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Seasonal dynamics of phytoplankton communities in relation to physicochemical variables in Karna and Khajjiar Lakes, India

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Abstract

Lakes are vast bodies of water that are encircled by land and home to a variety of aquatic life forms. They are impacted by both natural and man-made environmental processes. The present research aimed to determine the physicochemical properties and phytoplankton community in Karna Lake (Haryana) and Khajjiar Lake (Himachal Pradesh). Phytoplankton plays a vital role in the aquatic food chain, particularly for zooplankton. Water samples were collected from both lakes, i.e., from October 2023 to September 2024. Temperature, pH, conductivity, free carbon dioxide, chlorides, total hardness, biochemical oxygen demand, dissolved oxygen, alkalinity, sodium, potassium, phosphate, acidity, nitrate, were analyzed for both lakes. The physicochemical analysis indicated significant geographical and seasonal variations between the sampling sites. The water temperature fluctuated from 12.14 ± 4.21 °C to 20.05 ± 7.53 °C, and the pH remained slightly alkaline (7.23 ± 1.02 to 8.08 ± 0.03). Conductivity readings ranged from 266.17 ± 35.27 µS/cm to 413.50 ± 54.18 µS/cm, with greater values seen in Karna Lake. Dissolved oxygen concentrations ranged from 6.01 ± 2.32 mg/L to 9.26 ± 2.16 mg/L, while biological oxygen demand was 1.32 ± 1.66 mg/L to 3.59 ± 1.74 mg/L. Karna Lake had greater levels of nitrate (1.8 ± 0.389 mg/L) and phosphate (0.61 ± 0.41 mg/L), indicating nutrient enrichment. Statistical investigations revealed that conductivity, nitrate, phosphate, temperature, and biological oxygen demand were the most important environmental variables impacting phytoplankton dispersal. During the study period, 24 phytoplankton species were recorded by family, including Bacillariophyceae (10 species), Desmidiaceae (2 species), Cyanophyceae (6 species), Chlorophyceae (4 species), and Euglenaceae (2 species). The work emphasizes the ecological significance of phytoplankton as bioindicators of freshwater ecosystem variability and provides baseline limnological data for future monitoring and protection of lake ecosystems.

Keywords: Lakes; Physicochemical; Phytoplankton; Bacillariophyceae

1. Introduction

Freshwater lakes are important in aquatic habitats that sustain a variety of biological communities and contribute significantly to regional biodiversity and ecological balance.[1] The physicochemical features of lake water significantly impact aquatic productivity, nitrogen cycling, and biological interactions in freshwater ecosystems. Seasonal changes in environmental variables, such as temperature, pH, dissolved oxygen

(DO), conductivity, and nutrient content, influence the structure and composition of aquatic organisms, particularly phytoplankton.

The primary sources of nitrate in lakes include catchment-area inputs, such as sewage effluents, rainfall, and agricultural runoff, as well as the decomposition of suspended organic matter, such as dead microorganisms and algae that settle to the lake's bottom.[2] During decomposition, they carry their phosphorus and nitrogen with them. This nitrogen is released and becomes available for the later growth of aquatic biota. Orthophosphate is also termed inorganic phosphate, which is a soluble reactive phosphorus[3] and it plays an important role in the aquatic ecosystem, which is taken up by phytoplankton. Phytoplankton are the principal producers in freshwater ecosystems and are commonly regarded as sensitive bioindicators of environmental change and water quality.[4] Variations in phytoplankton diversity, abundance, and seasonal succession are strongly linked to the physicochemical conditions and trophic status of aquatic environments.[5] A healthy population of phytoplankton promotes stable biological interactions in the aquatic environment, improves nutrient cycling, and helps produce oxygen through photosynthesis. However, excessive phytoplankton growth—which is often driven by nutrient enrichment from human activities—can lead to eutrophication and algal blooms, harming aquatic life and water quality. Changes in nutrient availability, temperature, DO, and organic loading can all affect phytoplankton community composition, potentially favoring the dominance of certain resistant species. As a result, phytoplankton-based ecological evaluation gives useful information about the ecological status and seasonal dynamics of freshwater bodies.[6]

Bacillariophyceae, Cyanophyceae, Chlorophyceae, Euglenaceae, and Desmidiaceae are frequent phytoplankton groups found in freshwater habitats, and they respond differently to environmental changes. Bacillariophyceae are frequently associated with relatively oxygenated and stable aquatic conditions, but Cyanophyceae may become more numerous in high-nutrient and temperature environments. Similarly, Euglenaceae are commonly found in organically rich environments, whereas Desmidiaceae prefer more stable, less disturbed habitats. As a result, studying phytoplankton community structure in relation to physicochemical characteristics can provide valuable ecological insights into how freshwater ecosystems work.

In recent years, rising anthropogenic pressures, including urbanization, tourism, agricultural runoff, residential waste discharge, and catchment disturbances, have had a substantial impact on the ecological state of many freshwater ecosystems. Lakes are especially vulnerable to such environmental changes due to their ecological sensitivity, restricted water exchange, and reliance on seasonal hydrological processes. Nutrient enrichment and variations in water quality can alter phytoplankton community structure, thereby altering ecosystem production and trophic dynamics. As a result, regular monitoring of physicochemical properties and phytoplankton diversity is critical for assessing biological changes and ensuring the environmental sustainability of freshwater lakes.

Karna Lake and Khajjiar Lake were chosen for the current study because they are biologically significant in freshwater ecosystems with distinct limnological traits and environmental circumstances.[7] Both lakes have significant seasonal climatic swings and are vulnerable to varying degrees of anthropogenic influence from tourism and nearby watershed activities. However, extensive comparison data on physicochemical variability and phytoplankton diversity in these lakes are currently lacking.[8] As a result, the current study was designed to provide baseline limnological data and to assess the link between phytoplankton community structure and environmental variables in freshwater environments. It also sought to explore seasonal changes in physicochemical parameters and phytoplankton diversity at Karna Lake and Khajjiar Lake from October 2023 to September 2024. The study also sought to assess the ecological link between phytoplankton groups and environmental variables through statistical and diversity-based methods.

2. Materials and methods

2.1. Study area

The present study was conducted on two lakes: Karna Lake in Haryana and Khajjiar Lake in Himachal Pradesh, India. The topographic details are provided below:

2.1.1. Karna Lake

It is a man- made lake created for recreational purposes. It is one of the most popular tourist spots in Karnal, Haryana. The lake was developed by the Haryana Urban Development Authority and inaugurated in 2002. It is ~2.2 m deep and 6.8 acres in size (Figures 1 and 2).[9]

2.1.2. Khajjiar Lake

It is situated at an elevation of 1,920 m in the Chamba district of Himachal Pradesh, renowned for its breathtaking beauty, surrounded by lush Cedar forests. With an average depth of ~4 m, the lake is primarily fed by small streams originating from the Himalayan region (Figures 3 and 4).[10]

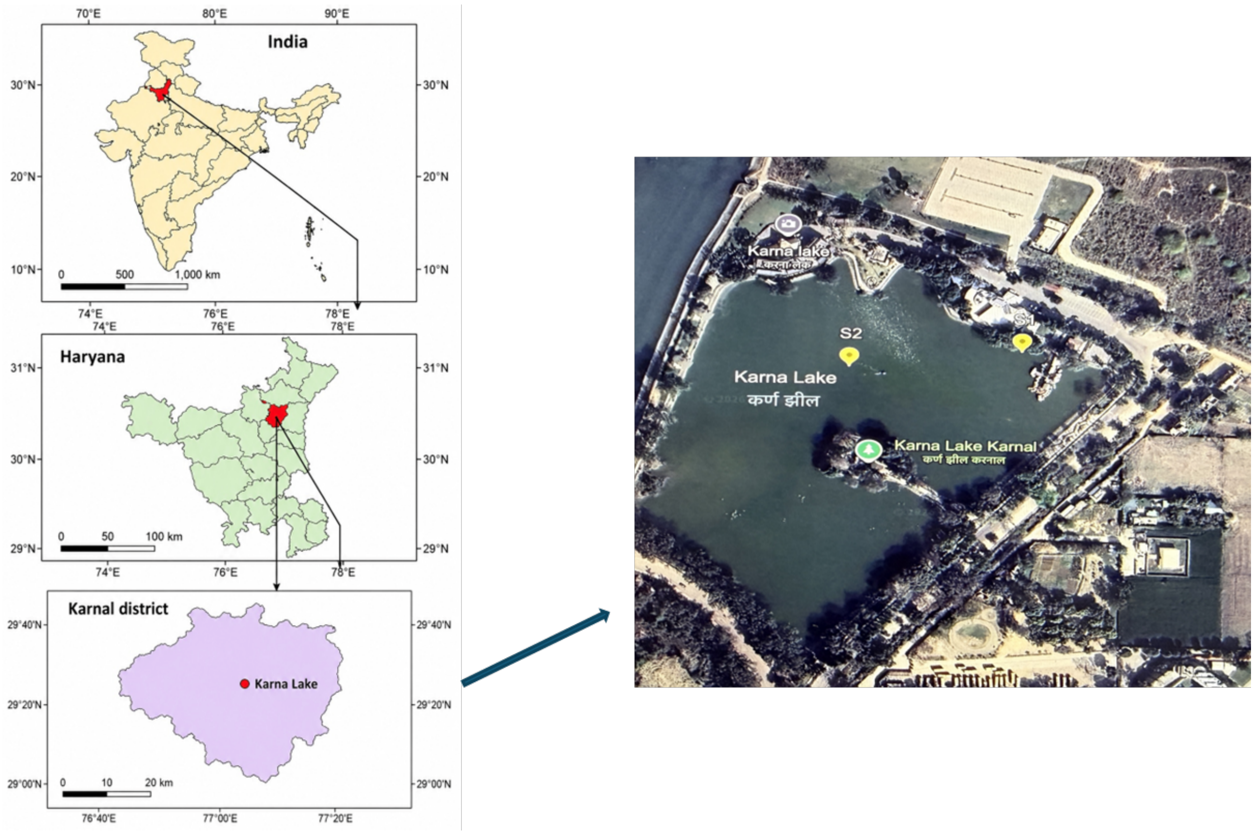


Figure 1. Map showing Karna Lake and sampling locations (Site-I near shore and Site-II mid lake) selected for water quality and phytoplankton analysis

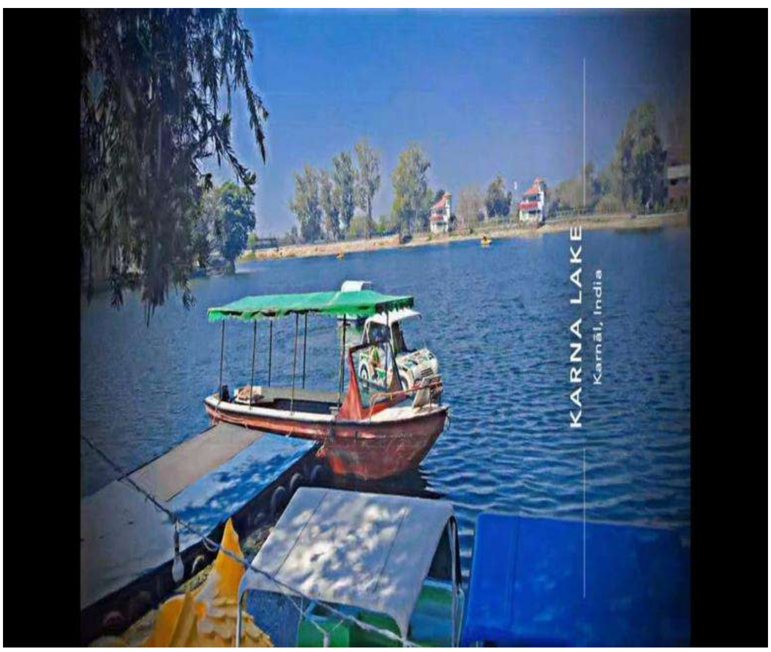


Figure 2. A view of Karna Lake

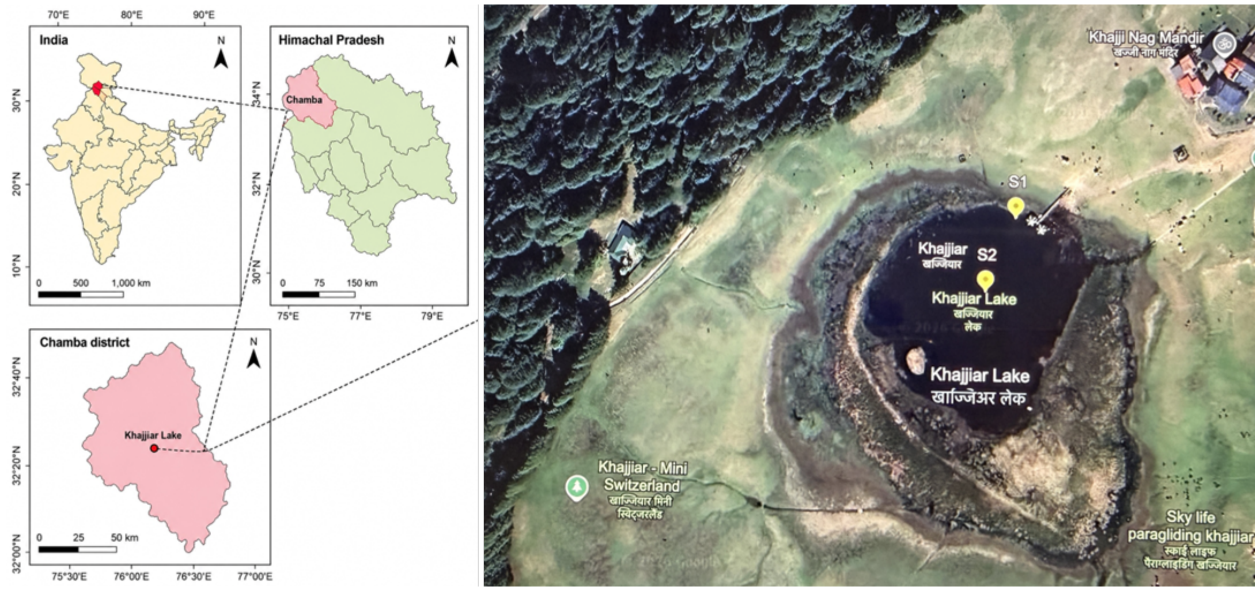


Figure 3. Map showing Khajjiar lake and sampling locations (Site-I near shore and Site-II mid lake) selected for water quality and phytoplankton analysis

Figure 4. A view of Khajjiar Lake

The climatic conditions of both Karna Lake and Khajjiar Lake were categorized according to the Köppen classification. Karna Lake in Haryana has a humid subtropical climate (Cwa). Hot summers, moderate to cool winters, and a distinct monsoon season are typical features of this type of climate. The region's summertime temperatures frequently climb significantly, raising surface water temperatures and increasing evaporation rates. These circumstances could affect the lake ecosystem's conductivity, nutrient availability, and DO concentration. Significant rainfall during the monsoon season increases surface runoff into the lake from nearby regions. The physicochemical properties and productivity of the lake may be impacted by this runoff's potential to carry nutrients, suspended particles, and organic matter from adjacent agricultural and urban areas. Because of the region's relatively mild winters, water conditions are often steady. Phytoplankton growth patterns, species succession, and overall biological productivity in Karna Lake can be greatly affected by seasonal temperature variations associated with the Cwa climate.

Khajjiar Lake, located in Himachal Pradesh's higher-altitude region, has a subtropical highland or temperate climate (Cwb). Cooler temperatures, mild summers, chilly winters, and heavy precipitation—particularly during the monsoon season—are usually associated with this type of climate. Khajjiar has lower annual temperatures than Karna Lake because of its higher elevation. Lower evaporation rates and higher DO levels in lake water may be maintained by cooler weather. Additionally, local humidity, runoff properties, and nutrient transport processes are influenced by the surrounding steep topography and forested landscape. The lake environment may receive fresh water and dissolved minerals from seasonal precipitation and snowmelt in neighboring highland areas, which could affect planktonic production and water chemistry. Compared to lowland subtropical lakes, the Cwb climate's relatively cooler and more stable environment may also support unique phytoplankton assemblages and biological interactions.

Understanding the alterations in physicochemical parameters and phytoplankton community structure seen during the investigation period depends on the environmental differences between the two study sites. Nutrient dynamics, primary production, and ecological functioning in both lake ecosystems may be collectively regulated by the temperature regime, rainfall intensity, hydrological inputs, and seasonal circulation patterns, all of which are influenced by these climatic circumstances.

2.2. Methodology

Water samples were collected four times a year from selected lakes between October 2023 and September 2024. For the current study, two sampling points were selected in each lake. Inlets, outlets, growth of aquatic vegetation, morphometric features, etc., are various important factors considered during the sampling site's selection. All times samples were taken from the same location. The locations were carefully selected based on several key factors, including ecological representativeness, anthropogenic pressure, hydrological parameters, and accessibility. While the second sampling site was selected from regions more directly impacted by human activities such as tourism, runoff, or shoreline contact, the first site represented relatively less disturbed open-water conditions. The selected locations also represented variations in the surrounding land-use patterns, water circulation, and nutrient inflow. This method preserved uniformity and viability for long-term monthly monitoring while enabling the study to capture spatial variance within each lake. In addition to providing a more comprehensive understanding of local environmental variability, the use of representative stations increased the dependability of comparisons across the two lakes.

2.3. Physicochemical analysis

Four sampling locations were selected (two in Karna Lake and two in Khajjiar Lake). Between October 2023 and September 2024, samples were collected four times a year (Oct, Jan, April, July) (Figures 5 and 6) for a total of 12 sampling sessions per location. To ensure data reliability and reduce sampling bias, three replicate water samples from each site were collected for physicochemical analysis. Glass sampling containers were used for collection. Before use, the containers were thoroughly washed with sampling water. After filling out the containers, they were secured and transferred to the laboratory for physical and chemical analysis. Physicochemical parameters of the water were analyzed according to standard methods from the American Public Health Association (APHA 2005).[11] Temperature and pH of water were analyzed on the spot, and for the other parameters, 1 L of water was analyzed for conductivity, free carbon dioxide, chlorides, total hardness, biological oxygen demand (BOD), DO, alkalinity, sodium, potassium, phosphate, acidity, and nitrate. Other parameters—pH meters, conductivity meters, DO meters, and other analytical instruments—were routinely calibrated using standard calibration solutions in accordance with recognized laboratory

Figure 5. Water sample of Karna Lake

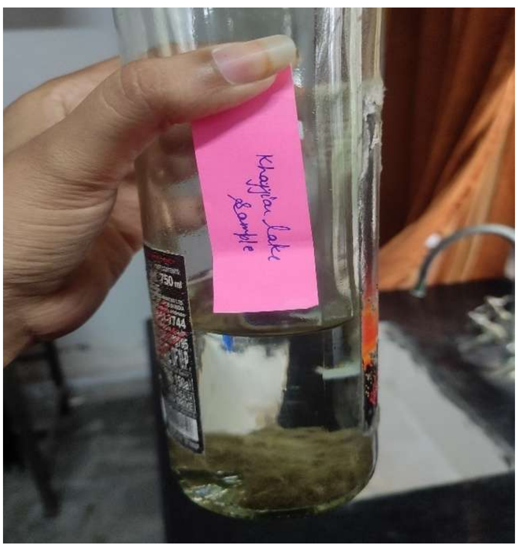


Figure 6. Water sample of Khajjiar Lake

processes and manufacturer specifications. To reduce instrumental errors and maintain measurement accuracy throughout the study period, calibration was performed before sample analysis. Consistency and comparability of results from many sampling events were guaranteed by the use of calibrated devices (Table 1).

2.4. Biological parameters

Samples of phytoplankton were collected using a 50 µm mesh plankton net. At each sampling site, a known volume of surface water ranging from 50 to 100 L was filtered through the net. The concentrated plankton samples were stored in 5% Lugol's iodine and then transported to the laboratory.[12] A total of 100 mL of the water sample was centrifuged at 1,500 rpm for 20 min. A small amount of the preserved sample was examined under a compound light microscope (Magnus CH-20i LED, Magnus Opto Systems India Pvt. Ltd., India). Phytoplankton was counted using a Sedgwick–Rafter counting chamber (1 mL capacity; Genex Sedgwick–Rafter counting cell, Genex, India).[13] Before analysis, the sample was homogenized, and 1 mL was carefully transferred to the chamber. Counting was performed using a compound microscope at (40× or 100×) magnification with typical random field selection. To ensure statistical reliability, at least 30 fields were counted per sample, totaling 100–200 units. Each sample was identified and counted in triplicate. The phytoplankton species were identified and classified based on their morphological characteristics, such as size, shape, color, and other distinguishing features (Figure 7). Phytoplankton has been identified to species level using manuals, monographs, and research articles. To ensure accuracy, species identification was cross-checked against multiple sources and tested against established regional algal checklists. Ambiguous specimens were re-examined at higher magnification. The calculation of phytoplankton concentration is expressed in terms of organisms per liter

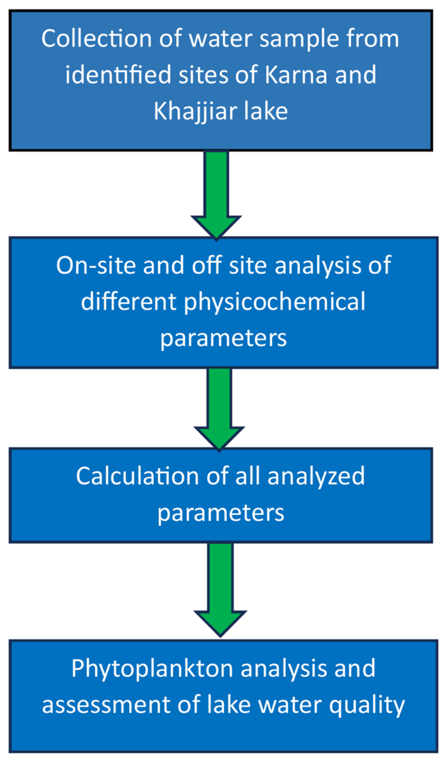


Figure 7. Methodical flowchart of physical and chemical parameters and analysis of phytoplankton of Karna and Khajjiar lake

Table 1. Examined water quality parameters with their testing methods, units, instruments, WHO standards (2006), and BIS (2012) permissible limits.

Water quality parameters	Unit	Testing methods	Instrument	2006, WHO international standards	2012, BIS permissible limits
pH	–	Electrode method used	pH meter	6.5–8.5	6.5–9.5
Temperature	°C	Instrumental	Mercury thermometer	–	–
Chlorides	mgL^{-1}	Argentometric method	Titration	250	250–1000
Hardness	mgL^{-1}	EDTA method	Titration	200	300–600
EC	$mScm^{-1}$	Electrode method	Conductivity meter	0.5	–
Free CO_2	mgL^{-1}	Titration method	Titration	10	–
Alkalinity	mgL^{-1}	Titration method	Titration	200	200–600
Potassium	mgL^{-1}	Flame photometer	Flame photometer	10	<10
Na	mgL^{-1}	Flame photometer	Flame photometer	200	50
Phosphate	mgL^{-1}	Turbidimetric method	UV- spectrophotometer used	0.5	–
Acidity	mgL^{-1}	Titration method	Titration	0–50	50
DO	mgL^{-1}	Winkler's Iodometric method	Titration	5	6.5–8.0
BOD	mgL^{-1}	Standard methods 5-day BOD	BOD incubator	<1	2
Nitrate	mgL^{-1}	Brucine method	Spectrophotometer	50	45

Abbreviations: BIS: Bureau of Indian Standards; BOD: Biological oxygen demand; CO2: Carbon dioxide; DO: Dissolved oxygen; EC: Electrical conductivity; EDTA: Ethylenediaminetetraacetic acid; UV: Ultraviolet; WHO: World Health Organization.

(Org/L) (**Equation 1**)[14]:

$$Phytoplankton\ concentration\left(Org / L\right) = \frac{n \times v}{V} \times 1000 \quad (1)$$

where:

n = Number of phytoplankton counted in 0.1 mL of concentrate.

v = Total volume of concentrate in mL.

V = Total volume of water (mL) filtered through the net.

3. Result and discussion

In the present study, 14 physical and chemical parameters were analyzed according to the standard methods of APHA (Table 2).

3.1. Temperature

Temperature influences the capacity of water to maintain dissolved oxygen, and cold water can hold more oxygen than warm water.[15] Temperature is directly proportional to alkalinity. High temperature, pH, and HCO_3, coupled with lower phosphates, promote the growth of chlorococcales.[16] Temperature showed spatial variation across the study sites. The highest mean temperature was recorded at Karna Lake Site-I (20.05 ± 7.53 °C), followed by Karna Lake Site-II (18.05 ± 5.53 °C). Lower mean temperatures were observed in Khajjiar Lake, with Site-I (12.21 ± 4.43 °C) and Site-II (12.14 ± 4.21 °C), indicating comparatively cooler conditions in Khajjiar Lake.

3.2. pH

Higher pH could be a factor which accelerates the pollution rate in lakes.[17] pH values indicated slightly alkaline conditions across all sites. The highest mean pH was observed at Karna Lake Site-I (8.08 ± 0.03), followed by Karna Lake Site-II (8.00 ± 0.03). Lower mean pH values were recorded in Khajjiar Lake Site-I (8.02 ± 0.03) and Site-II (7.23 ± 1.02), indicating mild spatial variation.

3.3. Total alkalinity

Total alkalinity increases with hydrogen ion concentration. As the alkalinity increases, the water body tends to become eutrophic.[18] High alkalinity and nutrients enrich the algal growth.[19] Alkalinity values were higher in Karna Lake. The highest mean alkalinity was recorded at Karna Lake Site-I (125.96 ± 19.66 mg/L), followed by Khajjiar Lake Site-I (122.42 ± 16.75 mg/L) and Karna Lake Site-II (112.97 ± 21.22 mg/L). The lowest value was observed at Khajjiar Lake Site-II (98.79 ± 18.98 mg/L).

3.4. Conductivity

It is a tool to evaluate the purity of water and compute the water's capability to transmit electric current.[20] The highest mean conductivity was recorded at Karna Lake Site-I (413.50 ± 54.18 μS/cm), followed by Site-II (398.23 ± 48.20 μS/cm). Lower values were observed in Khajjiar Lake Site-I (292.37 ± 42.67 μS/cm) and Site-II (266.17 ± 35.27 μS/cm), indicating reduced ionic content in Khajjiar Lake.

3.5. Dissolved oxygen

The high DO levels support the luxuriant growth of algae, particularly diatoms.[21] The decrease in DO concentration during summer is due to its utilization in the decomposition of organic matter, while the increase in the rainy season is due to inflow. Dissolved oxygen levels were higher in Karna Lake compared to Khajjiar Lake. The highest mean DO was recorded at Karna Lake Site-I (9.26 ± 2.16 mg/L), followed by Khajjiar Lake Site-I (7.67 ± 2.98 mg/L). Lower values were observed at Karna Lake Site-II (6.21 ± 2.42 mg/L) and Khajjiar Lake Site-II (6.01 ± 2.32 mg/L).

3.6. Biological oxygen demand

It is a measure of the active decomposition occurring in the water body. Lower BOD indicates rapid decomposition of organic matter. Low DO and high BOD in water bodies are attributed to sewage additions, which deplete DO by increasing bacterial oxidation of biodegradable matter.[22] BOD values indicated higher organic pollution in Karna Lake. The highest mean BOD was recorded at Karna Lake Site-I (3.59 ± 1.74 mg/L), followed by Khajjiar Lake Site-I

Table 2. Variations in mean and standard deviation values of various physicochemical parameters of the lakes from October 2023 to September 2024

S. No.	Parameters	Karna Lake		Khajjiar Lake	
		Site-I	Site-II	Site-I	Site-II
1	Temperature	20.05 ± 7.53	18.05 ± 5.53	12.21 ± 4.43	12.14 ± 4.21
2	pH	8.08 ± 0.03	8.00 ± 0.03	8.02 ± 0.03	7.23 ± 1.02
3	Conductivity	413.50 ± 54.18	398.23 ± 48.20	292.37 ± 42.67	266.17 ± 35.27
4	Free CO_2	12.79 ± 8.72	10.21 ± 8.22	10.42 ± 7.95	8.25 ± 5.12
5	Chlorides	7.66 ± 1.01	6.54 ± 3.01	2.55 ± 2.05	1.92 ± 1.72
6	Total hardness	198.12 ± 21.38	178.62 ± 19.23	192.65 ± 24.78	183.76 ± 22.21
7	BOD	3.59 ± 1.74	2.03 ± 1.09	2.05 ± 1.75	1.32 ± 1.66
8	DO	9.26 ± 2.16	6.21 ± 2.42	7.67 ± 2.98	6.01 ± 2.32
9	Alkalinity	125.96 ± 19.66	112.97 ± 21.22	122.42 ± 16.75	98.79 ± 18.98
10	Sodium	19.41 ± 4.36	14.12 ± 4.17	9.56 ± 5.21	7.11 ± 3.27
11	Potassium	3.41 ± 1.10	3.01 ± 1.02	2.34 ± 1.08	1.49 ± 1.02
12	Phosphate	0.61 ± 0.41	0.20 ± 0.04	0.2 ± 0.02	0.19 ± 0.01
13	Acidity	62.37 ± 6.72	54.21 ± 7.42	52.67 ± 5.41	48.97 ± 6.26
14	Nitrate	1.8 ± 0.389	1.2 ± 0.139	0.8 ± 0.233	0.4 ± 0.212

Abbreviations: BOD: Biological oxygen demand; CO_2: Carbon dioxide; DO: Dissolved oxygen.

(2.05 ± 1.75 mg/L) and Karna Lake Site-II (2.03 ± 1.09 mg/L). The lowest value was observed at Khajjiar Lake Site-II (1.32 ± 1.66 mg/L).

3.7. Hardness

Hardness is also the principal factor in assessing water potability. It is the sum of calcium (Ca) and magnesium (Mg) concentrations, both expressed as carbonates in mg/L.[23] Total hardness showed comparatively higher values in Karna Lake. The highest mean value was recorded at Karna Lake Site-I (198.12 ± 21.38 mg/L), followed by Khajjiar Lake Site-I (192.65 ± 24.78 mg/L) and Karna Lake Site-II (178.62 ± 19.23 mg/L). The lowest value was observed at Khajjiar Lake Site-II (183.76 ± 22.21 mg/L).

3.8. Nitrate

An increase in nitrate concentration promotes algal bloom formation and plays a key role in diatom bloom development.[24] Nitrate concentration was higher in Karna Lake compared to Khajjiar Lake. The highest mean value was observed at Karna Lake Site-I (1.80 ± 0.389 mg/L), followed by Karna Lake Site-II (1.20 ± 0.139 mg/L). Lower values were recorded at Khajjiar Lake Site-I (0.80 ± 0.233 mg/L) and the lowest at Khajjiar Lake Site-II (0.40 ± 0.212 mg/L).

3.9. Phosphates

Increased phosphate levels are due to organic pollution, and the amount of phosphates in water can be used as a measure of lake pollution.[25] Phosphate concentrations were higher in Karna Lake. The highest mean value was recorded at Karna Lake Site-I (0.61 ± 0.41 mg/L), followed by Karna Lake Site-II (0.20 ± 0.04 mg/L). Lower values were observed at Khajjiar Lake Site-I (0.20 ± 0.02 mg/L) and Site-II (0.19 ± 0.01 mg/L).

3.10. Free carbon dioxide

Carbon dioxide enters the lake from the decaying organic matter, the atmosphere, and the respiration of organic matter. Free carbon dioxide showed variation across sites, with the highest mean value recorded at Karna Lake Site-I (12.79 ± 8.72 mg/L). This was followed by Karna Lake Site-II (10.21 ± 8.22 mg/L), Khajjiar Lake Site-I (10.42 ± 7.95 mg/L), and the lowest at Khajjiar Lake Site-II (8.25 ± 5.12 mg/L).

3.11. Chlorides

The higher chloride content is due to increased pollution. Various studies have reported that high chloride concentrations indicate the trophic nature of water bodies.[26] Chloride concentration was higher in Karna Lake compared to Khajjiar Lake. The highest mean value was observed at Karna Lake Site-I (7.66 ± 1.01 mg/L), followed by Site-II (6.54 ± 3.01 mg/L). Lower concentrations were recorded at Khajjiar Lake Site-I (2.55 ± 2.05 mg/L) and Site-II (1.92 ± 1.72 mg/L).

3.12. Sodium

Sodium ion is an essential parameter that assesses the suitability of water for drinking and irrigation. Sodium concentration was higher in Karna Lake. The highest mean sodium value was recorded at Karna Lake Site-I (19.41 ± 4.36 mg/L), followed by Karna Lake Site-II (14.12 ± 4.17 mg/L). Lower values were observed at Khajjiar Lake Site-I (9.56 ± 5.21 mg/L) and Site-II (7.11 ± 3.27 mg/L).

3.13. Potassium

Potassium showed relatively low concentrations across all sites. The highest mean value was observed at Karna Lake Site-I (3.41 ± 1.10 mg/L), followed by Karna Lake Site-II (3.01 ± 1.02 mg/L), Khajjiar Lake Site-I (2.34 ± 1.08 mg/L), and the lowest at Khajjiar Lake Site-II (1.49 ± 1.02 mg/L).

3.14. Acidity

This is often related to the concentration of acidic compounds in water, most commonly free hydrogen ions, or, more practically, to the concentration of substances such as total acidity, which can be measured by titration with a base (usually sodium hydroxide).[27] Acidity showed higher values in Karna Lake. The highest mean acidity was recorded at Karna Lake Site-I (62.37 ± 6.72 mg/L), followed by Karna Lake Site-II (54.21 ± 7.42 mg/L). Lower values were observed in Khajjiar Lake Site-I (52.67 ± 5.41 mg/L) and Site-II (48.97 ± 6.26 mg/L).

Figure 8 clearly shows that phytoplankton species richness varies significantly across seasons in both lakes, with the largest diversity occurring during the post-monsoon season and the lowest during the winter. Seasonal environmental elements, such as nutrient availability, temperature, DO, and rainfall, have a substantial influence on phytoplankton community dynamics. Throughout the study period, Karna Lake had slightly higher species richness than Khajjiar Lake except in winter. This indicates that Karna Lake may have more favorable ecological and nutritional conditions for phytoplankton growth.

Karna Lake Site-I had higher mean values for conductivity, free carbon dioxide, chlorides, BOD, alkalinity, sodium, phosphate, and nitrate, indicating increased ionic concentration and nutrient enrichment. Lower mean values at Khajjiar Lake Site-II, on the other hand, indicate that the water quality is less damaged and

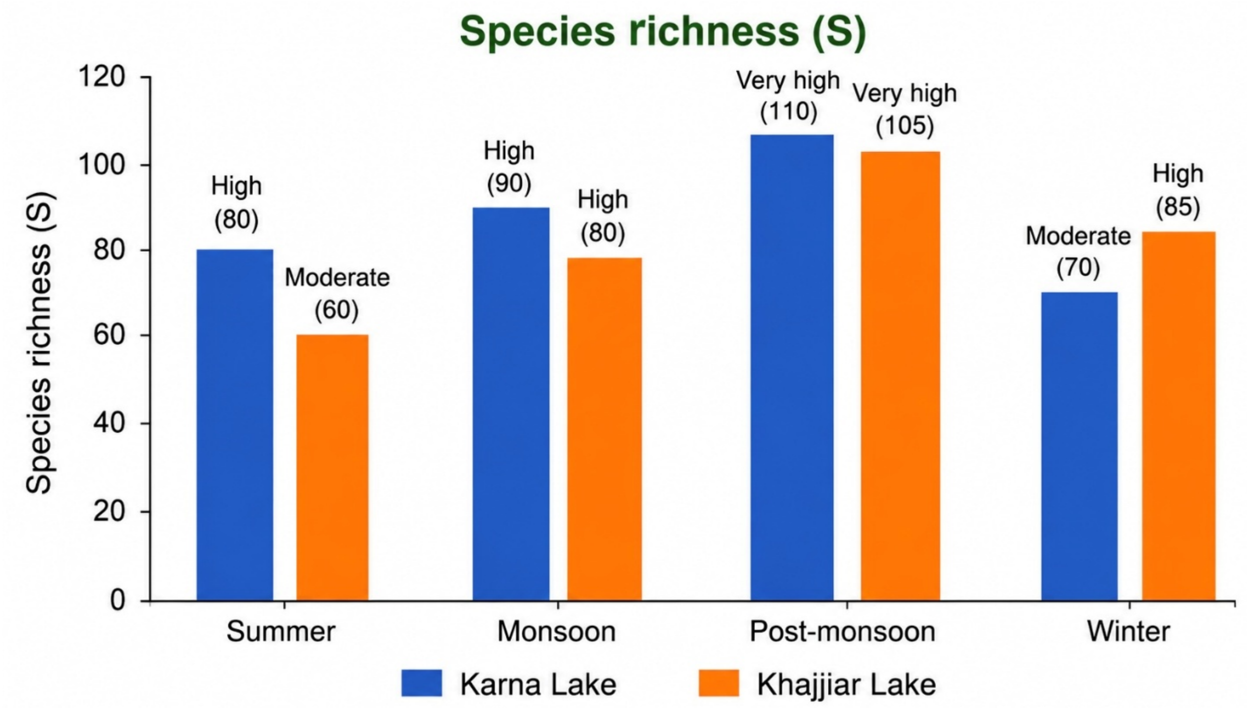


Figure 8. Seasonal variation in phytoplankton species richness in Karna Lake and Khajjiar Lake during October 2023–September 2024

Table 3. Comparative statistical variation in physicochemical parameters among lakes and sampling sites

Parameter	Site name with the highest mean value	Site name with the lowest mean value	Statistical trend
Temperature	Karna Lake Site-I	Khajjiar Lake Site-II	Observed seasonal variation
pH	Karna Lake Site-I	Khajjiar Lake Site-II	Slight alkaline variation among sites
Conductivity	Karna Lake Site-I	Khajjiar Lake Site-II	Increased ionic concentration in Karna Lake
Free CO_2	Karna Lake Site-I	Khajjiar Lake Site-II	Increased organic degradation in Karna Lake
Chlorides	Karna Lake Site-I	Khajjiar Lake Site-II	Elevated nutrient enrichment in Karna Lake
Total hardness	Karna Lake Site-I	Khajjiar Lake Site-II	Moderate spatial variability
BOD	Karna Lake Site-I	Khajjiar Lake Site-II	Higher organic load in Karna Lake
DO	Karna Lake Site-I	Khajjiar Lake Site-II	Diatoms thrived under oxygen-rich circumstances
Alkalinity	Karna Lake Site-I	Khajjiar Lake Site-II	Significant buffering capacity variation
Sodium	Karna Lake Site-I	Khajjiar Lake Site-II	Higher dissolved salts in Karna Lake
Potassium	Karna Lake Site-I	Khajjiar Lake Site-II	Moderate nutritional variation
Phosphate	Karna Lake Site-I	Khajjiar Lake Site-II	Significant impact on Cyanophyceae
Acidity	Karna Lake Site-I	Khajjiar Lake Site-II	Seasonal variation was noticed
Nitrate	Karna Lake Site-I	Khajjiar Lake Site-II	Significant nutrient variability

Abbreviations: BOD: Biological oxygen demand; CO_2: Carbon dioxide; DO: Dissolved oxygen.

more stable (Table 3). DO levels were substantially higher at Karna Lake Site-I, suggesting the presence of oxygen-demanding phytoplankton, such as diatoms, under favorable conditions. The results show substantial spatial variability between the two lakes, with Karna Lake having higher nutrient and organic loading, whilst Khajjiar Lake has less enriched conditions.

4. Identification of phytoplankton

Karna Lake and Khajjiar Lake have a wide variety of phytoplankton species, according to the investigation, including diatoms, green algae, and cyanobacteria. The community may be dominated by a few species of phytoplankton, whose biomass and abundance fluctuate according to the season and the lake's location.[28,29] The total number of organisms in the sample was calculated based on the number counted in the grid squares and the volume of the sample, and examined under a compound light microscope at different magnifications. Identification of phytoplankton species involved examining their physical traits, such as size and shape (Figures 9–11, Table 4).[30,31]

The dominant phytoplankton group was

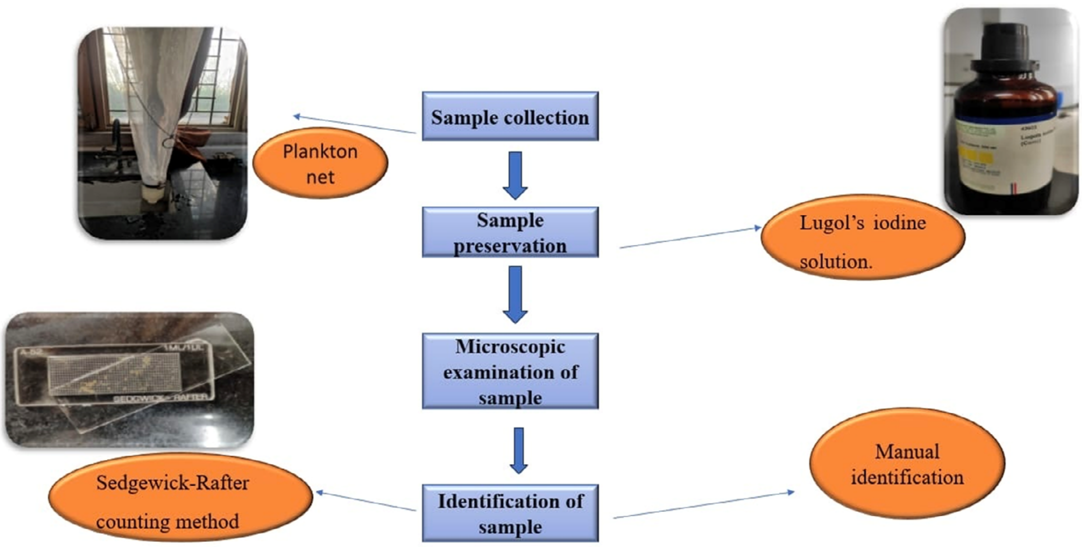


Figure 9. Identification of phytoplankton species

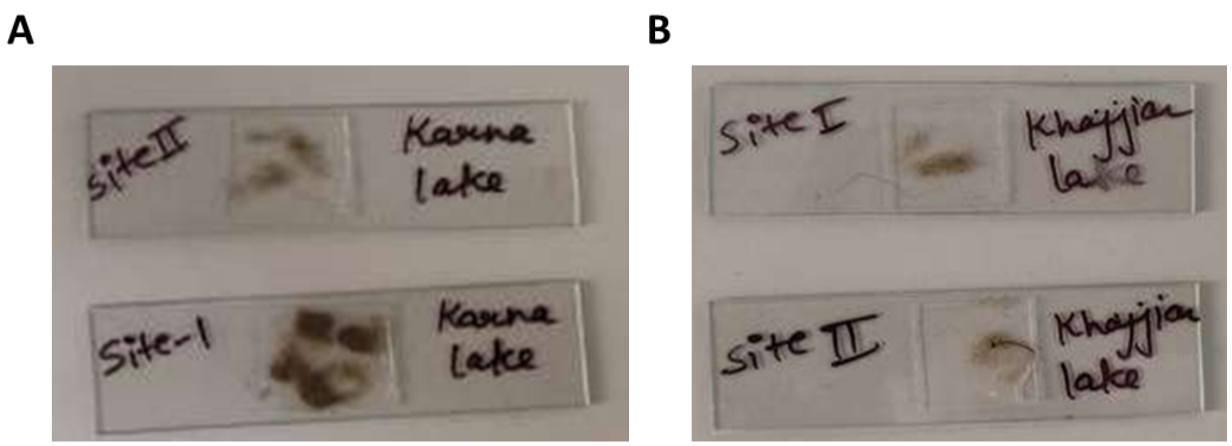


Figure 10. Representative microscopic field slides from different sampling sites of (A) Karna Lake and (B) Khajjiar Lake used for phytoplankton community observation and analysis

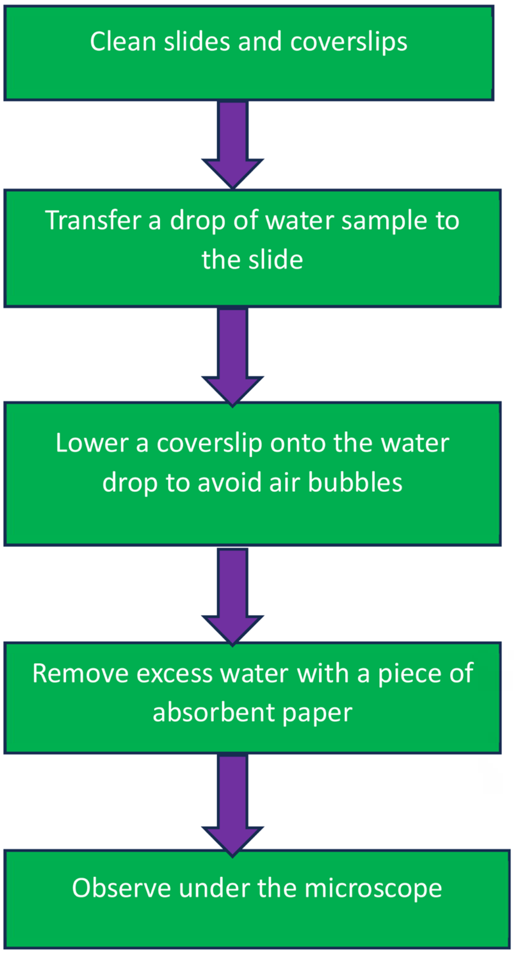


Figure 11. Steps to prepare slides of water samples

Bacillariophyceae, especially in the winter and post-monsoon seasons. Certain species, such as *Navicula halophila* and *Navicula rhynchocephala*, were found in several lakes and sampling locations. Higher quantities of nitrate, alkalinity, and DO were positively correlated with diatom dominance. The growth of Bacillariophyceae was encouraged by moderate alkalinity and moderately high DO levels (9.26 ± 2.16 mg/L at the Karna Lake Site-I), indicating a rather stable, oxygen-rich aquatic environment.

During the summer and monsoon seasons, Cyanophyceae were more abundant, especially in Karna Lake, where nutrient concentrations were relatively higher. During periods of high temperature, phosphate, conductivity, and nitrate levels, species such as *Anabaena affinis*, *Anabaena azollae*, and *Microcystis crassa* were predominant. Cyanophyceae abundance was found to be positively correlated with nutrient enrichment characteristics such as temperature (20.05 ± 7.53 °C), conductivity (413.50 ± 54.18 μS/cm), and phosphate (0.61 ± 0.41 mg/L). These results suggest that cyanobacterial growth was encouraged by eutrophic environments.

Chlorophyceae species such as *Scenedesmus bijugatus*, *Scenedesmus quadricauda*, and *Scenedesmus acuminatus* were most observed during the summer and post-monsoon seasons. Their occurrence was favorably associated with alkaline pH and moderate nutrient levels. The slightly alkaline quality of the water (pH 7.23–8.08) encouraged Chlorophyceae development over both lakes.

Members of Desmidiaceae, such as *Cosmarium ordinatum* and *Staurastrum wittrockii*, were found primarily during the winter and post-monsoon seasons, indicating a preference for less disturbed, somewhat oligotrophic environments. Their distribution exhibited a limited correlation with nutrient-rich settings.

Euglenaceae species, particularly *Euglena acus*, were more numerous in nutrient-rich locations with greater BOD) and free carbon dioxide levels. The considerably higher BOD values discovered in Karna Lake showed greater organic enrichment, which favored Euglenaceae growth.

Khajjiar Lake consistently had higher Shannon index (H′) values than Karna Lake, indicating greater phytoplankton diversity, reduced reliance on a single group, and improved ecological stability. The highest diversity, as measured by H′, was observed during the post-monsoon season (Figure 12), indicating the ideal environmental conditions for phytoplankton coexistence.

Khajjiar Lake had higher Simpson Index values throughout the study, indicating enhanced ecological stability, reduced toxic algal dominance, and a healthier phytoplankton community structure. Khajjiar Lake exhibited the highest Simpson value of 0.86 during the post-monsoon season (Figure 13), indicating optimal community stability and diversity.

The correlation study of phytoplankton groups and physicochemical factors reveals clear biological relationships between community structure and environmental circumstances in Karna Lake and Khajjiar Lake (Table 5). Bacillariophyceae showed positive associations with DO and nutrient levels, indicating a preference for well-oxygenated, stable aquatic habitats. Cyanophyceae showed strong positive associations with temperature, conductivity, nitrate, and phosphate, indicating their dominance in nutrient-rich, warm environments. Euglenaceae were positively associated with BOD and nutrients, suggesting they live in organically

Table 4. Species appearance, seasonality, and abundance of phytoplankton in both lakes at different sampling sites

S.No.	Name of species	Karna Lake		Khajjiar Lake		Seasonality
		Site I	Site II	Site I	Site II	
Bacillariophyceae						
1	*Achnanthes minutissima*	+	–	+	–	S-M
2	*Caloneis louisiana*	–	–	++	+	S-PM
3	*Cymbella leptoceros*	+	–	–	–	P
4	*Cymbella Cymbelliformis*	+	–	–	–	P
5	*Fragilaria brevistriata*	–	–	+	+	P
6	Melosira islandica	+	+	–	–	W
7	*Navicula halophila*	++	++	+	+	P
8	*Navicula rhynchocephala*	++	++	+	+	PM
9	*Pinnularia cardinaliculus*	+	–	–	–	PM
10	*Synedra tabulate*	+	–	+	–	P
Desmidiaceae						
11	*Cosmarium ordinatum*	+	–	–	–	S-W
12	*Staurastrum wittrockii*	++	+	+	–	S-W-PM
Cyanophyceae						
13	*Anabaena affinis*	++	+	++	+	S-M-PM
14	Anabaena azollae	++	+	++	+	S-M-PM
15	*Chroococcus turgidus*	–	–	+	–	S-PM
16	*Chroococcus varius*	–	–	+	–	M-PM
17	*Microcystis crassa*	++	–	–	–	S-M-PM
18	*Spirulina subsalsa*	+	+	–	–	W
Chlorophyceae						
19	*Pediastrum simplex*	–	–	+	+	S
20	*Scenedesmus bijugatus*	++	+	–	–	S-M-PM
21	*Scenedesmus quadricauda*	+	–	++	–	S-M-PM
22	*Scenedesmus acuminatus*	++	+	++	+	M-PM
Euglenaceae						
23	*Euglena acus*	++	–	++	–	S-M-PM
24	*Lepocinclis ovum*	+	–	–	–	PM-W

Notes: +Present; –Absent; ++Abundant.
Abbreviations: M: Monsoon; P: Perennial; PM: Post-monsoon; S: Summer; W: Winter.

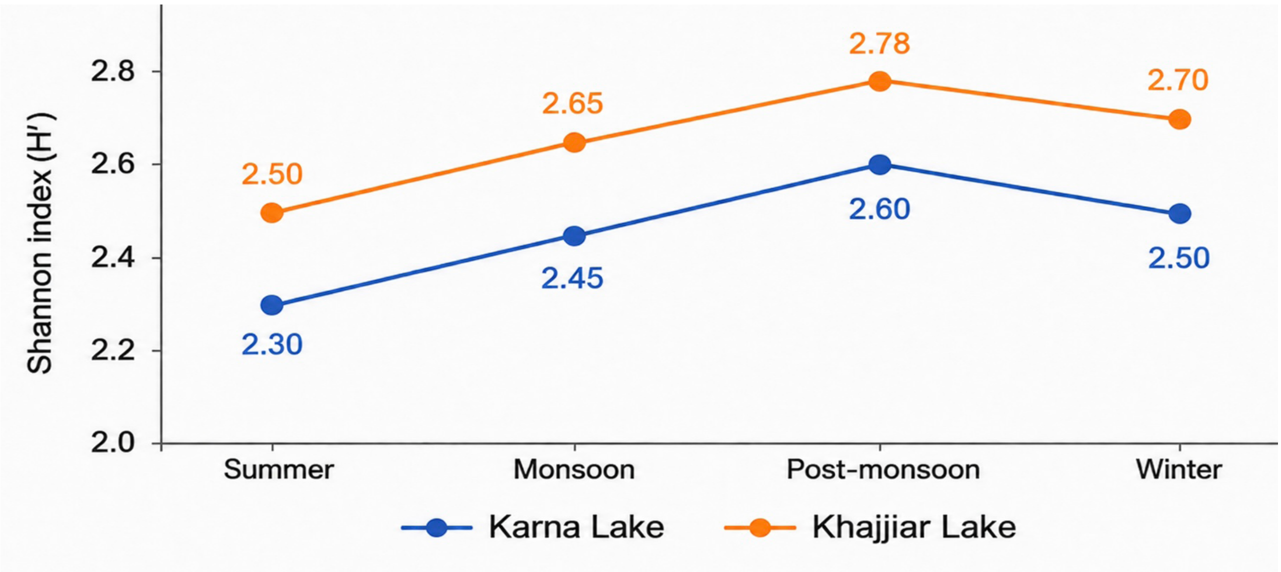


Figure 12. Shannon diversity index results based on phytoplankton data (presence/absence + frequency scores)

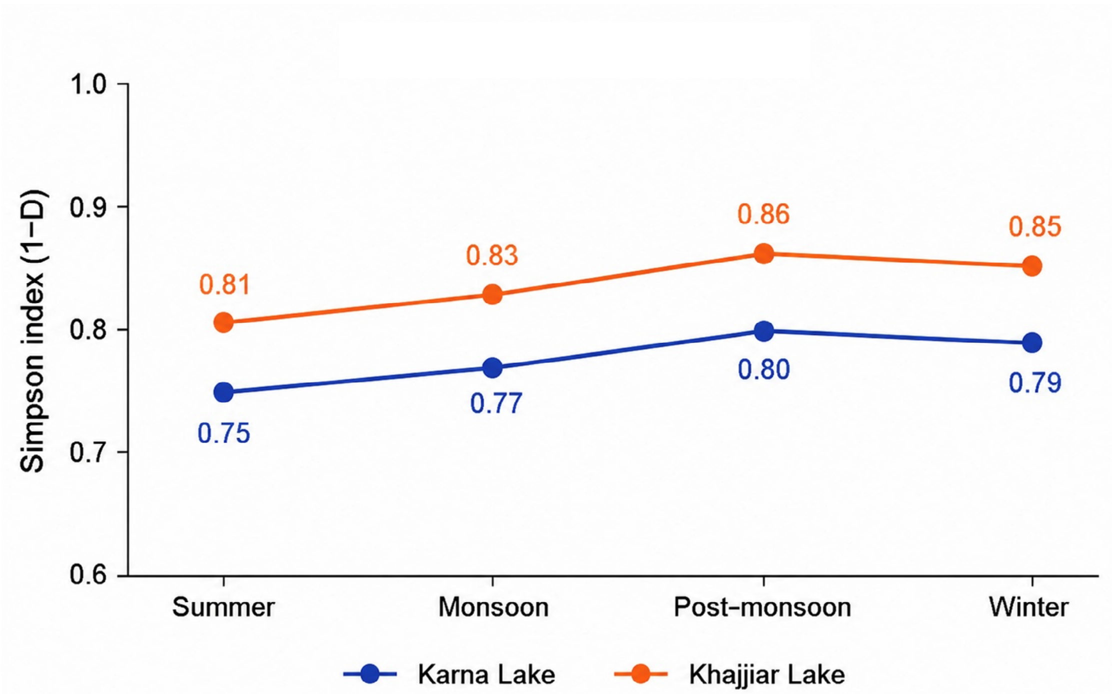


Figure 13. Simpson's diversity index (1 – D) based on phytoplankton data (presence/absence + frequency scores)

Table 5. Correlation between phytoplankton groups and environmental variables

Phytoplankton group	Temperature	DO	BOD	Conductivity	Phosphate	Nitrate	Ecological interpretation
Bacillariophyceae	Moderate (+)	Strong (+)	Weak (−)	Moderate (+)	Moderate (+)	Strong (+)	Dominant in oxygen-rich waters
Cyanophyceae	Strong (+)	Weak (−)	Moderate (+)	Strong (+)	Strong (+)	Strong (+)	Eutrophic environments are favorable
Euglenaceae	Moderate (+)	Weak (−)	Strong (+)	Moderate (+)	Moderate (+)	Moderate (+)	Associated with organic pollutants
Desmidiaceae	Weak (−)	Moderate (+)	Weak (−)	Weak (−)	Weak (−)	Weak (−)	Highly sensitive to nutrient enrichment
Chlorophyceae	Moderate (+)	Moderate (+)	Weak (+)	Moderate (+)	Moderate (+)	Moderate (+)	Stable alkaline waters

Abbreviations: BOD: Biological oxygen demand; DO: Dissolved oxygen.

enriched waters. Desmidiaceae showed weak or negative correlations with most nutritional variables, indicating sensitivity to nutrient enrichment, whereas Chlorophyceae showed moderate correlations across factors, indicating tolerance to a wide range of environmental conditions.

The principal component analysis (PCA) ordination revealed that the first two principal components accounted for a substantial proportion of the environmental variability among sampling sites. PC1 was strongly associated with conductivity, nitrate, phosphate, sodium, and alkalinity, indicating nutrient enrichment gradients, whereas PC2 was primarily influenced by DO and pH. The ordination pattern showed clear ecological separation between Karna Lake and Khajjiar Lake, with Karna Lake exhibiting higher nutrient loading and phytoplankton productivity (Table 6 and Figure 14).

According to PCA, the most important environmental variables impacting phytoplankton community structure were conductivity, phosphate, nitrate, alkalinity, and temperature. The study revealed that Karna Lake was associated with increased nutrient loading, whereas Khajjiar Lake had lower nutrient concentrations and Bacillariophyceae dominance.

The potential bioindicators of pollution identified in this study are summarized in Figures 15 and 16. Bacillariophyceae was dominant, and Euglenaceae was rarely found in both lakes. The occurrence of these bioindicators reflects the condition of aquatic ecosystems and serves as an effective means for evaluating the water quality of lakes[32,33], a conclusion further corroborated by their physicochemical analysis across various seasons. Our findings indicate that management strategies should be tailored to address the declining water quality in these lakes. Both lakes are affected by point and non-point sources of pollution. Point-source pollution can result from anthropogenic activity along lake margins, tourism-related garbage disposal, and local sewage discharge. Plastics, food scraps, packing materials, and other biodegradable and non-biodegradable trash can accumulate in Karna Lake and Khajjiar Lake due to year-round tourist traffic. Organic debris and nutrients may be gradually released into the aquatic ecosystem if improperly disposed of near the lake's edge. Additionally, untreated or partially treated wastewater may be introduced into the lakes by local sewage discharge from surrounding residential areas, hotels, restaurants, and temporary tourist facilities. These releases can increase nutrient concentrations, especially phosphates and nitrates, leading to greater eutrophication and excessive growth of algae and phytoplankton. Washing habits, recreational activities, and other direct human activities along the coastline may further disturb sediment layers and alter water physicochemical characteristics.

Agriculture runoff, soil erosion, and surface runoff that enter lakes with suspended particles and nutrients are examples of non-point-source pollution. Phytoplankton production and community composition are strongly impacted by nutrient loading, which can be greatly increased by the input of nitrogen and phosphorus-rich compounds from agricultural areas. In addition, suspended sediments and particulate matter may be introduced into water bodies through soil erosion in nearby catchment areas, increasing turbidity and reducing light penetration. Alkalinity, conductivity, DO, and other physicochemical properties can be altered by surface runoff after heavy precipitation, which can introduce a mixture of dissolved

Table 6. Principal component analysis loading pattern

Environmental variable	PC1	PC2	Interpretation
Conductivity	0.82	0.21	Nutrient enrichment gradient
Phosphate	0.79	0.18	Eutrophication indicator
Nitrate	0.76	0.25	Nutrient loading
Temperature	0.72	0.31	Seasonal influence
BOD	0.68	0.42	Pollution from organic sources
DO	−0.34	0.81	Oxygen regulation
pH	0.29	0.73	Alkalinity control
Alkalinity	0.65	0.44	Buffering capacity

Abbreviations: BOD: Biological oxygen demand; DO: Dissolved oxygen; PC: Principal component.

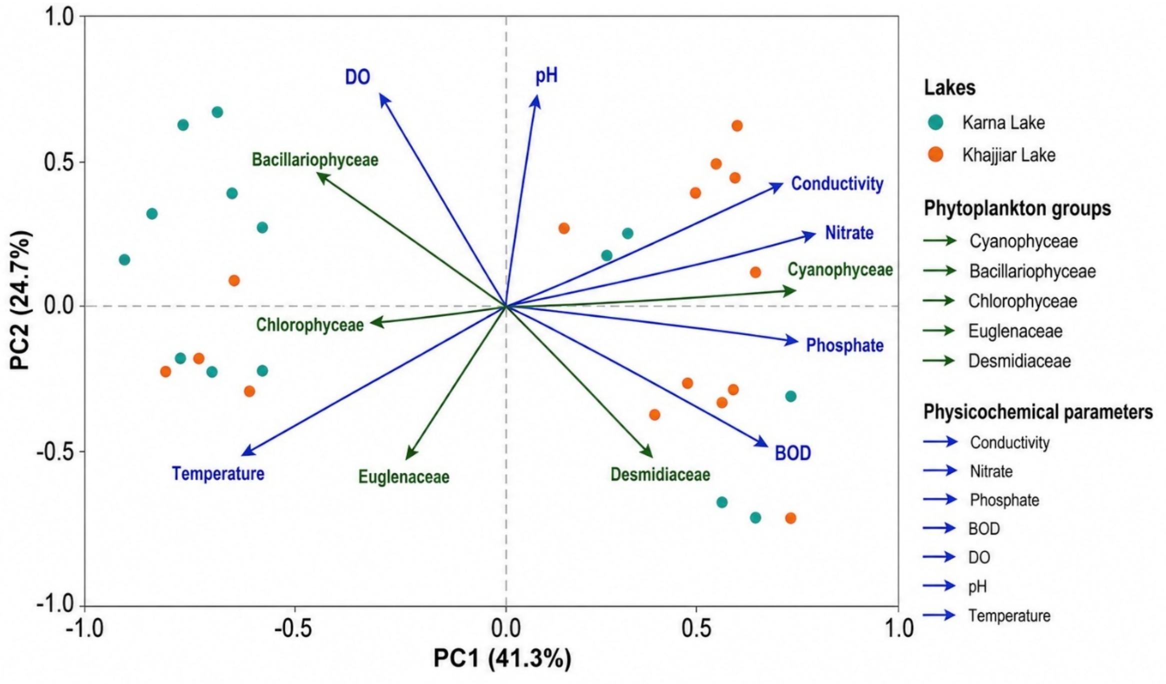
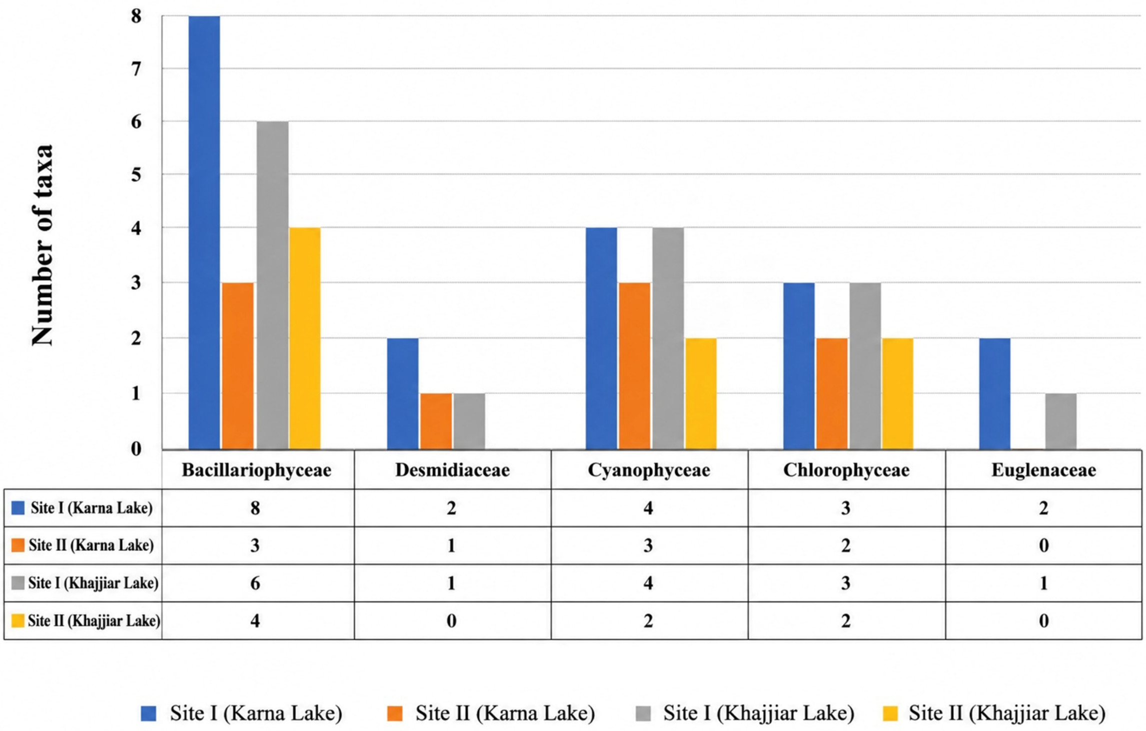


Figure 14. Principal component analysis showing the relationship between phytoplankton groups and physicochemical parameters in Karna Lake and Khajjiar Lake during October 2023–September 2024
Abbreviations: BOD: Biological oxygen demand; DO: Dissolved oxygen; PC: Principal component.



	Bacillariophyceae	Desmidiaceae	Cyanophyceae	Chlorophyceae	Euglenaceae
Site I (Karna Lake)	8	2	4	3	2
Site II (Karna Lake)	3	1	3	2	0
Site I (Khajjiar Lake)	6	1	4	3	1
Site II (Khajjiar Lake)	4	0	2	2	0

Figure 15. Number of phytoplankton species reported in Karna and Khajjiar lakes at different sampling sites

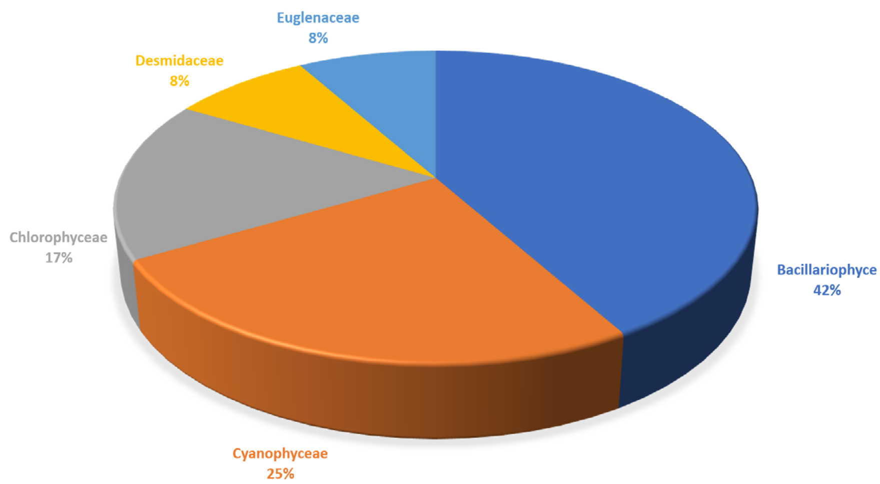


Figure 16. Percentage of phytoplankton species reported with respect to their families at different sampling sites

Table 7. Correlation interpretation

Phytoplankton group	Positively associated variables	Ecological interpretation
Bacillariophyceae	DO, nitrate, alkalinity	Dominance in oxygen-rich waters
Cyanophyceae	Temperature, conductivity, phosphate	Nutrient enrichment promotes growth
Chlorophyceae	pH, transparency	Prefer constant alkaline conditions
Euglenaceae	BOD, free CO_2	An indicator of organic contamination
Desmidiaceae	Moderate pH, low nutrients,	Sensitive to environmental variations

Abbreviations: BOD: Biological oxygen demand; CO_2: Carbon dioxide; DO: Dissolved oxygen.

nutrients, organic debris, and small soil particles into the lakes. Due to their widespread distribution across the watershed, diffuse pollution sources are often difficult to control.

In the lakes under study, atmospheric deposition may also contribute to seasonal fluctuations in water quality and nutrient enrichment. Agricultural aerosols, automobile pollution, industrial emissions, and airborne dust particles can all travel through the atmosphere and land directly on the lake's surface or nearby catchment regions. Additional nitrogenous and phosphatic chemicals may enter the aquatic environment through wet deposition from rainfall and dry deposition from air particles. Precipitation-mediated nutrient and suspended particle transport during the monsoon season may increase nutrient availability, thereby affecting species diversity and phytoplankton abundance. Furthermore, atmospheric deposition of contaminants may alter pH, conductivity, and ionic composition of lake water over time. Thus, the ecological health and limnological features of Karna Lake and Khajjiar Lake are influenced by both regional atmospheric processes and local pollution inputs.

The link between phytoplankton dispersion patterns and observed physicochemical factors served as the foundation for ecological interpretation in the current investigation (Table 7 and Figure 17). Bacillariophyceae were found in areas with increased DO and stable environmental conditions, indicating generally balanced aquatic ecosystems throughout specific seasons. Cyanophyceae, on the other hand, are more abundant under nutrient-rich settings, particularly when phosphate and temperature levels are high, implying that these taxa thrive in eutrophic or nutrient-rich habitats.

Euglenaceae were abundant in areas with high BOD, demonstrating tolerance to organically rich environments. Chlorophyceae showed moderate distribution patterns, indicating intermediate nutrient levels, whereas Desmidiaceae were often associated with less disturbed environments.

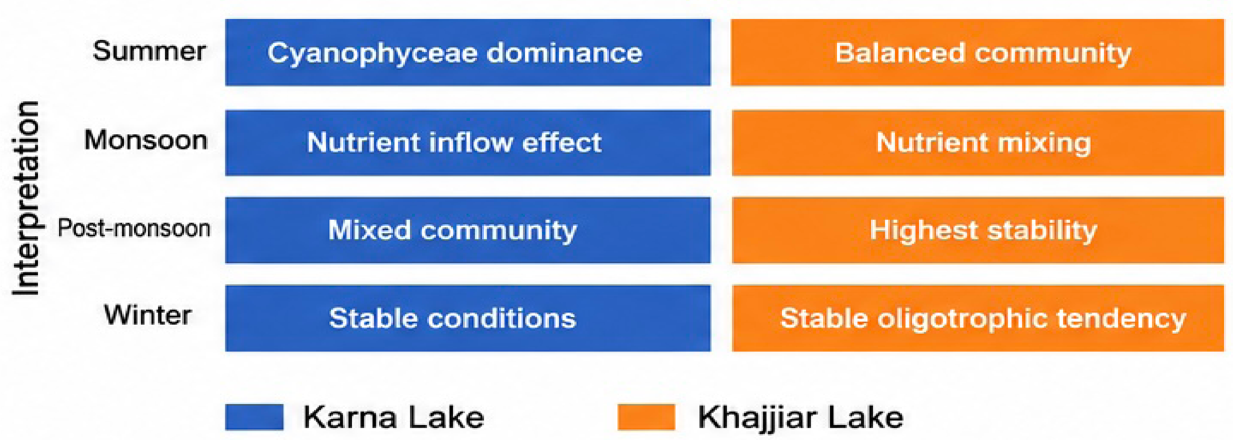


Figure 17. Ecological conditions seasonally of both lakes

5. Seasonal mixing, stratification, and their influence on lake ecology

Lakes' hydrological and temperature regimes significantly impact biological productivity and water quality. The circulation and mixing patterns of Karna Lake and Khajjiar Lake were shown to be significantly influenced by seasonal fluctuations in temperature, rainfall, and wind conditions. Increased precipitation and surface runoff during the monsoon season bring more water into the lakes, increasing water movement and turbulence. During the wetter months, these mixing activities help maintain relatively consistent physicochemical conditions in the lake ecosystem.

The lakes may undergo partial thermal stratification during warmer summer months, especially when the atmosphere is calm and the wind is light.[34] Different temperature zones form within the lake due to thermal stratification, in which surface water becomes warmer and less dense than deeper layers.

The winter and monsoon seasons are more likely to see enhanced vertical mixing due to lower air temperatures, stronger winds, and turbulence induced by rainfall.[35] Surface waters sink and mix with deeper layers when temperatures drop because they become denser.

The distribution of DO in the lakes is greatly impacted by these mixing and stratification processes. Oxygen exchange between the surface and deeper waters may become limited under stratified conditions. Because of direct air interaction and phytoplankton photosynthetic activity, surface layers often maintain greater DO concentrations, while lower layers may gradually experience oxygen depletion due to organic matter decomposition and decreased circulation. Nutrients such as phosphates and nitrates confined to deeper layers may be transferred to the upper, sunlit layers during mixing periods, where they become accessible to phytoplankton uptake and growth.

Variations in temperature, light availability, nutrient concentration, and water stability affect phytoplankton groups in distinct ways. The dominance of Bacillariophyceae observed across several sampling periods may reflect comparatively stable, oxygenated aquatic conditions, as supported by measured DO and alkalinity values. On the other hand, some Cyanophyceae species may benefit from longer stratification and warmer stagnant conditions. Thus, phytoplankton diversity, succession, and ecological balance in Karna Lake and Khajjiar Lake are significantly influenced by seasonal heat dynamics and circulation patterns.

6. Remediation measures for physicochemical parameters

Effective remediation of physicochemical parameters in aquatic ecosystems is essential for maintaining water quality and ecological balance. Various physical, chemical, and biological approaches can be employed to reduce pollutant loads and restore healthy aquatic conditions. The key remediation measures include the following:

(i) Nutrient management: Implement measures to reduce nitrogen and phosphorus inputs, such as improved agricultural practices (e.g., reduced fertilizer use), wastewater treatment improvements, or controlling sewage discharge.[36]
(ii) Bioremediation: Use algae or plants to absorb excess nutrients, or specialized microbes to degrade pollutants.[37]
(iii) Aeration: Increase oxygen levels in the water through aerators or fountains. This helps reduce anaerobic conditions and may also help reduce pollutants such as ammonia or hydrogen sulfide.
(iv) Coagulation and flocculation: This method involves adding chemicals to bind suspended solids or dissolved substances into flocs, which are then removed from the water.[38]
(v) Activated carbon filtration: Activated carbon can help adsorb organic pollutants from water, especially when chemical contamination is high.[39]
(vi) Dredging: Removing contaminated sediments that may contribute to the pollutant load can help restore water quality, especially when pollutants are trapped at the lake's bottom.

7. Remediation for phytoplankton control (eutrophication management)

Effective management of phytoplankton proliferation is crucial for controlling eutrophication and maintaining ecological balance in freshwater ecosystems. Excess nutrient enrichment often leads to harmful algal blooms, which can degrade water quality and disrupt aquatic life. Various physical, biological, and ecological remediation strategies are therefore employed to regulate phytoplankton growth and restore lake health. The key approaches include the following:

(i) Phytoplankton removal: If there are harmful algal blooms, physical removal using booms or skimmers can be an immediate measure. Chemical treatments, such as algaecides, may also be used, but they should be applied cautiously, as they can harm other aquatic organisms.[40]

(ii) Harvesting phytoplankton: In some cases, algae harvesting can reduce nutrient levels and prevent further blooms.
(iii) Macrophyte planting: The introduction of aquatic plants (macrophytes) can help absorb nutrients from the water and outcompete phytoplankton. These plants also provide oxygen to the water, which can mitigate anaerobic conditions.[41,42]
(iv) Wetland construction: Constructing artificial wetlands can help filter and absorb excess nutrients before they enter the lake.[43]

8. Methodological limitations

Certain methodological limitations should be addressed when evaluating the current study's findings. The use of a 50 μm mesh plankton net may have led to underrepresentation of smaller phytoplankton fractions, particularly picoplankton and nanoplankton. These can contribute significantly to total phytoplankton diversity in freshwater ecosystems. Additionally, net-based sampling favors bigger and colonial forms, which may influence community composition patterns. As a result, seasonal mixing patterns are interpreted using both ecological observations and comparisons to past limnological investigations. Despite these limitations, the work provides useful baseline data on phytoplankton diversity and seasonal biological variability in the freshwater environments studied.

9. Conclusion

The present study found significant seasonal and geographical fluctuations in the physicochemical properties and phytoplankton variety of Karna Lake and Khajjiar Lake between October 2023 and September 2024. Twenty-four phytoplankton species from the Bacillariophyceae, Cyanophyceae, Chlorophyceae, Desmidiaceae, and Euglenaceae families were discovered, demonstrating the biological diversity of the freshwater systems studied. The physicochemical analysis revealed that most parameters remained within moderate ranges, though higher values of conductivity, nutrients (nitrate and phosphate), and BOD were observed in specific Karna Lake sampling sites, indicating localized nutrient enrichment and organic loading. Statistical analysis also demonstrated that environmental variables, including conductivity, phosphate, nitrate, temperature, and DO, had a substantial impact on phytoplankton dispersion and seasonal succession.

Bacillariophyceae dominate in oxygen-rich conditions, while Cyanophyceae are more common in nutrient-rich situations, indicating that trophic features in the lakes are changing. However, the observed changes do not always indicate serious ecological degradation; rather, they reflect natural seasonal dynamics, with varying degrees of anthropogenic interference. Changes in water temperature, DO concentration, nutrient availability, and seasonal mixing patterns were all associated with variations in the composition of phytoplankton communities. The predominance of Bacillariophyceae in both lakes was attributed to ecological stability, water movement, and favorable nutrient conditions. Phytoplankton productivity and community succession were also examined in relation to seasonal nutrient enrichment driven by monsoon runoff and human inputs.

Overall, the work emphasizes the importance of phytoplankton as bioindicators of freshwater ecosystem health and provides critical baseline data for future limnological monitoring and the sustainable management of lake ecosystems. Continued monitoring is necessary to better understand long-term ecological changes and support freshwater conservation measures.

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Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

Conceptualization: All authors
Data curation: Ekta Antil
Formal analysis: All authors
Methodology: All authors
Writing–original draft: Ekta Antil
Writing–review & editing: All authors

Availability of data

The data generated during this study are available from the corresponding author on reasonable request.

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