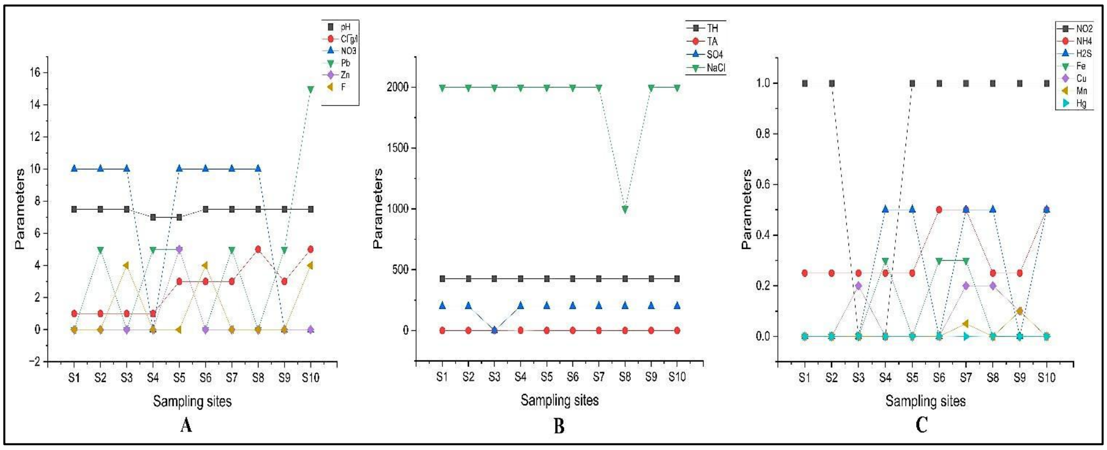

Figure 6: Variation of physicochemical parameters across sampling sites (S1–S10) during the winter season (A) pH, Cl^-, NO_3^-, Pb, Zn and F^-, (B) TH (Total Hardness), TA (Total Alkalinity), SO_4^{2-} and NaCl, (C) NO_2^-, NH_4^+, H_2S, Fe, Cu, Mn and Hg

During the rainy season, the water had a low chloride level of S3, 0.5gm/l (Figure 7). This might be because of how quickly water evaporates and seawater seeps in. The open inflow of seawater via the mouth of the outer channel during the summer may be the reason for the high chloride level in the outer channel (22). The lowest chloride concentration in the Central sector can be attributed to rivers and runoff mixing fresh water into the lake and during summer days, an increase in the chloride level of the outer channel (23) as shown in Tables 2 and 3. In 2013, the pre-monsoon period had the greatest NO_2^- concentrations, followed by the post-monsoon period, while the monsoon season had the lowest values. Contrary to NO_3^-, there was no discernible trend in the temporal change of NO_2^-. Contrary to the trend from the year before, in 2014, the post-monsoon period was when NO_2^- concentrations were highest, while the monsoon season was once again when those were lowest. The spatial distribution of NO_2^- indicated that the northern sectors had a higher concentration during the study period than the southern sectors (19). According to recent studies, the core and outside portions of Chilika Lake have higher NO_2^- concentrations than other areas (Figure 6). During the summer, the highest nitrite concentrations were found at locations S1, S5, S6, S7, S8 and S10. The nitrite concentrations were low all winter long compared to past seasons. The study discovered that S6, S7, S8 and S10 had the highest nitrite content during the wet season as shown in Table 4. The necessary inorganic nutrient NH_4^+ is secreted by aquatic animals and used by phytoplankton (24, 25). Demineralization of organic matter and zooplankton excretion are significant factors in phytoplankton ecology, but NH_4^+ is mostly delivered into the lagoon by terrestrial runoff. This examination found that the central sector, S6, S7 and S8 had higher-than-normal NH_4^+ concentrations. S6, S7 and S10 had the highest NH_4^+ concentrations during the winter and these concentrations were lower on days when it rained than during the other two seasons.

Heavy Metals and Toxic Elements, Lead (Pb), Zinc (Zn), Fluoride (F^-), Sulfate (SO_4), Sulfide (H_2S), Iron (Fe), Copper (Cu), Manganese (Mn) and Mercury (Hg)

During the summer, the highest levels of lead [15 ppm] were found at stations S5 and S8, which are much higher than the safe limit set by the WHO, 0.01 ppm. Copper levels also went up to 0.4 ppm. Manganese and mercury were sometimes found, especially near towns and jetties. If people are exposed to these metals for a long time, it can cause serious health problems. Lead and mercury can harm the brain and nervous system. Copper and zinc can damage the liver and kidneys. These metals are especially harmful to children as they can affect their growth and development. Also, when fish in the lake take in these metals, the harmful substances can build up in their bodies. If people eat these fish, they can also be affected. Throughout the year, the Pb value ranged from 5 to 15 ppm. Lead was detected at the maximum level during the summer at S5 and S8 as shown in Table 2, or 15 ppm. The maximum level was noted at S10 during the winter as shown in Table 3 and S2 during the wet season as shown in Table 4. Zinc concentration was observed as 5 ppm in Chilika at sites S1, S2, S3, S4, S7, 9 and 10 during summer, S5 in winter and S3, S5 and S6 in the rainy season as shown in Figure 8. F^- concentration showed 4ppm at S1, S3, S5, S6, S8, S9 and S10 during summer season, at S3, S6 and S10 during winter and at S4, S6, S7 and S10 during rainy season as shown in Figures 7 and 8.

Table 4: Water Parameters of Chilika Lake in Rainy

	RAINY																
Parameters (ppm)	pH	TH	TA	SO_4	Cl^-g/l	NO2⁻	NO_3^-	NH_4^+	H_2S	Fe	Cu	Pb	Mn	Hg	Zn	F^-	NaCl
S1	6	210	0	200	1	1	25	0.5	0.5	0	0	5	0.05	0	0	0	1000
S2	7	425	0	0	1	1	10	0.5	0.5	0	0.1	15	0.05	0	0	0	1000
S3	7	425	0	0	0.5	1	25	0.5	0.5	0.3	0.1	0	0	0	5	0	1000
S4	6.5	220	0	0	5	1	10	0.5	0.5	0	0.2	5	0	0.002	0	4	2000
S5	6.5	220	0	200	3	1	10	0.5	0.5	0	0.1	0	0	0	5	0	2000
S6	7	425	0	200	3	5	25	0.25	0.5	0.3	0.1	0	0	0	5	4	2000
S7	6.5	220	0	200	5	5	25	0.25	0.5	0.3	0.2	5	0.1	0	0	4	2000
S8	7	425	0	200	3	5	25	0.5	1	0	0.1	0	0	0.002	0	0	1000
S9	6.5	220	0	200	5	1	10	0.5	1	0	0	5	0.05	0	0	0	1000
S10	7	425	0	200	10	5	10	0.5	0.5	0	0	5	0	0	0	4	2000

*pH: Potential of hydrogen (unitless measure of acidity/alkalinity); TH: Total Hardness (mg/L as $CaCO_3$); TA: Total Alkalinity (mg/L as $CaCO_3$); SO_4^{2-}:Sulphate (mg/L); Cl^-: Chloride (g/L); NO_2^-:Nitrite (mg/L); NO_3^-: Nitrate (mg/L); NH_4^+:Ammonium (mg/L); H_2S: Hydrogen sulphide (mg/L); Fe: Iron (mg/L); Cu: Copper (mg/L); Pb: Lead (mg/L); Mn: Manganese (mg/L); Hg: Mercury (mg/L); Zn: Zinc (mg/L); F^-: Fluoride (mg/L); NaCl: Sodium chloride (mg/L), Notation: S1–S10: Sites of Chilika Lake during the rainy season

Notes: All parameters are expressed in mg/L (ppm) unless otherwise stated. Chloride (Cl^-) is expressed in g/L. Values represent measured concentrations at respective sampling sites. "0" indicates below the detectable limit or absence of the parameter.

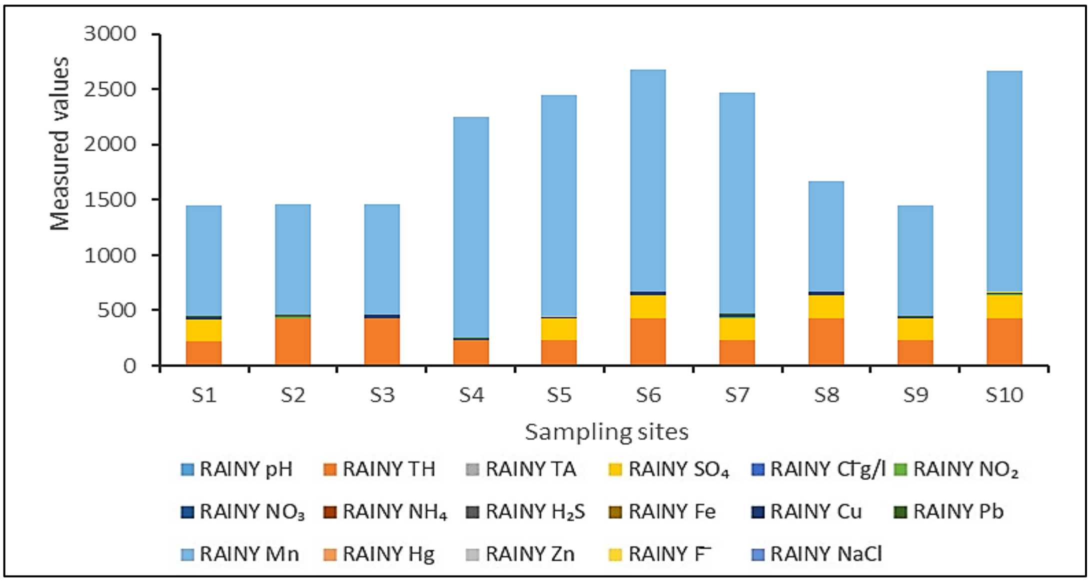

Figure 7: Spatial Variation of Physicochemical Parameters in Water Samples Collected from Different Sampling Sites (S1-S10) During the Rainy Season

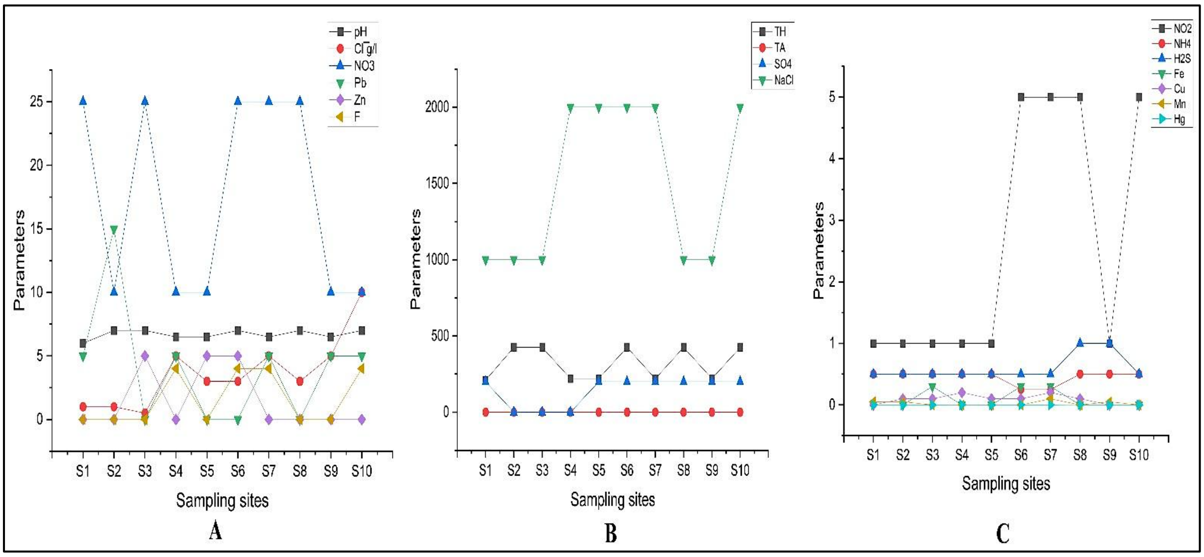

Figure 8: Variation of physicochemical parameters across sampling sites (S1–S10) during the rainy season (A) pH, Cl^-, NO_3^-, Pb, Zn and F^-, (B) TH (Total Hardness), TA (Total Alkalinity), SO_4^{2-} and NaCl, (C) NO_2^-, NH_4^+, H_2S, Fe, Cu, Mn and Hg

It was observed that the water in Chilika had high alkalinity and the water from both summer and winter had a hardness of 425 ppm in every area. During the wet season, S1 had a lower hardness, whereas S2, S3, S6, S8 and S10 had a higher hardness as shown in Figure 8. The concentration of SO_4 was highest in S1, S2, S4, S5, S6, S7, S8 and S10 during the summer season and lowest in S1, S2, S3 and S4 during the winter season 200 ppm. It was noted that S1, S5, S6, S7, S8, S9 and S10 had the maximum content during the wet season (Table 4). In summer, H_2S was found at S7 and S8, H_2S was found at S7 and S8; in winter, it was observed at S4, S5, S7, S8 and S10. During the rainy season observed H_2S was found at S1, S2, S3, S4, S5, S6, S7 and S10 (Figure 8). According to recent data, iron concentrations were found to be 0.3 ppm at S4, S5, S6, S8 and S9 during the summer, S4, S6 and S7 during the winter and S3, S6, S7 during the rainy season (Figure 8). Throughout the year, the copper concentration ranged from 0.1 to 0.4 ppm. Cu levels were highest at S8 during the summer and lowest at S1, S4, S5, S6, S7 and S10. During the winter, Cu levels were highest at S3, S7 and S8; during the rainy season, they were highest at S4 and S7. The quantity of Mn in Lake Chilika ranged from 0.05 to 0.1 ppm. Mn level was highest at site S8 during the summer, site S9 during the winter

and site S7 during the wet season. Hg was found to be very low throughout the year in all seasons.
ANOVA showed significant seasonal variation, $p < 0.05$ for criteria, pH, nitrate, ammonium, fluoride and lead. Greater variance during the monsoon because of storms, runoff and exchange of water. A water quality assessment of Lake Chilika is bid with coefficient analysis in the three seasons provided upper and individual lower values for each recorded parameter and those parameters were identified with one variable with an increased with other one with a decreased value; particularly, the zero [0] value indicated no relationship. Correlations and quality of fit between the parameters were determined by taking water samples from the lake at pre-arranged sampling locations and using linear regression analysis on those samples. After establishing the relationship between parameters, the water samples were subjected to a one-way ANOVA. The hypothesis was used to assess the water quality with evaluated probability and residual outputs, which could explain the several changes in water parameters in all seasons. The residual output was explained by the difference between the actual output and the predicted output of the parameters. The residual output of the summer season was predicted by the NaCl parameter, with residuals and standard residuals tabulated and accessed to determine the probability output that determined the null hypothesis to be correct. The structural images had all the parameters, pH, hardness, alkalinity, sulfate, chlorides, nitrates, nitrites, ammonium, hydrogen sulfides; and additionally, metallic contents namely, iron, copper, lead, manganese, mercury, zinc, fluoride; while with the salinity level was explained the changes of the variability of the rest parameters with several seasons (Figures 9-16).

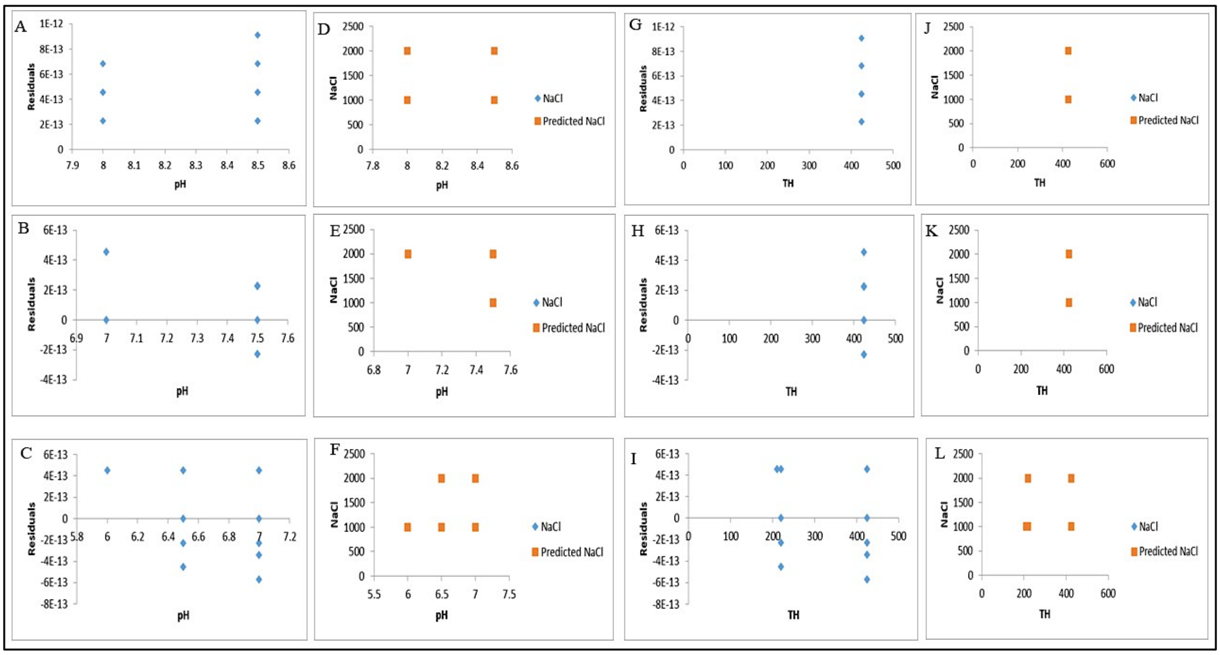

Figure 9: (A) pH Residual Plot in Summer, (B) pH Residual Plot in Winter, (C) pH Residual Plot in Monsoon, (D) pH Line Fit Plot in Summer, (E) pH Line Fit Plot in Winter, (F) pH Line Fit Plot in Monsoon, (G) TH Residual Plot in Summer, (H) TH Residual Plot in Winter, (I) TH Residual Plot in Monsoon, (J) TH Line Fit Plot in Summer, (K) TH Line Fit Plot in Winter and (L) TH Line Fit Plot in Monsoon

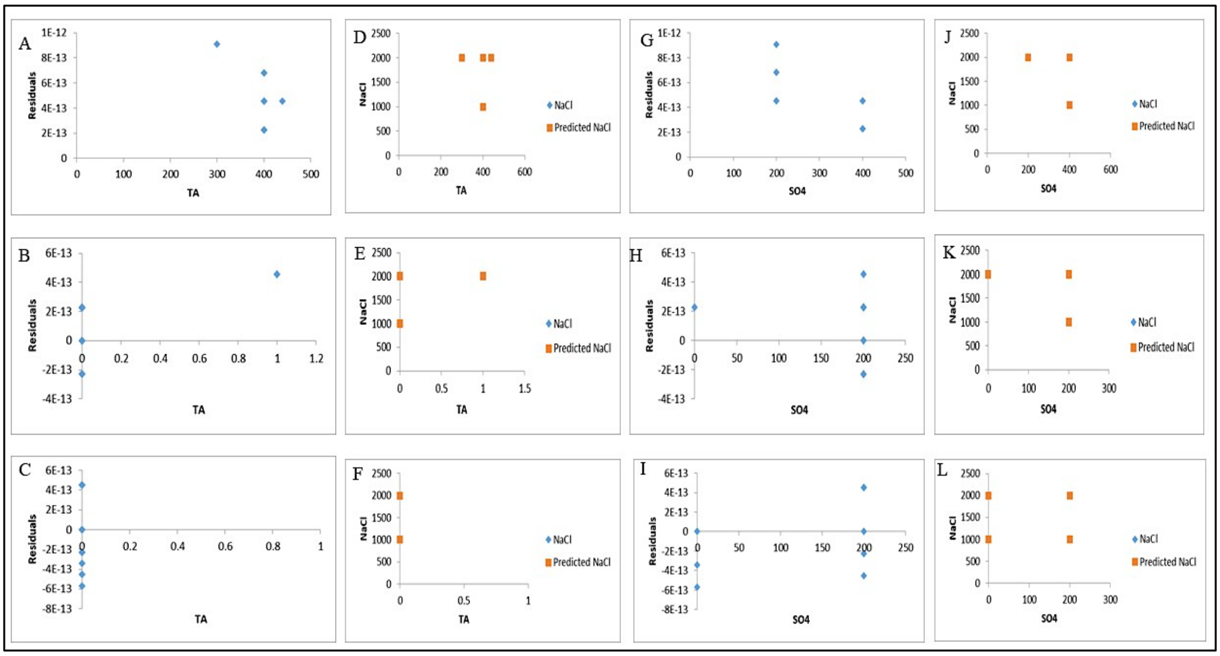

Figure 10: (A) TA Residual Plot in Summer, (B) TA Residual Plot in Winter, (C) TA Residual Plot in Monsoon, (D) TA Line Fit Plot in Summer, (E) TA Line Fit Plot in Winter, (F) TA Line Fit Plot in Monsoon, (G) SO_4 Residual Plot in Summer, (H) SO_4 Residual Plot in Winter, (I) SO_4 Residual Plot in Monsoon, (J) SO_4 Line Fit Plot in Summer, (K) SO_4 Line Fit Plot in Winter and (L) SO_4 Line Fit Plot in Monsoon

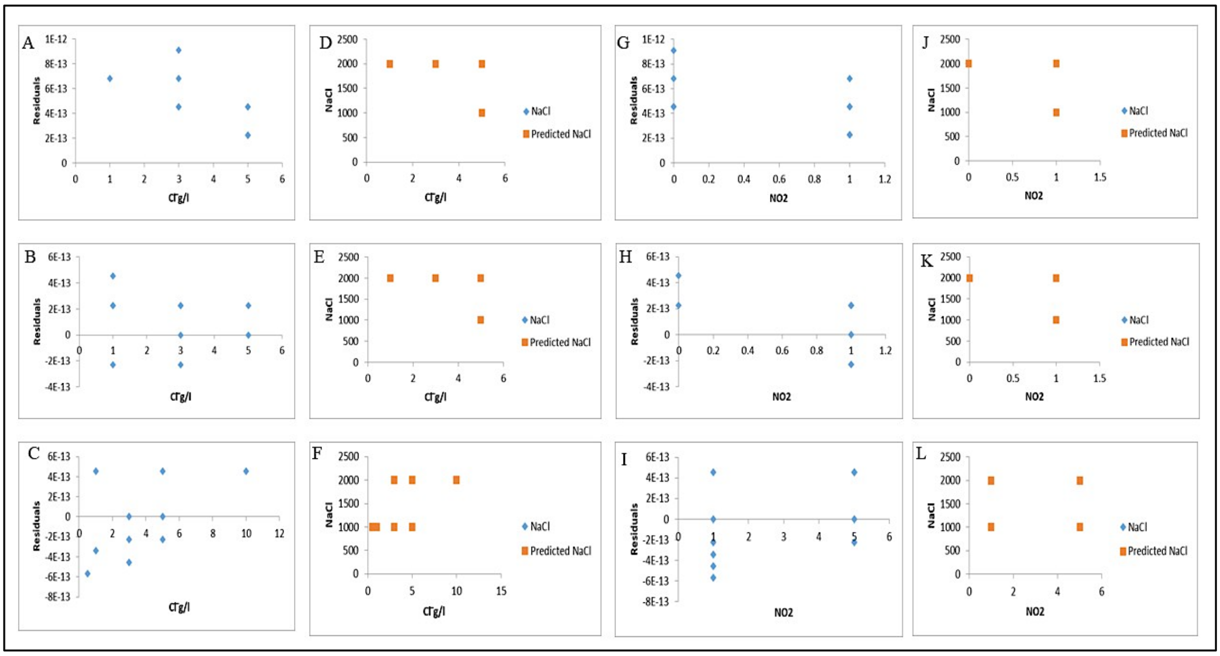

Figure 11: (A) Cl^- Residual Plot in Summer, (B)Cl^- Residual Plot in Winter, (C) Cl^- Residual Plot in Monsoon, (D) Cl^- Line Fit Plot in Summer, (E) Cl^- Line Fit Plot in Winter, (F) Cl^- Line Fit Plot in Monsoon, (G) NO_2 Residual Plot in Summer, (H) NO_2 Residual Plot in Winter, (I) NO_2 Residual Plot in Monsoon, (J) NO_2 Line Fit Plot in Summer, (K) NO_2 Line Fit Plot in Winter and (L) NO_2 Line Fit Plot in Monsoon

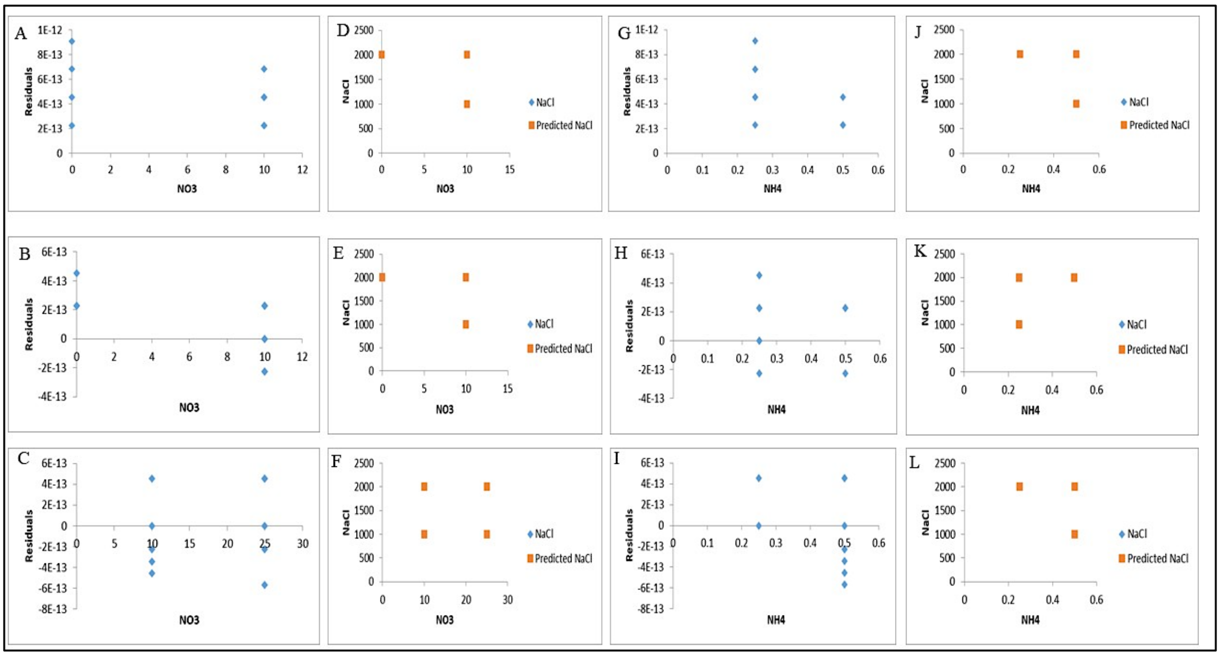

Figure 12: (A) NO_3 Residual Plot in Summer, (B) NO_3 Residual Plot in Winter, (C) NO_3 Residual Plot in Monsoon, (D) NO_3 Line Fit Plot in Summer, (E) NO_3 Line Fit Plot in Winter, (F) NO_3 Line Fit Plot in Monsoon, (G) NH_4 Residual Plot in Summer, (H) NH_4 Residual Plot in Winter, (I) NH_4 Residual Plot in Monsoon, (J) NH_4 Line Fit Plot in Summer, (K) NH_4 Line Fit Plot in Winter and (L) NH_4 Line Fit Plot in Monsoon

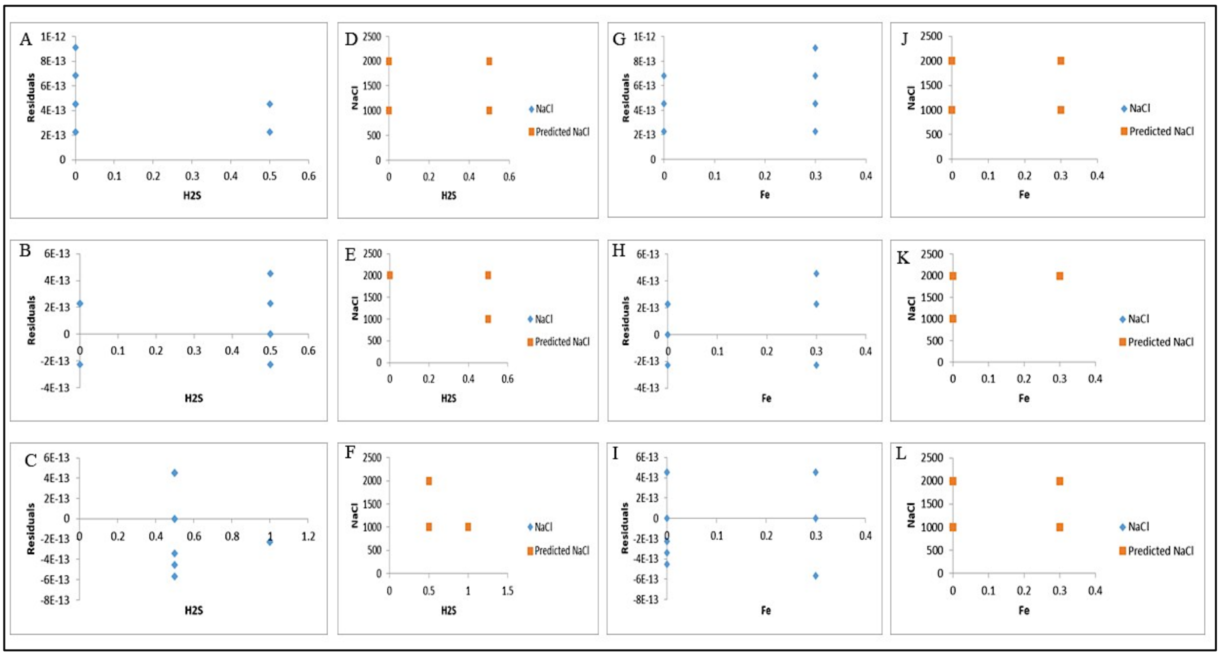

Figure 13: (A)H_2S Residual Plot in Summer, (B) H_2S Residual Plot in Winter, (C) H_2S Residual Plot in Monsoon, (D) H_2S Line Fit Plot in Summer, (E) H_2S Line Fit Plot in Winter, (F) H_2S Line Fit Plot in Monsoon, (G) Fe Residual Plot in Summer, (H) Fe Residual Plot in Winter, (I) Fe Residual Plot in Monsoon, (J) Fe Line Fit Plot in Summer, (K) Fe Line Fit Plot in Winter and (L) Fe Line Fit Plot in Monsoon

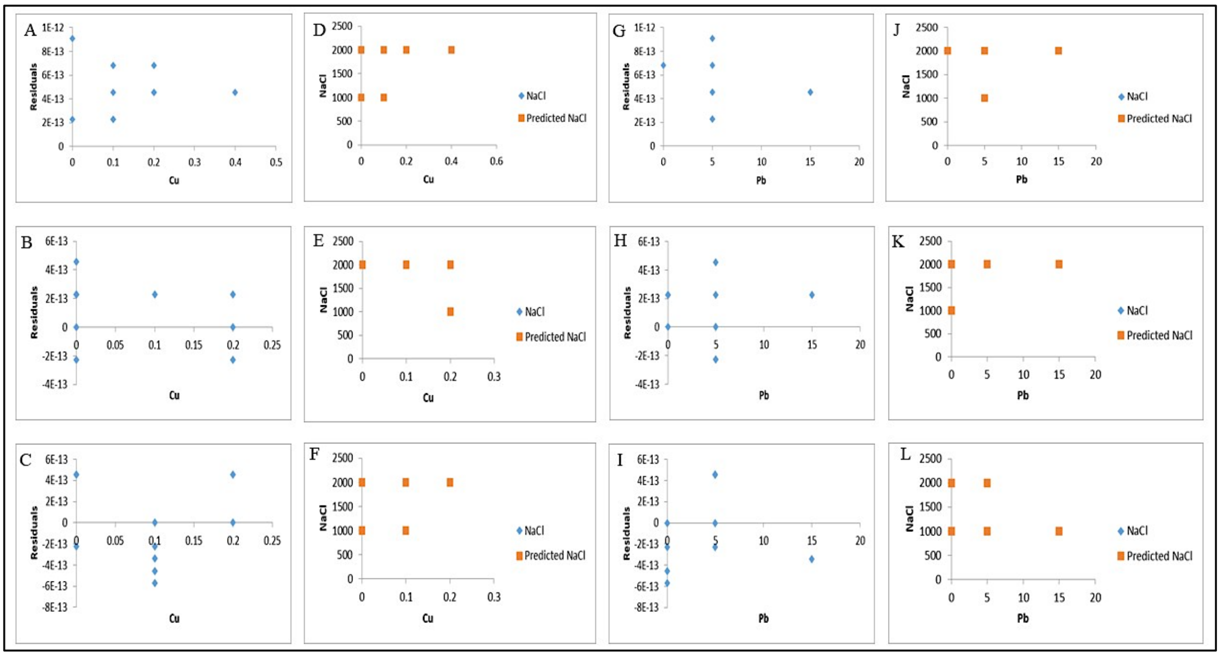

Figure 14: (A) Cu Residual Plot in Summer, (B) Cu Residual Plot in Winter, (C) Cu Residual Plot in Monsoon, (D) Cu Line Fit Plot in Summer, (E) Cu Line Fit Plot in Winter, (F) Cu Line Fit Plot in Monsoon, (G) Pb Residual Plot in Summer, (H) Pb Residual Plot in Winter, (I) Pb Residual Plot in Monsoon, (J) Pb Line Fit Plot in Summer, (K) Pb Line Fit Plot in Winter and (L) Pb Line Fit Plot in Monsoon

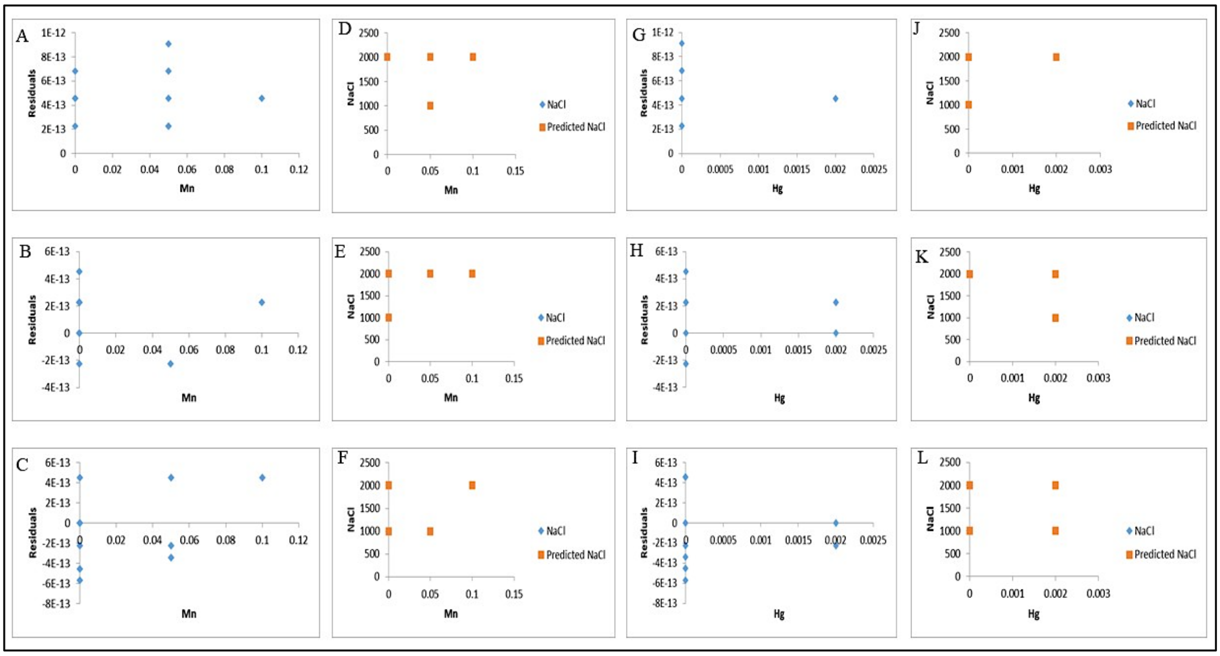

Figure 15: (A) Mn Residual Plot in Summer, (B) Mn Residual Plot in Winter, (C) Mn Residual Plot in Monsoon, (D) Mn Line Fit Plot in Summer, (E) Mn Line Fit Plot in Winter, (F) Mn Line Fit Plot in Monsoon, (G) Hg Residual Plot in Summer, (H) Hg Residual Plot in Winter, (I) Hg Residual Plot in Monsoon, (J) Hg Line Fit Plot in Summer, (K) Hg Line Fit Plot in Winter and (L) Hg Line Fit Plot in Monsoon

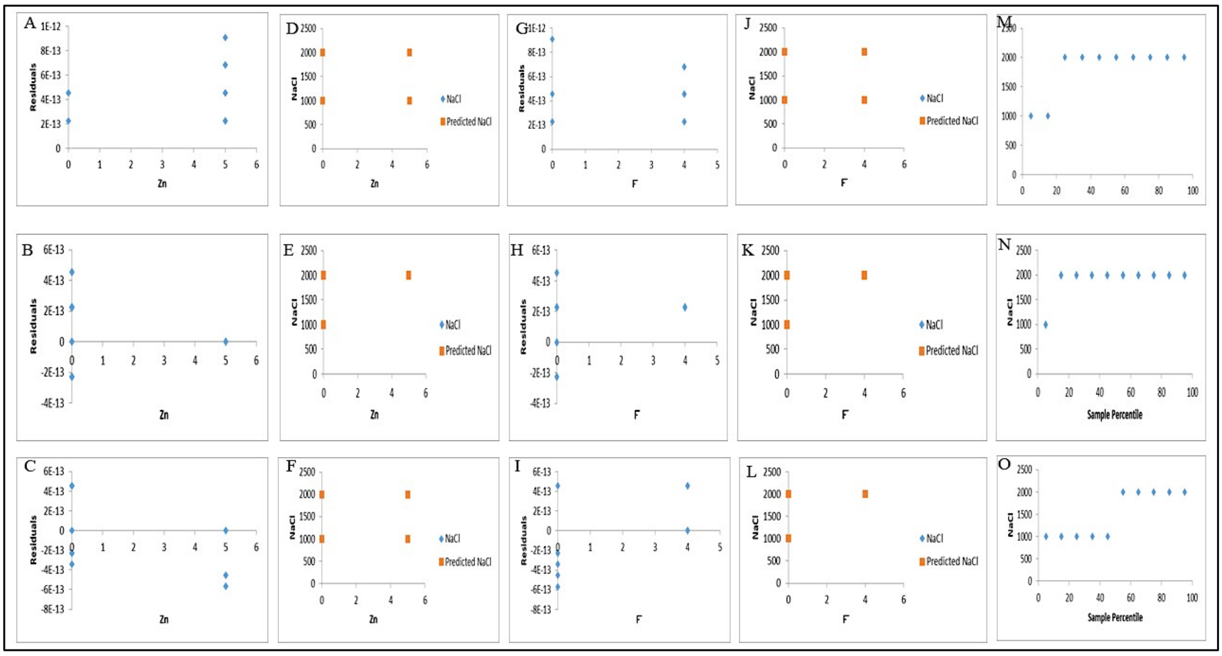

Figure 16: (A) Zn Residual Plot in Summer, (B) Zn Residual Plot in Winter, (C) Zn Residual Plot in Monsoon, (D) Zn Line Fit Plot in Summer, (E) Zn Line Fit Plot in Winter, (F) Zn Line Fit Plot in Monsoon, (G) F- Residual Plot in Summer, (H) F- Residual Plot in Winter, (I) F- Residual Plot in Monsoon, (J) F- Line Fit Plot in Summer, (K) F- Line Fit Plot in Winter and (L) F- Line Fit Plot in Monsoon (M) normal probability plot for summer, (N) normal probability plot for winter and (O) normal probability plot for monsoon

Identification of Bacteria

Using the VITEK 2 systems, two low-discrimination bacteria were analyzed. Using the GP test card, Gram-positive bacteria, specifically *Staphylococcus* sp. were discovered, viz., *Staphylococcus gallinarum* dRAFFINOSE [99] and *Staphylococcus xylosus* dRAFFINOSE [1], with contraindicating some typical biopatterns dSOR [80], SAL [80], dXYL [99] and dRAF [2], dXYL [99], with numbers signposted against each. Instead of identifying a single definitive species, the biochemical patterns generated by the isolates' low-discrimination bacterial profiles matched a large number of possible taxa within the same genus, with similarity indexes determining the likelihood. In particular, the following identification probabilities were used to identify *Staphylococcus* sp. For d-raffinose utilization (dRAF), *Staphylococcus gallinarum* is connected to a 99% chance of a favorable result. While other selected studies provide different results, *Staphylococcus xylosus* has a 1% possibility of fermenting raffinose. The VITEK 2 system also detected several contraindicative biopatterns, which differ from the most likely identification in test results. For d-sorbitol [dSOR, 80%], salicin [SAL, 80%] and d-xylose [dXYL, 99%], these included adverse reactions that did not fully match the typical biochemical profile of the species at the top of the list. This implies that the automated method could not be able to differentiate between closely related species of *Staphylococcus* or might reveal an uncommon strain variation (26, 27).

Public Health Impacts

Chilika Lake is an important water body in Odisha. It supports local people through commercial fishing, tourism and fish-farming. However, the quality of water in the lake changes with seasons, which affects public health. In summer, the level of harmful heavy metals like, lead, mercury and copper increase due to waste from factories and chemicals from farms. These metals are dangerous, especially for children and pregnant women. For example, lead can reach up to 15 ppm and mercury up to 0.1 ppm, which can harm brain, kidneys and the development of children (28). Nitrate levels also increase during the rainy season in areas like S1, S3, S6, S7 and S8. High nitrate, up to 25 ppm from fertilizers can cause a disease called 'blue baby syndrome' in infants and stomach problems in adults (29).

During the rainy season, the lake becomes more polluted because of dirty water flowing in from sewage, farm runoff and bird droppings, especially in the Mangaljodi area. There is also more ammonium, 0.5 ppm, hydrogen sulfide gas and high nitrate levels, which shows that the water is getting polluted by fecal waste and germs (30). This can cause diseases like diarrhea, vomiting and skin infections. Places like S1 (near Mangaljodi sewer outlet) and S5 (Balugaon jetty) are very dangerous because they have both heavy metals and harmful microbes. These pose serious health risks for local fishers, school children, tourists and boat workers. In winter, there is less biological activity, but the water still contains leftover heavy metals. Some areas show zero alkalinity, which means the water cannot balance pH levels properly. This can lead to sudden changes in pH, making the water unstable. In some places, the water becomes acidic as low as pH 6 and very hard, 425 ppm. This can irritate the skin and eyes and can also damage water pipes, causing more metals to mix into the water. High salt levels up to 2000 ppm can also harm people, especially those with high blood pressure and make the water unfit for farming and animals (31). Different places in the lake have different problems. S1 has high nitrate, ammonia and hydrogen sulfide, which can cause diseases. S5 has lead, copper and fecal waste, putting tourists and boat workers at risk. The site S8 (Kalijai) shows mercury and copper pollution, which is dangerous for pilgrims and boat riders. The site S10 (Satapada), a dolphin-watching spot, has problems with ammonium, zinc and salt, affecting tourists and local guides. Certain groups of people are more vulnerable to these problems. Children are easily affected by lead and nitrate. Pregnant women are at risk of mercury. Tourists may not be aware of the dangers in the water. Fishermen are most at risk because they are in contact with the lake water every day, which can cause skin, stomach and breathing problems. Every season brings different health risks. Summer has more heavy metal pollution, which can damage the brain and kidneys. Winter has long-term risks due to leftover metals and unstable water chemistry. The rainy season is the most dangerous because of infections and nutrient pollution. To protect public health, several steps are needed. First, install water filters in high-risk areas like Mangaljodi and Balugaon. Second, start public awareness campaigns to teach people and tourists about water safety. Third, stop fishing and tourism in areas with high lead and mercury during the summer. Fourth, test the water regularly using lab methods like PCR to find germs early. Lastly, grow wetland plants like *Typha* and *Phragmites* to clean the water naturally and improve the aquatic health of Chilika Lake.

Discussion

The main causes of the significant seasonal and regional fluctuations in the physicochemical and microbiological properties of Chilika Lake are human activities, seawater intrusion and monsoonal freshwater influx. Previous research on Chilika Lagoon (7, 9) indicated that the alkaline pH observed in summer and winter was attributed to marine influence and buffering capacity, whereas freshwater dilution and the decomposition of organic matter explain the monsoon-related pH decline in the northern sector. Reduced salinity in the northern sector during the monsoon emphasizes the primary function of riverine flow, while higher salinity and chloride concentrations in the outer channel confirm continued seawater intrusion (8, 19). As previously noted, the notable rise in nitrate and ammonium levels during the rainy season suggests nutrient enrichment from sewage inputs and agricultural runoff, raising the possibility of eutrophication (20, 21). Previous studies from the lagoon indicate that heavy metal contamination, particularly lead and copper exceeding permitted levels at several sites, suggests localised pollution from tourism, watercraft and urban effluents (10–12). Microbial pollution linked to sewage outflow and bird activity is further suggested by the discovery of human bacteria *S. gallinarum* and *S. xylosus*, which may pose health hazards to humans and animals (26, 27). Overall, the findings show that anthropogenic stressors are exacerbated by seasonal hydrological forcing, highlighting the necessity of ongoing monitoring and integrated management techniques to safeguard this Ramsar-designated wetland.

Conclusion

Chilika Lake is impacted by nutrient enrichment due to the inflow of salt water from the adjoining Bay of Bengal, while with influx of fresh water from river tributaries continues, causing a dynamism in water quality. Residual agricultural chemicals, such as organics and residues of chemical fertilisers and pesticides enter the lake;

additionally, fishing and aquaculture operations increase ammoniacal/ nitrite/ nitrate contents. Moreover, several anthropogenic activities, fishing, travelling through diesel powered boats causing petroleum pollution, impact the Lake water quality. Variations in several physicochemical parameters recorded herein may be caused by changes in environmental conditions, caused by water exchange between the sea and the lake. The changes in salinity, river inlets and rapidly expanding resident vegetation complicate the physicochemical characteristics of the Chilika Lake. Ten years ago, similar investigations were conducted; currently, several physicochemical qualities of the lake have deteriorated. However, continued biogeochemical monitoring is necessary to prevent environmental pollution in Chilika Lake. The most obvious changes occurred during the monsoon season, when levels of lead, nutrition and other metals increased, suggesting increase of human influences. Obviously, when there is a lot of runoff and sewage input, natural buffering mechanisms seem to be less effective than they are in the summer. Antibiotic resistance profiling should be used in future research to track new threats from harmful bacteria. This work shows substantial seasonal and spatial variations in the microbial and physicochemical quality of Chilika Lake. A new way to study this is by using maps with GIS and special machines, VITEK-2 to check and profile the contamination in water. In future, workers could also look at antibiotic-resistant mapping and how metals get into the soil/sediment and lake water to guide long-term conservation.

Abbreviations

ArcGIS: Arc Geographic Information System, dRAF: d-raffinose, dSOR: d-sorbitol, dXYL: d-xylose, GP: Gram Positive, QGIS: Quantum Geographic Information System, S: Site, SAL: salicin, TA: total alkalinity, TH: total hardness.

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Author Contributions

Shuvasree Bej: conceptualization, writing- original draft, writing review and editing, visualization, Rabindra Nath Padhy: writing review and editing, supervision, fund acquisition.

Conflict of Interest

The authors declare no competing interests.

Data Availability

The datasets used and analyzed during the current study are available from the corresponding authors upon reasonable request.

Declaration of generative AI and AI assisted technologies in the writing process

The authors declare no use of artificial intelligence (AI) for the write-up of the manuscript.

Ethics Approval

Not applicable.

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