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Knowledge mining for the differentiation pattern with respect to the productivity and trophic status of some selected lakes of Western Himalayas

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The present study deals with an account of the primary productivity and trophic status of Rewalsar, Kuntbhyog, and Prashar lakes of Western Himalayas. Seasonal variations in gross primary productivity (GPP) (g C m^{-2} day^{-1}), net primary productivity (NPP, respiration (R), and the NPP/R ratio have been studied and compared with hydrobiological factors. Among various factors, temperature, light, nutrients, and chlorophyll a were accountable for high productivity. Nygaard's trophic state indices were calculated. GPP showed a positive relationship with water temperature, penetration of light, nitrate, and with phosphate. The extensive range of the compound index observed in Rewalsar (12.00–20.00) and Kuntbhyog lakes (12.50–18.00) confirmed their eutrophic nature. Based on the trophic classification of waters and on the basis of productivity, Nygaard's trophic state indices, and richness of nutrients, Rewalsar and Kuntbhyog lakes could be categorized as eutrophic, whereas Prashar Lake, as oligo-eutrophic. Based on the presence, absence, frequency of appearance, and abundance of different organisms recorded during the present investigation, bioindicators of trophic status have been determined.

KEYWORDS

Western Himalayan Lakes, trophic status (TSI, TLI), knowledge mining model, principal component analysis, planktonic abundance

Introduction

Many shallow lakes in different regions of the world have been subjected to eutrophication in the last century (Scheffer, 1998). Studies made by several workers have shown marked differences in the biotic composition of oligotrophic and eutrophic waters, and various species of different groups of plankton have been identified as indicators of trophic status (Ganapati, 1960; Hutchinson, 1967; Palmer, 1969; Jindal and Thakur, 2009; Thakur et al., 2013). Every water body has a particular "trophic state," which changes over a period of time. Eutrophication, the biological response to the excess input of nutrients into a water body, can arise rarely under natural conditions but is more commonly recognized as a consequence of human activities (Moss, 2009). Cunha et al. (2013) reported that ultraoligotrophic or oligotrophic lakes have low productivity. Changes in the aquatic environment accompanying anthropogenic pollution are a

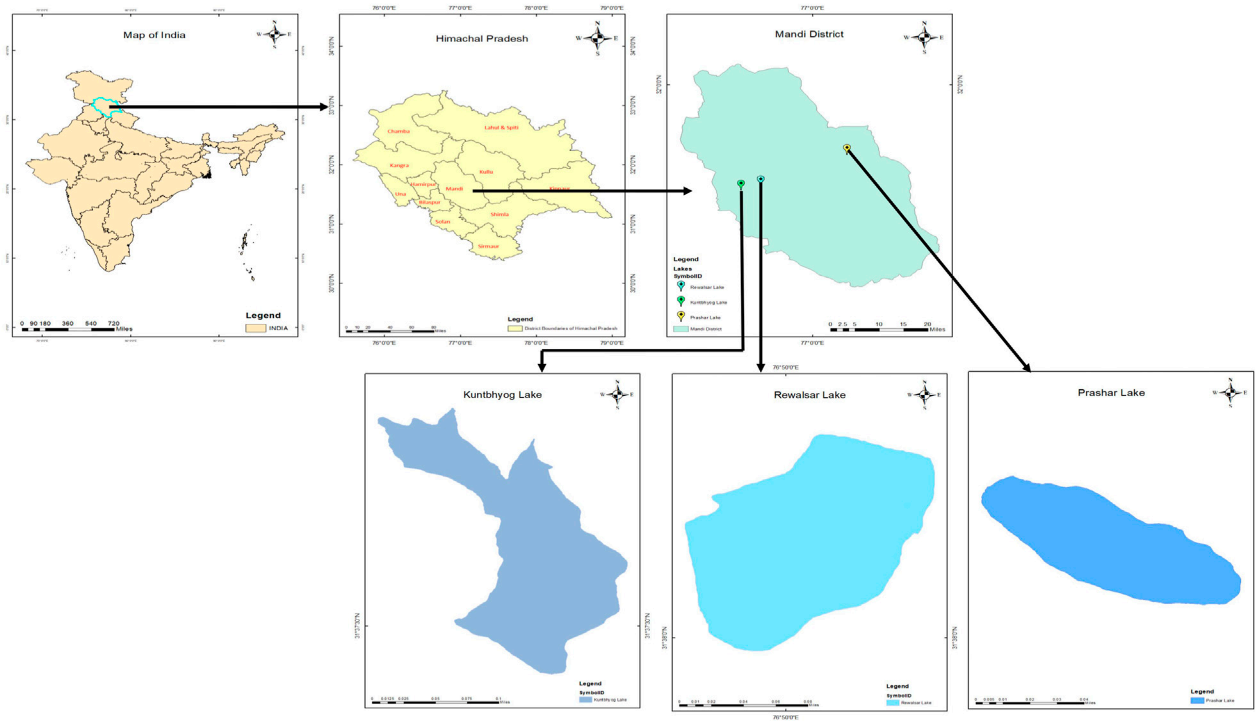

FIGURE 1
ArcGIS map showing the selected sampling lakes in Himachal Pradesh.

cause of growing concern and require monitoring of the surface waters and organisms inhabiting them (Vandysh, 2004). The mere presence of these plankton indicates the status of water bodies and can be used as a reliable tool for the assessment of the water quality of freshwater bodies. The influence of eutrophication is usually associated with a loss of structural diversity, and as a result, a diminution in biodiversity at the higher trophic levels takes place (Hanson and Butler, 1994; Gaur, 1997). Although oligotrophic lakes are generally clear, hypertrophic lakes are frequently turbid, and shallow lakes at intermediate nutrient concentrations may exhibit either clear water or turbid states (Scheffer et al., 1993).

For the last few decades, freshwater bodies like lakes facing the stress of pollution due to anthropogenic activities have become a serious problem all over the world (Jindal and Vatsal, 2005; Thakur et al., 2022). Because of global climate change, gross primary productivity (GPP) is often one of the most important components of aquatic food webs in lakes and reservoirs (Malik et al., 2021). Due to the rapid global climate change, lakes and reservoirs are gradually becoming warmer and receiving more terrestrial-colored dissolved organic carbon (Malik et al., 2021; Puts et al., 2022). The habitat ecological parameters of high-altitude water bodies have significantly contributed to altering the magnitude of biological dynamics and shown interrelationships, either positive or negative, in an existing ecosystem (Malik and Bharti, 2012). Plankton also play an important role in the productivity of freshwater bodies and thus act as primary producers in lake ecosystems (Patil, 2012). Based upon the aforementioned factors, the primary aim of the present research was to estimate the differentiation pattern with respect to the productivity and trophic nature of some selected lakes of Western Himalayas.

Materials and methods

Study area

The present study has been conducted on three freshwater lakes *viz.*, Rewalsar , Kuntbhyog , and Prashar lakes in the Mandi district (Long: 76° 37′ 20” - 77° 23′ 15″ E, Lat: 31° 13′ 50” - 32° 04′ 30″ N) of Himachal Pradesh (Figure 1). The topographic details of these lakes are as follows: Rewalsar Lake is situated at 1,360 m above MSL (76°49′E, 31°37′N). It is oval in shape, having a depth of 6 m and an area of 2.6 ha. There are two seasonal inlets and one perennial outlet with definite boundaries bordered by thick patches of macrophytic vegetation. Kuntbhyog Lake is situated at 1750 m above MSL (76°49′6″E, 31°37′N). It is crescent in shape, having a depth of 12–15 m and an area of 3 ha. The lake is surrounded by mountains and forests. It is spring and rain fed and is without any specific outlet. The water of the lake is used for drinking and irrigation. Prashar Lake is situated at 2,730 m above MSL (77° 06′ E, 31°45′30″N). It is oval in shape, having a depth of 4–5 m and an area of 2.3 ha. It is surrounded by mountains. The water of this lake is used for drinking and domestic purposes. In the winter, this lake is surrounded by snow.

Sampling and analysis

For the present studies, water samples were collected monthly from the selected lakes for a period of 2 years, from March 2007 to February 2009. The physicochemical parameters of the water were analyzed according to the standard methods (APHA, 2005). Identification of the plankton was performed following Smith

(1950), Desikachary (1959), Edmondson (1959), Kudo (1986), and Pennak (1978). Parameters, like temperature, pH, dissolved oxygen, and electrical conductance, were measured with the help of a Multi 340i/set water analysis kit, penetration of light with a Secchi disc, free carbon dioxide by the titrimetric method, and TDS with a TDS meter on the spot. For the rest of the parameters, 2.5 L of the water sample was brought to the laboratory. It was filtered and analyzed for turbidity, total alkalinity, total hardness, chloride, nitrate, nitrite, phosphate, and silicate. The primary productivity of the ecosystems was determined by the "light and dark bottle method" (Wetzel and Likens, 2000). Dissolved oxygen values (mg L^{-1} h^{-1}) of gross primary productivity (GPP), net primary productivity (NPP), and community respiration (CR) were converted in g C m^{-2} d^{-1}. Primary productivity was estimated thrice a day, i.e., morning, midday, and evening, and the average value was taken. For the assessment of chlorophyll "a," 200 mL of the water sample containing phytoplankton was centrifuged. The settled mass of phytoplankton was treated with 1% $MgCO_3$ solution and 90% acetone. After that, this sample was kept at 4 °C in the dark for 24 h to extract the pigment. The extract was again centrifuged for 20 min at 2,500–3,000 rpm for clarification. The volume of the clear extract was made to a fixed volume. The optical density (OD) at wavelengths 750 nm, 630 nm, 647 nm, and 664 nm was noted spectrophotometrically. The OD at 750 nm is a correction for turbidity. Chlorophyll "a" was calculated by inserting observed optical densities in the following equation (APHA, 2005):

$$\mathrm{Chl_a} = 11.85\,(\mathrm{OD}\,664) - 1.54\,(\mathrm{OD}\,647) - 0.08\,(\mathrm{OD}\,630),$$

where

$$\mathrm{Chl_a} = \text{concentration of Chlorophyll}\,'a'.$$

OD 664, OD 647, and OD 630 are corrected optical densities at respective wavelengths.

By knowing the pigment concentration, the chlorophyll value of the sample was calculated by the following formula:

$$\mathrm{Chl_a}\,\mathrm{mg\,m^{-3}} = \frac{\mathrm{Chl_a}\ \text{X volume of extract, L}}{\text{Volume of sample, m}^3}.$$

Statistical analysis

Biodiversity indices and the trophic status index (Nygaard, 1949; Shannon and Wiener, 1949; Simpson, 1949; Margalef, 1958; Berger and Parker, 1970) were determined. Statistical analysis was carried out using the PASW 19 software package (SPSS Inc.). Logarithmic transformation was applied to phytoplankton and zooplankton abundance data. The TN/TP ratio was calculated and taken as one individual variable. Plankton population, with eight physicochemical parameters with a complete data set, were accessed with the Kaiser–Meyer–Olkin (KMO) measure of sample adequacy, and Bartlett's test of sphericity (w^2 with degrees of freedom = 1/2 [p(p - 1)]) was used to verify the applicability of PCA and t-stochastic neighbor embedding (t-SNE). A decision tree-based water sample classification system was developed on the basis of selected physico-chemical features with a significant Gini index. The parameters governing the lake productivity were also analyzed by PCA. Correlation analysis is only appropriate to explore the relationship between variables and not to infer a causal relationship. In descriptive statistics, a box plot or boxplot (also known as a box and whisker plot) is a type of chart often used in explanatory data analysis. Box plots visually show the distribution of numerical data and skewness by displaying the data quartiles (or percentiles) and averages. Box plots show the five-number summary of a set of data, including the minimum score, first (lower) quartile, median, third (upper) quartile, and maximum score.

Results

The physico-chemical factors in Rewalsar, Kuntbhyog, and Prashar lakes that ranged monthly are as follows: the temperature of water (°C) 10.00–27.20, 8.10–26.00, and 5.00–22.60, with lower values during winter and higher values during late summer; electrical conductivity (µS cm^{-1}) 180.00–460.00, 135.00–385.00, and 114.00–285.00, with lower values during winter and higher values during late summer; pH 7.05–8.34, 7.90–8.64, and 7.22–8.24, with lower values during monsoon and higher values during winter; total dissolved solids (mg L^{-1}) 115.00–294.00, 86.00–246.00, and 72.00–182.00, with lower values during winter and higher values during late summer; penetration of light (cm) 30.80–137.20, 72.50–230.20, and 22.80–178.30, with lower values during monsoon and higher values during winter; turbidity (NTU) 45.50–350.40, 3.50–65.40, and 3.30–74.20, with lower values during winter and higher values during monsoon; dissolved oxygen (mg L^{-1}) 3.05–9.98, 6.92–12.32, and 5.45–13.21, with lower values during summer and higher values during winter; BOD (mg L^{-1}) 0.00–8.20, 0.55–4.00, and 0.20–4.00, with lower values during winter and higher values during summer and monsoon; free carbon dioxide (mg L^{-1}) 0.00–32.46, 0.00–20.05, and 1.55–25.20, with lower values during winter and higher values during summer and monsoon; carbonate (mg L^{-1}) 0.00–6.80, 0.00–24.20, and 0.00–0.00, present only during winter and early summer; bicarbonate (mg L^{-1}) 91.20–170.50, 68.80–150.00, and 60.40–95.05, with lower values during winter and higher values during monsoon; total hardness (mg L^{-1}) 101.00–182.30, 52.05–123.22, and 20.04–75.25, with lower values during winter and higher values during late summer and monsoon; chloride (mg L^{-1}) 23.18–58.20, 7.20–20.08, and 4.80–9.05, with lower values during winter and higher values during summer; ammonia (µg L^{-1}) 8.20–36.40, 0.00–11.30, and 0.00–5.00, with lower values during winter and higher values during monsoon; nitrite (µg L^{-1}) 0.00–62.40, 12.10–55.00, and 0.00–48.50, with lower values during winter and higher values during summer and monsoon; nitrate (µg L^{-1}) 90.60–320.60, 70.80–210.20, and 30.40–130.30, with lower values during winter and higher values during monsoon; phosphate (µg L^{-1}) 28.20–110.70, 14.20–61.40, and 5.00–24.50, with lower values during winter and higher values during late summer and monsoon; sulfate (mg L^{-1}) 138.00–280.60, 30.15–140.20, and 16.35–80.07, with lower values during winter and higher values during summer; and silicate (mg L^{-1}) 4.83–13.15, 3.45–13.15, and 7.10–17.52, with lower values during winter and higher values during monsoon and post-monsoon.

Plankton were composed of phytoplankton and zooplankton. Among these, phytoplankton constituted the dominant component, and zooplankton constituted the subdominant component. Amongst phytoplankton, Cyanophyceae (*Anabaena* sp. and *Oscillatoria* sp.) and Bacillariophyceae (*Cosmarium* sp. and *Staurastrum* sp.) constituted the dominant/subdominant component; Chlorophyceae (*Ankistrodesmus* sp., *Pediastrum* sp. and *Scenedesmus* sp.) was

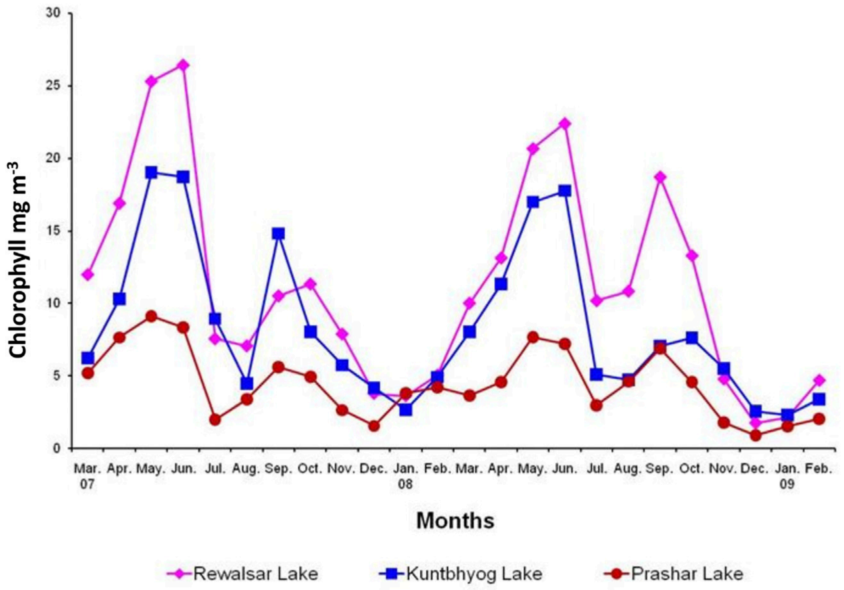

FIGURE 2
Monthly fluctuations in chlorophyll 'a' in different lakes.

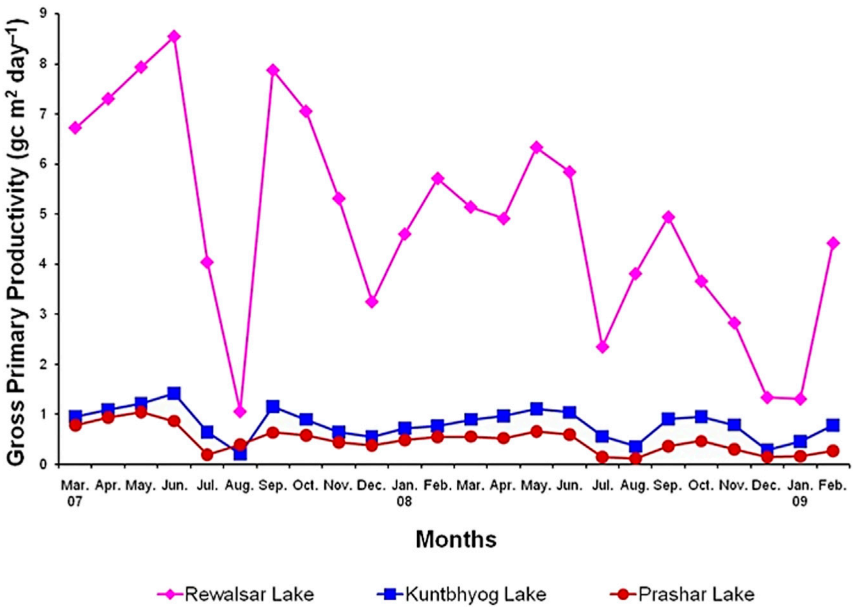

FIGURE 3
Monthly fluctuations in primary productivity in different lakes.

subdominant; and Euglenophyceae, Chrysophyceae (*Dinobryon* sp.), Cryptophyceae, and Dinophyceae were the minor components. Among zooplankton, Rotifera (*Rotaria rotatoria, Brachionus angularis*) formed the dominant component; Protozoa, Cladocera (*Daphnia magna*), and Copepoda (*Cyclops brevicornis*) formed the subdominant component, whereas Ostracoda formed the minor component.

The monthly average value of chlorophyll 'a' (mg m^{-3}) and its range were 11.440 ± 7.724 (3.608–26.429), 8.982 ± 5.640 (2.662–19.008), and 4.873 ± 2.457 (1.560–9.120) in 2007–08, and 11.037 ± 6.989 (1.738–22.386), 7.678 ± 5.186 (2.277–17.727), and 4.034 ± 2.313 (0.905–7.678) in 2008–09 in Rewalsar, Kuntbhyog, and Prashar lakes, respectively (Figure 2).

Monthly values of gross primary productivity (GPP), net primary productivity (NPP), and community respiration (CR) in the different lakes are depicted in Figure 3. The monthly average values of GPP (g C m^{-2} day^{-1}) with its range were 5.782 ± 2.232 (1.055–8.540), 0.848 ± 0.333 (0.203–1.407), and 0.602 ± 0.252 (0.192–1.037) in 2007–08, and

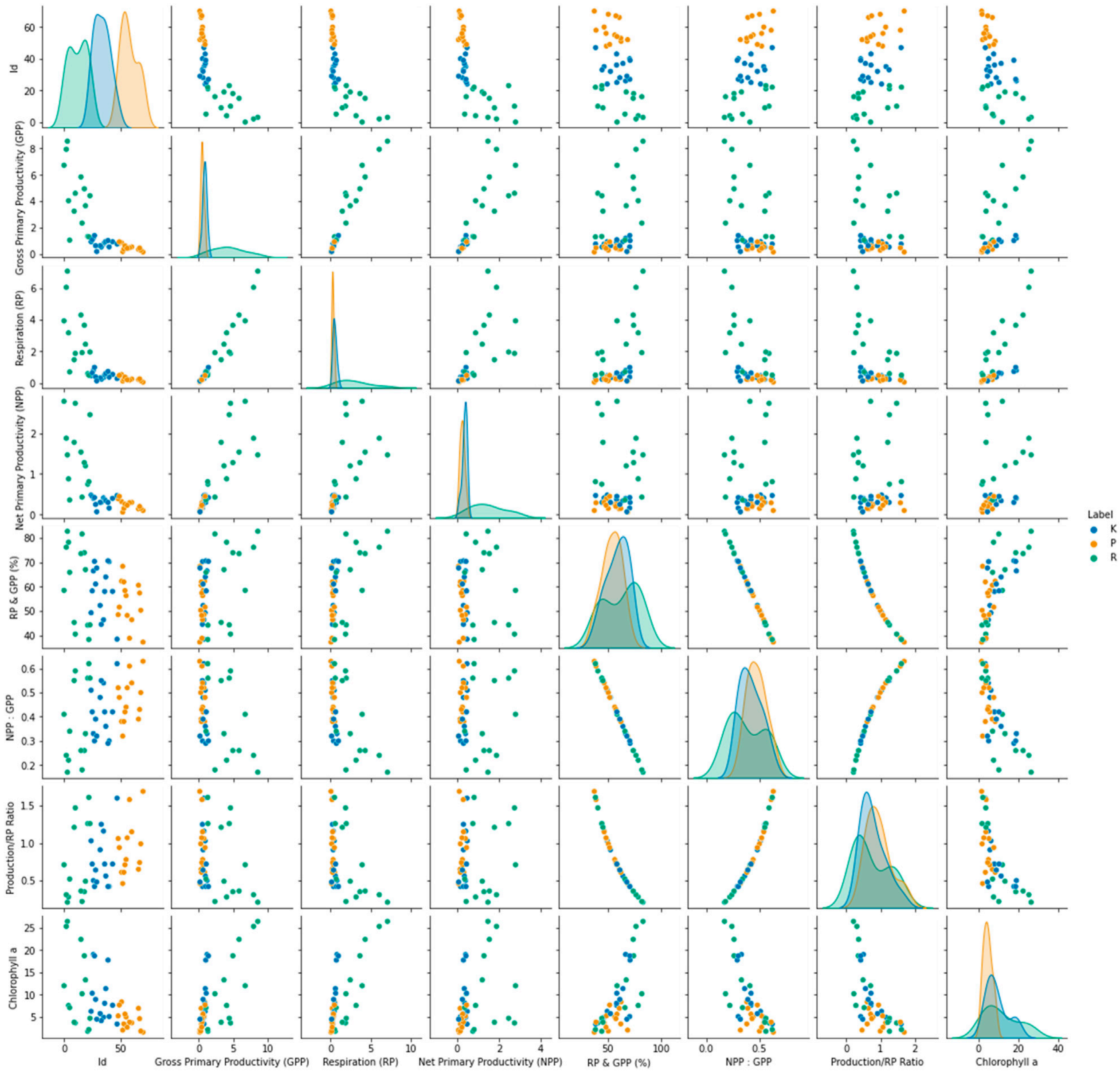

FIGURE 4
Productivity analysis of three lakes in the Western Himalayan region: Rewalsar (R-Green), Kuntbhyog (K-Orange), and Prashar (P-blue) lakes. The data on gross primary productivity (GPP), respiration (RP), net primary productivity (NPP), chlorophyll a, and their respective proportions were plotted for the three lakes. The parametric spread for the three lakes indicated the relative similarity in K and P lakes vis-à-vis R. The GPP of K and P was very low as compared to R. The GPP of R demonstrated a very wide variation. Inclusion of the respiration parameter makes this difference more pronounced.

3.906 ± 1.663 (1.305–6.329), 0.750 ± 0.275 (0.282–1.098), and 0.355 ± 0.195 (0.111–0.652) in 2008–09 in Rewalsar, Kuntbhyog, and Prashar lakes, respectively. The monthly average values of respiration (g C m^{-3} day^{-1}) with its range were 3.732 ± 1.948 (0.695–7.072), 0.480 ± 0.245 (0.137–0.991), (0.316–0.798), and 0.192 ± 0.116 (0.060–0.375) in 2008–09 in Rewalsar, Kuntbhyog, and Prashar lakes, respectively (Figure 4).

Correlation analysis in the interval/ratio variable prerequisites confirms a linear relationship and no outlier in the data using scatterplots. This technique was applied to determine the highest correlating factors, as shown in Figure 5. The physico-chemical parameters of the three lakes were subjected to correlation analysis to identify the most significant contributors to the information content of the data. The penetration of light did not correlate with any other factor. The dissolved oxygen had a high degree of relationship with pH. Turbidity correlated with the nitrites, sulfates, phosphates, and other inorganic salts. Interestingly, free CO_2 showed a high degree of correlation with the nitrites. One reason for this could be a bloom of microbes due to the increased nitrogen content, which led to the increased decay of organic matter, thereby increasing the free CO_2 concentration.

The spread of some of the high-information content parameters was analyzed through box plots. The box plots were created for the five factors with the highest information-contributing potentials

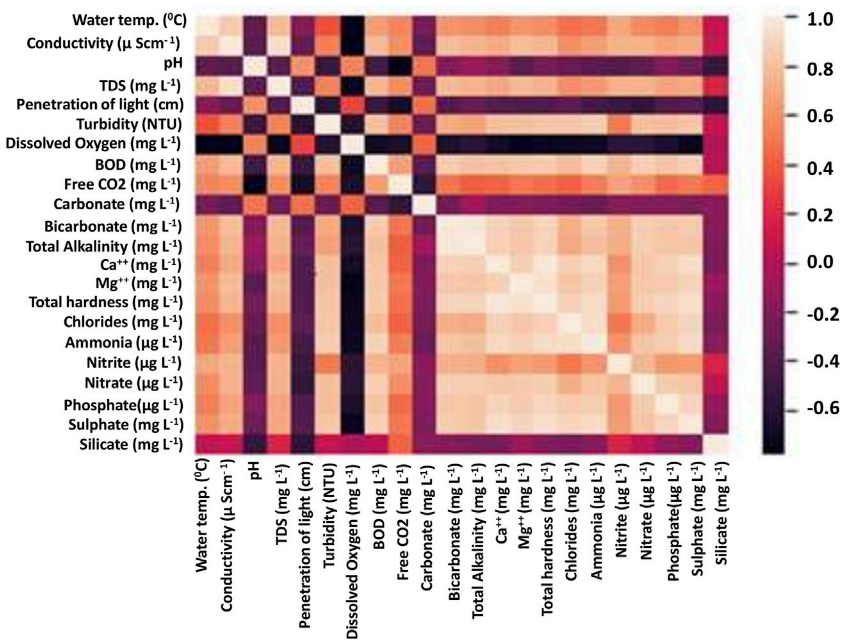

FIGURE 5
Correlation among various factors. The negative correlation depicts the inverse relationship (for instance, between dissolved oxygen and salt concentration).

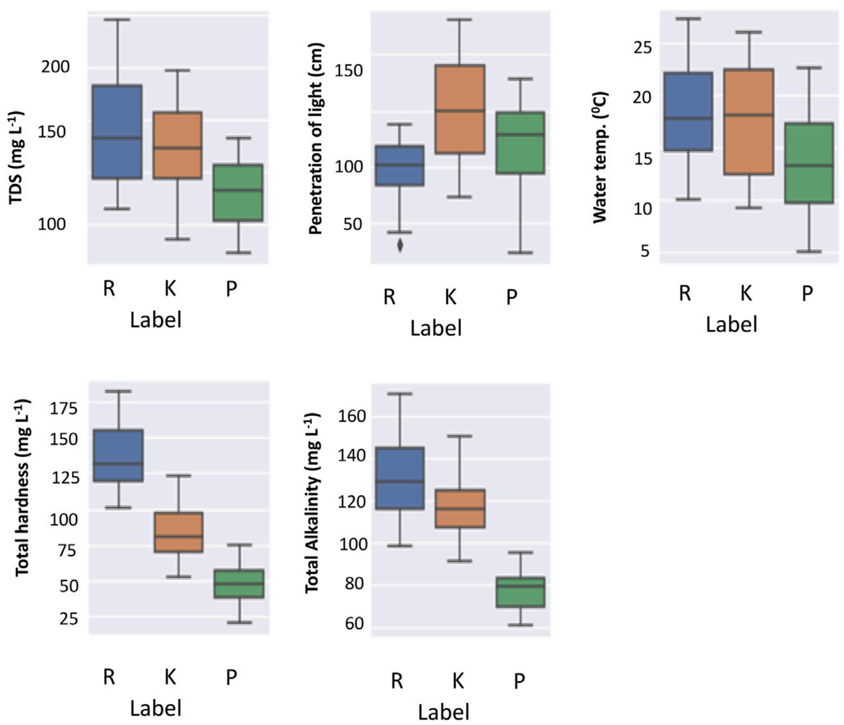

FIGURE 6
Top five parameters that contributed the information entropy were analyzed for the spread. Rewalsar (R-Blue), Kuntbhyog (K-Orange), and Prashar (P-green) lakes. The spread of the values of the three lakes is shown.

(Figure 6). This showed a clear correlation with the altitude of the lakes, for instance, the total alkalinity for Prashar Lake was the least, and that of Rewalsar was the highest. A similar trend was observed for the total hardness and TDS parameters. The penetration of light was inversely proportional to the dissolved solids, and this was also evident from the data on the three lakes. The penetration of light was the

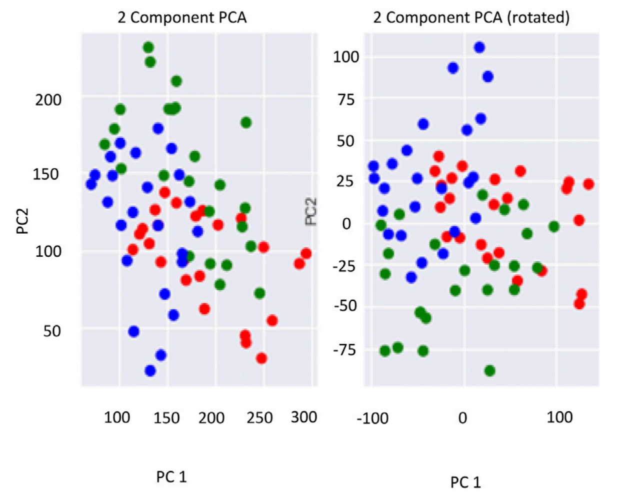

FIGURE 7
Two-component principal component analysis of the parameters for the three lakes. The green rounded circles represent Prashar Lake; the red rounded circles represent Kuntbhyog Lake, and the blue rounded circles represent Rewalsar Lake.

highest for Prashar Lake and the least for Rewalsar Lake. The penetration of light was inversely proportional to the concentration of silicates. This was supported by the strong negative correlation observed between the two parameters. The pH value and concentration of carbonate salts had an insignificant correlation with the penetration of light. One reason for this observation is perhaps the colorless nature of most of the carbonate salts. Another interesting pattern that emerged was a negative correlation between the concentration of CO_2 and the concentration of carbonates. The concentration of dissolved oxygen exhibited a negative correlation with most of the parameters. This is a peculiar pattern as this factor alone could be a very high information parameter with respect to the pollution level in the water bodies. Silicate concentration was more of a neutral parameter as it showed almost no correlation with other parameters, except penetration of light (Figure 7).

Principal component analysis (PCA) is an important technique to understand in the fields of statistics and data science, especially with respect to large datasets, which are often difficult to interpret. PCA is a technique for reducing the dimensionality of large datasets. It improves the interpretability of the factors while simultaneously minimizing information loss by maximizing variance. Finding such new variables, the principal components reduce to solve an eigenvalue/eigenvector problem, and the new variables are defined by the dataset at hand, not *a priori*, hence making PCA an adaptive data analysis technique. A two-component PCA was applied to the lake data to understand the differentiation pattern amongst the data regarding the lakes (Figure 7).

Discussion

A definite pattern in seasonal variations in GPP was observed. Irrespective of differences in the production capacities, all the lakes showed a bimodal pattern of rise and fall in productivity. Higher values of GPP were recorded during summer and post-monsoon, and least, during monsoon (July–August) and winter. High productivity during summer and post-monsoon could be attributed to higher values of temperature, alkalinity, hardness, nutrients and phytoplankton, and moderate values of water turbidity. Singh et al. (2016) reported higher productivity during winter and spring, whereas lower productivity in monsoon and in summer in Nachiketa Tal Lake, and also explained that higher productivity in winter and spring might be due to the abundance of plankton in these seasons. Scharfenberger et al., 2019 reported that GPP and NPP were significantly higher in eutrophic mesocosms than in mesotrophic mesocosms.

The maximum value of respiration was recorded during summer and post-monsoon, and the minimum, in winter. However, the respiration percentage of GPP was Rewalsar > Kuntbhyog > Prashar Lake and was maximum during monsoon and minimum in the winter. Higher values during monsoon were due to high temperatures enhancing the rate of respiration of organisms and the low ratio of producers to consumers.

The lowest value of GPP was recorded during monsoon, which was because of high turbidity, cloudy weather, and dilution in the concentration of some salts, whereas relatively less productivity during winter was mainly because of low values of temperature and nutrients. A similar pattern of seasonal fluctuations in productivity was reported by Zafar (1986) in his work on south Indian waters, Sen et al. (1992) on Ranchi lakes (Bihar), and Verma and Mohanty (1994) on Orissa lakes. The summer peak of GPP was also reported by Murugavel and Pandian (2000) in a Tamil Nadu reservoir and Wanganeo (1984) in a Kashmir lake. However, Durve and Rao (1987) registered higher values during July and November in Rajasthan Lake. According to Feresin et al. (2010), the Lower Mekong Basin (LMB) water bodies have an annual PP ranging from 40 to 302 g C/m^2/y, which is lower than the PP previously reported for tropical reservoirs in Asia, Africa, and South America.

A direct relationship was recorded between water temperature and productivity (r = 0.491 in Rewalsar Lake, r = 0.483 in Kuntbhyog Lake, and r = 0.402 in Prashar Lake). This is in agreement with the findings of Khatri (1984), Durve and Rao (1987), Singh (1990), Verma and Mohanty (1994), and Jindal and Prajapat (2005). Conversely, during the present investigation during monsoon and on certain occasions during summer, a decline in productivity was recorded. This, as suggested by Oswald (1988), was because at higher temperatures, a greater fraction of daily organic production was consumed in respiration. The water qualities of hill streams have fundamentally contributed to altering the magnitude of biological dynamics and shown interrelationships, either positive or negative, in an existing environment (Malik and Bharti, 2012).

Verma and Mohanty (1994), in their work on Orissa lakes, observed an inverse correlation between alkalinity and primary productivity. However, present findings are in conformity with the findings of Sreenivasan (1964), Vijayaraghavan (1971a, b), and Singh (1986). However, Khatri (1984) reported a linear correlation between these factors only during the summer months.

The ebb and flow in the values of chlorophyll "a" were similar to those of gross primary productivity. Higher values were observed during summer and post-monsoon, and lower values during, winter and monsoon. A positive correlation ($p \leq 0.01$) between primary productivity and chlorophyll "a" was observed in the present study. The results of the present findings are in concurrence with those of Durve and Rao (1987). However, Kalff (1967) and Bohra (1976), during their investigations, reported that primary production and chlorophyll 'a' were correlated in certain seasons only. Durve and Rao (1987) and Verma and Datta Munshi (1989) also observed a positive correlation with chlorophyll "a," although it was not statistically significant.

During the present investigation in Rewalsar Lake, at certain times, the respiration was 98.80%, thereby depicting the insalubrious condition of the lake. A high rate of respiration could be endorsed to a higher microbial population dominant in the lake (Saha and Pandit, 1987). Rewalsar Lake showed unhealthy and polluted status. The Shannon–Wiener index of species diversity for the planktonic community was also found to decrease with the increase in eutrophication.

On comparing the productivity of the three lakes under investigation, it was found that the value of GPP was less in Prashar Lake, which could be because of the less number of phytoplankton, low values of chlorophyll "a," and nutrients. The contemporary examination also proved that the members of Cyanophyceae and Chlorococcales were found commonly in the eutrophic waters of Rewalsar and Kuntbhyog lakes, while desmids were found to tolerate high nutrient levels, and these showed abundance in Prashar Lake with oligotrophic conditions (Rawson, 1956; Brook, 1965; Patrick, 1965; Palmer, 1969). Only 1 desmid species was collected in Rewalsar Lake, 5 species in Kuntbhyog Lake, and 11 species in Prashar Lake. It was also observed that GPP values were higher in tropical fresh waters than those in temperate fresh waters. This might be due to uniformly high temperatures, greater intensity of solar radiation, and absence of critical winter season in tropical conditions. Temperature and light were never a limiting factor under tropical conditions, and the addition of a small amount of nutrients greatly increased the productivity (Marshall and Falconer, 1973; Jindal and Thakur, 2009; Thakur et al., 2013; Jindal and Thakur, 2014). A similar observation was recorded by Jindal and Thakur (2014) while working on Kuntbhyog Lake, and it was observed that plankton diversity depends upon water quality and different habitat parameters. During the present investigation, it was observed that an increase in temperature enhanced the production. During summer, both temperature and production were at the peak, but during monsoon season (July–August), in spite of the higher temperature, productivity was lowest, which was due to high turbidity, resulting in less penetration of light and less phytoplankton.

During the present investigation, the monthly average values of the P/R ratio in different lakes were 0.679 ± 0.405 (0.208–1.467), 0.843 ± 0.310 (0.420–1.361), and 0.989 ± 0.435 (0.462–1.913) in 2007–08, and 0.657 ± 0.506 (0.012–1.610), 0.882 ± 0.547 (0.377–1.806), and 0.937 ± 0.363 (0.543–1.687) in 2008–09 in Rewalsar, Kuntbhyog, and Prashar lakes, respectively. These values were the lowest in the cloudburst (July–August) due to high temperature, low penetration of light, and a decline in the density of phytoplankton. The present findings are in concurrence with the findings of Oswald (1988), Jindal and Prajapat (2005), and Thakur et al. (2013).

Monthly fluctuations in the values of various Nygaard's trophic status indices (Nygaard, 1949) and the resultant trophic status of the lakes under investigation have been given in Supplementary Tables S1–S4. Relatively, a wide range in the values of Myxophycean, Chlorophycean, and compound indices and a narrow range for Euglenophycean indices were observed. However, in Prashar Lake, the Chlorophycean index showed a wide range (1.50–1.75) and the Euglenophycean index showed a narrow range (0.20–0.50). The wide range of the Chlorophycean index in this lake could be attributed to a relatively higher number of desmid species, and the narrow range of the Euglenophycean index was because of the low number of euglenoid species. Furthermore, it is supported by the presence of more desmids and fewer euglenoids due to low nutrients in this lake. A relatively wide range of compound index values in Rewalsar (12.00–20.00) and Kuntbhyog lakes (12.50–18.00) confirmed their eutrophic nature. This might be due to the addition of organic water observed during present studies of animal origin. However, a narrow range of the compound index was observed in Prashar Lake (3.00–3.30). It was also noted that pinnate diatoms generally did not tolerate a high nutrient level as 18 species of pinnate diatoms were encountered in Prashar Lake, which is oligotrophic Thakur et al., 2013.

As suggested by Datta (1997), the eutrophic nature of Rewalsar Lake is further confirmed by the higher values of GPP. The classification of the trophic status of European water bodies in relation to productivity has been given by Vollenweider (1968) and Rodhe (1969). According to Vollenweider (1968), water having a primary productivity rate of 65–300 mg C m^{-2} day^{-1} was considered to be oligotrophic, 250–1,000 mg C m^{-2} day^{-1} as mesotrophic, and 1,000–8,000 mg C m^{-2} day^{-1} as eutrophic. Contrary to this, Rodhe (1969) has given the values 30–100 mg C m^{-2} day^{-1} for oligotrophic and 300–1,000 mg C m^{-2} day^{-1} for natural eutrophic waters. Gessner (1949) reported that the gross primary productivity of temperate eutrophic water varies between 500 and 5,000 mg C m^{-2} day^{-1}. Based on the trophic classification of water given by the aforementioned studies and on the basis of productivity among the lakes under study, Rewalsar Lake could be designated as eutrophic, Kuntbhyog Lake as mesotrophic to eutrophic, and Prashar Lake as oligotrophic–mesotrophic in nature. To sum up, on the basis of Nygaard's trophic state indices, productivity values, and richness of nutrients, Rewalsar and Kuntbhyog lakes could be categorized as eutrophic and Prashar Lake as oligotrophic to eutrophic.

Statistics of the principal component analysis showed that eigen values were a maximum of 2.948, 2.511, and 3.416; the correlation was less, i.e., 42.114, 41.846, and 42.706, of Rewalsar, Kuntbhyog, and Prashar lakes, respectively. Plankton with physicochemical parameters showed a direct correlation, and some showed a negative correlation (Figure 5). Malik et al. (2021) reported that phytoplanktons showed a negative correlation with temperature, pH, alkalinity sodium, *etc.,* and a positive correlation with D.O. and water velocity. This study highlights that plankton's growth directly or indirectly depended upon D.O. and the flow of the lakes and rivers.

Studies conducted by several workers have shown marked differences in the floristic composition of oligotrophic and eutrophic waters, and various species of different groups of algae have been identified as indicators of the level of trophic status (Hutchinson, 1967; Palmer, 1969; Thakur et al., 2013). Hutchinson (1967) and Thakur et al. (2013) described eutrophic diatom association as *Asteronella* sp., *Fragilaria* sp., *Melosira* sp., *Stephanodiscus* sp., and *Synedra* sp.; eutrophic Myxophycean association as *Aphanizomenon* sp., *Anabaena* sp., and *Oscillatoria* sp.; eutrophic desmideae association as *Cosmarium* sp. and *Staurastrum* sp.; and eutrophic Chlorococcales association as *Ankistrodesmus* sp., *Pediastrum* sp., and *Scenedesmus* sp.

Forms like *Asplanchna brightwelli* (Gosse), *Brachionus angularis* (Gosse), *Cyclops brevicornis* (Baird), *Chlorella vulgaris* Beyerinck (Beijerinck), *Closterium acerosum* (Ehrenberg), *Chlamydomonas reinhardi* (Dangeard), *Cryptomonas erosa* (Ehrenberg), *Daphnia magna* (Straus), *Microcystis aeruginosa* (Kützing), *Euglena oxyuris*

(Ehrenberg), *E. viridis* (Ehrenberg), *Gomphonema gracile* (Ehrenberg), *Navicula cryptocephela* (Kützing), *Nitzschia palea* (Kützing), *Oscillatoria limosa* (Agardh), *Rotaria rotatoria* (Pallas), *Scenedesmus qudricauda* (Meyen), *Synedra ulna* (Ehrenberg) Nitzschia, and *Vorticella convallaria* (Linnaeus), were tolerant to eutrophic conditions, whereas species like *Closterium pseudodianae*, *Daphnia* sp., *Dimorphococcus lunatus* (Braun), *Dinobryon* sp. (Ehrenberg), *Euastrum* sp. (Ehrenberg), *Euchlanis dialata* (Ehrenberg), *Gloeocapsa* sp. (Kützing), *Notholca* sp. (Gosse), *Synura adamsii* (Ehrenberg), and *Vorticella nebularia* (Linnaeus) were found to be sensitive to eutrophic conditions.

Conclusion

During the present study, the GPP (g C m^2 d^{-1}) of Rewalsar Lake ranged from 3.906 ± 1.663 to 5.782 ± 2.232, followed by Kuntbhyog Lake (0.750 ± 0.275 to 0.848 ± 0.333) and Prasher Lake (0.355 ± 0.195 to 0.602 ± 0.252). The NPP of Rewalsar Lake ranged from 1.055 ± 1.663 to 5.782 ± 2.232, followed by Kuntbhyog Lake (0.750 ± 0.275 to 0.848 ± 0.333) and Prasher Lake (0.355 ± 0.195 to 0.602 ± 0.252). A higher diversity index was recorded in Prasher Lake, and a lower diversity index, in Rewalsar Lake. The habitat ecological parameters, i.e., temperature, light intensity, nutrients, and chlorophyll-a, were liable for higher productivity. Based on the results of habitat ecological parameters, GPP, chlorophyll-a, and planktonic composition of the lakes, it may be concluded that these lakes are tending toward fast eutrophism, particularly Rewalsar Lake. The changes in temporal and spatial composition of the plankton that occurred in the three lakes were mainly due to eutrophication. In addition, from the study, it was clearly observed that dissolved oxygen was the dominant parameter for the pristine nature of freshwater bodies. The anthropogenic activities, urbanized catchment areas, and agricultural runoff were mainly responsible for the eutrophication of these lakes. These kinds of activities should be consistently checked and should be checked by scientific methods.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

RK and RJ: conceived the idea; RK: prepared the study design; DM, MK, and AS: data mining; RK, MK, DS, and KT: data analysis; SK, AK, AS, and BB: formal analysis; RK, MK, and DS: original draft preparation; SK, AK, RK, and RJ: manuscript editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1009942/full#supplementary-material

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