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RESEARCH

Anthropogenic disturbances influence mineral and elemental constituents of freshwater lake sediments

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Abstract Lake sediments can provide valuable insights into anthropogenic disturbances such as intensive aquaculture and land use changes. These disturbances often manifest as elevated levels of nutrients and elements within the sediments. This paper uses several analytical techniques, i.e., FTIR (Fourier-transform infrared spectroscopy), XRD (X-ray diffraction), EDS (energy-dispersive X-ray spectroscopy), and SEM (scanning electron microscopy), to examine the elemental constituents of lake sediments, along with their relative mineral abundances and surface morphology. The selected freshwater lakes are from the Central Gangetic Plain. The analysis provides a "fingerprint" of geogenic and biogenic mineral constituents of the sediments. Physicochemical, mineralogical, and elemental analysis shows that intensive aquaculture activities in lake alter the sediment chemistry as evidenced by the increase in pH, organic carbon, organic matter, and total phosphorus which is not observed in the lake where aquaculture is prohibited. Freshwater lake sediment is characterized by a high content of biogenic silica and carbonate minerals. The variations in sediment nutrients and mineral fluxes of the selected lakes are mainly attributed to diverse anthropogenic pressures, differences in lake productivity, and the overall ecological condition of the lakes. In the selected three lakes, major variation was reported in the autochthonous sediments in comparison to the allochthonous sediments. The study concludes that catchment and biotic deposit variations in the lakes cannot be evened out by in-lake mixing mechanisms due to variations in the terrigenous and pelagic deposits of the lake. The results highlight the importance of studying annual fluctuations and spatial variations in geogenic and biogenic mineral particle fluxes in lakes. Such investigations provide valuable insights into the annual dynamics of minerals within lakes, contributing to a more comprehensive understanding of their behavior and distribution.

Keywords Aquaculture · Lacustrine ecosystem · Biogenic silica · Geogenic minerals · Sediment organic carbon

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Introduction

Lakes are important ecosystems as they support both aquatic and terrestrial biodiversity and provide various ecological services for societal well-being (Mazzotta et al., 2019; Sánchez-González et al., 2019). Currently, numerous lakes in urban areas face the risk of degradation caused by the influx of various pollutants from surface runoff, municipal wastewater discharges, and atmospheric depositions (Mikac et al., 2011; Yuan et al., 2021; Zang et al., 2022). Sediments are important components of the lake ecosystem. They provide information about various paleolimnological activities during a particular course of time caused due to anthropogenic disturbances as well as natural processes (Forghani et al., 2009; Petrovskii et al., 2016). They are valuable storehouses of various environmental parameters (Renjith and Chandramohanakumar, 2007; Fedotov et al., 2013; Saha et al., 2020).

Major constituents of the lake sediments include quartz, feldspars, clay, calcium carbonate, and numerous silicate minerals along with organic matters, which originate from vegetative debris, decayed remains of aquatic plants and animals, and humic substances (Boldea et al., 2013; Khang et al., 2016). Minerals in sediments are commonly classified as primary and secondary minerals. Primary minerals, like quartz and feldspar, are abraded and broken down under weathering due to various physical conditions of temperature and pressure, leading to the formation of secondary clay minerals such as kaolinite and chlorite (Karathanasis, 2009; Saha et al., 2020). The mineralogical characterization of complex sediment samples is an essential method for evaluating anthropogenic influences and changes in chemical and physical properties, as well as changes in functionality within the lake. Mineralogy has a considerable influence on sediment-water interaction, and it is critical for resolving multiple challenges linked with the geoenvironmental status of a lake (Siročić et al., 2020).

Different criteria for the classification of lake sediments are based on the source of origin, particle size, and geochemical composition (Savic et al., 2021). Based on their origin, sediments are categorized into two types. The first type of sediments is allochthonous mainly geogenic in nature, which are formed outside of the lake. These sediments comprise mineral components like quartz, feldspars, and various other minerals that flow into a lake from catchment runoff (Melack, 2020). The second type of sediment is autochthonous which originates within the lake through inner functional processes. These autochthonous sediments are mainly biogenic in origin and include biogenic silica (from diatoms), carbonates (precipitating from water), and organic carbon humic substances as residuals of different living aquatic organisms present in the lacustrine ecosystem (Muanbari, 2018). Biogenic silica is a kind of amorphous silica that is largely generated from siliceous creatures like sponges, diatoms, and radiolarians. Unique information about the spatial and temporal distribution of primary productivity can be found in the biogenic silica of lake sediments (Wen et al., 2020; Yongxiu et al., 2020; Yuan et al., 2021).

Significant global research has been conducted on the variations in elements and minerals within lakes, with a focus on understanding the weathering processes affecting these lakes (Mir et al., 2022; Liu et al., 2023; Sandeep et al., 2022). Additionally, paleolimnological studies have also contributed to this field (Xia et al., 2022; Farooqui et al., 2023). Numerous research studies have explored the anthropogenic effects on sediment mineral and elemental composition in various environments, including the sea (Mikac et al., 2022) and cave ecosystems (Addesso et al., 2022). For instance, in the North Yellow Sea, researchers have monitored trace metals in sediments to examine the historical record of anthropogenic impacts (Rogozin et al., 2023). However, it is worth noting that there is currently a paucity of studies that specifically address anthropogenic impacts on mineral and nutrient dynamics, as well as temporal and spatial variations, within lentic ecosystems in the tropical region of the Central Gangetic Plain in South Asia.

The primary objective of this paper is to identify and analyze the key physicochemical parameters as well as the mineral and elemental compositions of freshwater lake sediments and establish potential connections between sediment mineralogy, ecological conditions, and catchment characteristics. The study aims to investigate the temporal and spatial variations in sediment chemistry within lakes located in the Central Gangetic Plain experiencing varying degrees of stress and anthropogenic disturbances. The research delves into the impact of freshwater ecological conditions, biotic decomposition, and aquaculture, as well as catchment characteristics on nutrient status and mineral and elemental compositions of lake sediments along with morphological changes. Understanding these linkages is vital for managing and preserving lake ecosystems as changes in sediment nutrient loads, mineralogy, and elemental composition can have cascading effects on the sediment-water quality, aquatic life, and overall ecosystem health of the freshwater lake.

Methodology

About the study area

Three freshwater lakes from the Central Gangetic Plain have been selected for this study. These lakes are characterized by different catchment characteristics and anthropogenic stresses. Two lakes are from the urban area of Lucknow—the capital of Uttar Pradesh, namely, Kathauta (L1) and Haibatmau Lake (L2), and the third lake, Samaspur Lake (L3), is situated in a protected site in the rural catchment of Raebareli district (Fig. 1). A brief depiction of three lakes is provided in Table 1.

Collection of sediment sample

The lake sediments were collected from four different locations of the selected three lakes labeled as K1 to K4 for lake 1, H1 to H4 for lake 2, and S1 to S4 for lake 3 in the month of September (i.e., post-monsoon season) for two consecutive years in 2018 and 2019. Sediment samples were collected from each site at 2–15 cm depth from the surface with the help of a dredge and then labeled and taken to the university laboratory. Prior to drying, all the impurities

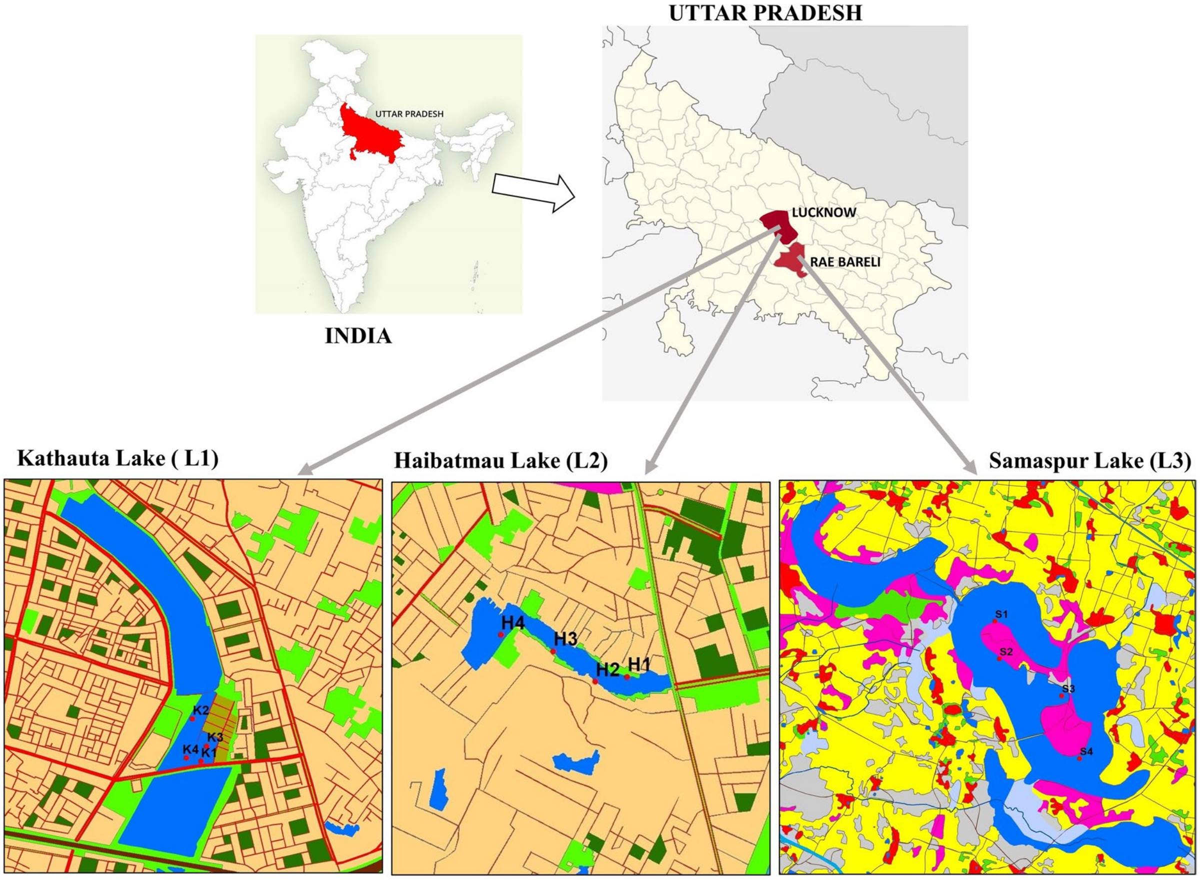

Fig. 1 Location of the study area and sampling sites from the selected lakes. **A** Kathauta Lake (L1). **B** Haibatmau Lake (L2). **C** Samaspur Lake (L3)

Table 1 Characteristics of the selected three lakes having direct or indirect impacts on sediment quality

Features	Kathauta Lake (L1)	Haibatmau Lake (L2)	Samaspur Lake (L3)
Location	Gomti Nagar, Lucknow, Uttar Pradesh, extending between 81.03°E longitude and 26.86°N latitude	The southern side of Lucknow extends between 80.94°E longitude and 26.75°N latitude	Near Salon block in the Raebareli district of Uttar Pradesh, extending between longitude 81°21′34″ to 81°25′11″E and latitude 25°57′49″ to 26°01′05″N
Catchment	Urban	Urban	Rural
Source of water	Sharda Canal which relies on the Sharda River, a tributary of the Ganges	Groundwater fed	Sharda Canal which relies on the Sharda River, a tributary of the Ganges
Area	Fragmented into two segments; the larger segment has permanent fenced boundaries with an area of 59.09 acres and a perimeter of 2.79 km. The other small, isolated segment has an area of 34.33 acres and a perimeter of 1.14 km	The perimeter of 2.04 km and an area of 13.14 acres	This wetland covering about an area of 1927 acres is formed by six interconnected lakes, namely, Gorwa, Mamuni, Nakganj, Hasanpur, Rohinia, and Bisaiya Choti. The perimeter of the wetland is about 18.06 km
Status	Used for aquaculture activities (*Trapa* cultivation and fishing)	Excessive growth of invasive macrophytes	Inside a protected area, included in the list of Ramsar sites by UNESCO
Shoreline degradation	Moderate	High	Low
Aquaculture (fish rearing)	Extensively used for fish rearing	Not reported	Fish rearing is prohibited
Trapa/Euryale ferox (fox nut cultivation)	Half of the lake used for *Trapa* cultivation	Not reported	Premonsoon fox nut cultivation done in one-fourth area of the lake
Use of additional nutrients for aquaculture	Reported	Not reported	Aquaculture not practiced
Status of macrophytic growth	Dominance of *Trapa natans* along with few invasive macrophytes and sedges on the shoreline during the first year of sampling, macrophytes were uprooted for the purpose of fish rearing during the second year	Excessive growth of invasive macrophytes	Moderate free-floating and submerged macrophytes
Status of algal/diatom growth	No algal growth in *Trapa* section whereas the fishing section showed flourishing growth of diatoms and *Euglena* algal species	Presence of diatoms and planktonic as well as filamentous algae	Presence of diatoms and planktonic as well as filamentous algae
Wastewater discharge	Reported	Reported	Not reported
Non-point runoff	Reported	Reported	Reported
Encroachment activities	Not reported	Reported	Not reported

like leaves, twigs, and branches of the aquatic macrophytes were removed from the collected sediments. The samples were then air-dried at room temperature to prevent the loss of any volatile element for 7 days and then ground with the use of ceramic mortar and pestle till a standardized sediment powder was gained. Processed sediment was then dried in the oven until persistent sediment samples were obtained. The grounded sediment samples were then passed through 10 and 80-mesh sieves for further analysis. Sieved sediments were again oven-dried at 60°C for 2 h to get rid of the additional water content. The sediment samples were then used for further laboratory analysis (Siročić et al., 2020).

Physicochemical analysis of the lake sediments

Initial physicochemical parameters of the sediments including pH (measured using a Hanna portable meter), organic matter, organic carbon (Yu et al., 2015), and total phosphorus by the titration method (Ruban, 2001) were analyzed using methods described by Jackson (1967, 2005) and Zhu et al. (2013) in the university laboratory. Organic matter on average contains 58% carbon; the percent organic matter can be obtained by multiplying the percent organic carbon by 100/58 or 1.724 which is also known as the van Bemmelen factor. Sediment organic matter was calculated using the formula SOM = SOC ×1.724 (Mayer et al., 2004). It has a vital role in supporting the lake's biological productivity.

Analytical methods used for the study

Analytical techniques used in the mineralogical and elemental analysis of the lake sediments along with their specific objectives are briefly outlined in Table 2.

Mineralogical analysis of the lake sediment by Fourier-transform infrared spectroscopy (FTIR)

FTIR analysis helps in identifying functional groups of organic and inorganic compounds present in the sediments. Minerals in the sediment samples were identified using an FTIR spectrometer (Nocolet 6700; manufacturer: Thermo-Scientific, USA) in the University Sophisticated Instrumentation Centre (USIC). For mineral analysis in the sediments, the KBr pellet technique was followed. FTIR spectra of the sediments were recorded between the wavelength 4000 and 400 cm^{-1} (mid-infrared) with a spectral resolution of 4 cm^{-1}. From the FTIR spectra, the peaks were analyzed for their absorption frequencies, visual intensities, and their relevant tentative assignments of the selected three lakes. The small quantity of the powdered sediment sample, about 0.1–2% of the KBr amount, was ground to fine powder until crystallites could no longer be seen. This is done to prevent large particles from scattering the infrared beam which causes a slope baseline of the spectrum. The die was cleaned with acetone and water and assembled to prepare fine powder for a 7-mm collar. Die is put along with the powder into the hydraulic press. Sediment is pressed for 2 min to form a thin and transparent pellet of KBr. The presence of a white spot in the pellet should be avoided, as it suggests inadequate grinding of the sediment or improper dispersion within the pellets. Further, the die set was disassembled and the 7-mm collar was put along with the pellet onto the sediment sample holder. The sediment sample holder was fixed in the FTIR spectrometer and the analysis was done at the spectral region 4000–400 cm^{-1} against the KBr background (Ravisankar et al., 2010).

Mineralogical analysis of lake sediment by X-ray diffraction spectroscopy (XRD)

X-ray powder diffraction (XRD) is a reliable analytical method for describing crystalline and polycrystalline materials. It delivers information on structural parameters, such as strain, average grain size, crystal defects, and crystallinity including information on crystal structure and phase composition of the material. It is crucial for mineralogical analysis of rocks, sediments, and other crystalline substances. Mineral identification in sediments is based on relative peak intensities and d-spacing and is much easier if the sample contains only one type of mineral. The sediment mineral phase, on the other hand, is a mixture of different minerals that have complex XRD patterns and present a challenge for their identification. One of the main limitations of the XRD technique is the detection limit, which is around 1% of weight (Bruckman & Wriessnig, 2013). The diffraction patterns were obtained from 5 to 90° (2θ). The mineralogical characterization was based on the comparison with a database and available literature (Siročić et al., 2020). The XRD analysis of the powdered

Table 2 Analytical techniques used in the mineralogical and elemental analysis of the lake sediments

Analytical techniques used in the study	Purpose	Specific objectives	Expected outcome
Fourier-transform infrared spectroscopy (FTIR)	Mineralogical analysis	To get the "fingerprint" of geogenic and biogenic mineral constituents in the lake sediments as well as biogenic organic matter	■ Distinct mineral composition ■ Absorption spectra present the clear richness of the quality of lake sediments ■ Confirms the presence of biogenic organic matter, cellulose, and hemicellulose compounds
X-ray diffraction (XRD)	Mineralogical analysis	To get information about the crystallographic structure, chemical composition, and physical properties of the sediment	■ Lake sediment inherits the geogenic terrigenous mineral composition that enters the lake with runoff water
Energy-dispersive X-ray spectroscopy (EDS)	Elemental analysis	To get the compositional information and elemental chemistry of the sediment, allows evaluation of an abundance of the relative minerals	■ Weight percent of the elements present in the lake sediments ■ Heterogeneous composition of the lake sediment samples ■ Concentration ratios for organic carbon, calcium, iron, and manganese to clarify spatial differences in the particle composition
Scanning electron microscopy (SEM)	Morphological variations	To know about the shape, size, and amorphous nature of the sediment, interpretation of diverse sedimentary lacustrine environments	■ Sediment samples present complex aggregates, with symmetrical and spheroidal forms

composite sediment samples of the selected lakes was performed with Model D8 Advance Eco (manufacturer: Bruker, Germany) present in the USIC facility. Sediment samples are prepared for X-ray diffraction by grinding to a powder form (<0.062 mm). Samples were then placed in desiccators for drying, and the desiccated samples were transferred to the sample holder for XRD analysis. The powdered sediment samples were placed in the center of the sample holder and packed in the shallow cavities of the glass slides to minimize the preferred orientation. The output of the XRD pattern gave several peaks for each sample, and they were analyzed and identified with the reference of the available literature. From the output, prominent values of d-spacing were found with corresponding 2θ. The identification of mineralogical peaks and XRD d-spacing for the minerals present in the sediments was done with the support of accessible research papers (Uzarowicz et al., 2011; Saikia et al., 2015a, 2015b, 2016) and by utilizing the record of the International Center for Diffraction Data (ICDD, 2017).

Elemental analysis of lake sediment using energy-dispersive X-ray spectroscopy (EDS)

The composite sediment samples of the selected lakes were observed in EDS for their elemental constituents. EDS (OXFORD INCA X-act model 51-ADD0013 having a resolution at 5.9 KeV) was used to obtain the elemental composition of the lake sediments. The computer-controlled elemental analysis using EDS provided compositional information on sediment particles and helped in the estimation of relative mineral abundances in the sediments based on elemental composition (Pirrie et al., 2004). The EDS technique senses X-rays emitted from the sample during bombardment by an electron beam which characterizes the elemental composition of the sediment sample.

Surface morphology of lake sediment using scanning electron microscope (SEM)

A scanning electron microscope (SEM) (Model no. JSM- 6490LV, Jeol Japan) was used for the surface morphology of the sediment collected from the lakes. The specimens were observed under SEM for information about the shape, size, and surface texture which may be of as small as 3 mm or less (Krinsley et al., 1998; Pirrie et al., 2004).

Results and discussion

Physicochemical analysis of lake sediments

In L1, changes in pH were observed in the year 2019 as compared to the year 2018 (Table 3). It is due to the use of the lake for fish rearing which causes an increase in organic matter with a consequent decrease in the sediment pH (Saha et al., 2020). The pH plays a crucial role in regulating the metal and nutrient availability, both in water and the sediments. pH is determined by a variety of factors, including photosynthesis, respiration, decomposition, and chemical reactions in the lake (Saad et al., 2017; Heneash et al., 2021). The decrease in pH may be caused by the high levels of organic matter inputs from the aquaculture activities, resulting in increased decomposition (Heneash & Alprol, 2020; Heneash et al., 2021). Hence, aquaculture activities in the lake could alter the sediment hydrogen ion concentration. A negative correlation was observed between organic carbon and pH in lake sediments as seen in L1 in the year 2019. In lake L2, negligible changes were reported in the pH in both years as there was no major alteration in the conditions of the lakes. In lake L3, the pH was close to the neutral range and approximately the same in both the years 2018 and 2019 without any major variation as this lake was situated in the protected area with the least anthropogenic interferences.

Lake L1 reported an increase in organic carbon and organic matter in the year 2019 in comparison to 2018 in all four selected sites due to fish-rearing activities in the year 2019. An increase in organic matter in the year 2019 in lake L1 is due to excess waste from fish feed used for fish rearing, dead and decaying macrophytes, and senescent phytoplankton (Banerjea, 1967). Uneaten fish food and fish excreta include large quantities of carbon, nitrogen, phosphorus, and metals in the sediment of the fish-rearing lake compared to the reference sites (Morrisey et al., 2000; Aslam et al., 2020). The residual food materials and excreta are oxidized to soluble substances and partially consumed by lake plankton resulting in their excessive growth (Perez et al., 2014).

In lake L2, organic carbon and organic matter show no notable difference during 2018 and 2019 for all the selected four sites. The major source which has resulted in the increase of organic matter and organic carbon in lake L2 is mainly due to the

Table 3 The geogenic and biogenic minerals and biogenic organic matter reported through FTIR analysis in the selected lakes during 2018 and 2019

Lake	Lake 1		Lake 2		Lake 3	
Year	2018	2019	2018	2019	2018	2019
Geogenic minerals	Quartz, kaolinite, montmorillonite, calcite	Quartz, kaolinite, montmorillonite, calcite	Quartz, kaolinite, montmorillonite, calcite	Quartz, kaolinite, montmorillonite, calcite	Quartz, kaolinite, montmorillonite, calcite	Quartz, kaolinite, montmorillonite, calcite
Biogenic minerals	Calcite, biogenic silica	Calcite, biogenic silica	Calcite, biogenic silica	Calcite, biogenic silica, carbonate	Calcite, biogenic silica, carbonate	Calcite, biogenic silica
Biogenic organic matter	Amides, carboxylic group, humic compounds, organic matter	Amides, carboxyl group, humic compounds, organic matter	Total organic carbon, amides, carboxyl group, humic compounds, organic compounds	Amides, carboxylic acid, humic, organic matter	Total organic carbon, amides, carboxylic, humic compounds, organic matter	Amides, carboxylic groups, humic compounds, organic matter, total organic carbon, cellulose, hemicellulose, lignin

excessive growth and decomposition of the invasive free-floating macrophytes *Eichhornia crassipes*. In lake L3, organic carbon and organic matter are high at sites S1 and S2 as these two sites are close to the littoral area. The growth and decay of invasive free-floating macrophytes cause an increase in SOC and SOM, whereas sites S3 and S4 are in the middle of the lake which is devoid of free-floating macrophytes leading to lesser SOC and SOM inputs.

Particulate form of organic matter derived from the fish excretions and uneaten fish food precipitates quickly on the lake floor and leads to variations in sediment characteristics. The accumulation of organic material in the lake has a relation with the lake size, local hydrological and geomorphological properties, production capacity of the aquaculture, and quality of feed.

Sediment organic carbon (SOC) is a critical component of the global carbon cycle, and its degradation influences a wide range of phenomena, including the magnitude of carbon sequestration over geologic timescales, the recycling of inorganic carbon and nutrients, the dissolution and precipitation of carbonates, the production of methane, and the nature of the benthic biosphere. SOC is the amount of oxidizable carbon present in the sediment. It relies on several factors like deposition and supply of organic matter in the sediment, sediment granulometric compositions, and their rate of decomposition (Koshy, 2002). SOC is a component of sediment organic matter (SOM). SOM contains carbon compounds that are formed by living organisms and cover a wide range of things like lawn clippings, leaves, stems, branches, mosses, algae, lichens, parts of animals, manure, droppings, sewage sludge, sawdust, insects, earthworms, and microbes. Organic matter is usually a component of sedimentary material even if it is present in low quantity, usually lower than 1% (Shakeel et al., 2022).

Lake L1 reported an increase in total phosphorous (TP) in the year 2019 for all the selected four sites because of intensive fish rearing. The amount of TP increases because of a substantial rise in fertilizers and fish feeds, as well as the use of water-purifying agents for aquaculture purposes (Zhang et al., 2019). The mobilization of phosphorus from sediment is significantly influenced by the physicochemical characteristics. TP levels were greater in aquaculture locations than in non-aquaculture sites (Jia et al., 2015). Significant changes in sediment physicochemical properties have an impact on the microbial breakdown of organic material in anoxic environments which modifies the forms of nutrients, particularly phosphorus (Matijević et al., 2012).

In lake L1, the sediment TP contents remained consistently low throughout the year 2018, indicating a limited incidence of anthropogenic (mainly aquaculture) activities in the lake. Prior to that, the TP input was primarily natural and included air deposition, surface runoff, and wastewater discharge from neighboring locations. Due to a sharp increase in anthropogenic TP discharges into the lake, the sediment phosphorus concentration grew quickly in the second year, indicating a large intake of feeds and fertilization, as well as its concomitant mineralization, which was not observed in lake 2 or lake 3 (Burford and Williams, 2001). Lake sediment composition is influenced by in-lake and shoreline vegetation cover as the degradation of dead and decaying plant biomass is a major source of organic matter and biogenic minerals in the sediment. The elevated nutrient levels in the lakes result in higher organic content within the sediment. The buildup of organic material within the lake is closely tied to several factors, including the lake's size, local hydrological characteristics, geomorphological features, and the scale of aquaculture operations.

In lakes L2 and L3, TP content shows minimum variation between 2018 and 2019 as shown in Table 3. The laboratory sediment analysis results along with ANOVA of all three lakes are given in Table 3. The parameters of sediments showed noteworthy differences among the selected lakes. A bar graph of the sediment physicochemical parameters shows the major variations in physicochemical parameters with respect to different sites in the selected three lakes (Fig. 2).

Mineralogical analysis of sediments using FTIR

Lake sediments have minerals that are both geogenic and biogenic in origin. Geogenic minerals are formed from weathering and erosion of parent rocks whereas biogenic minerals are biological in origin and derived from aquatic biota and other biological materials. Along with geogenic and biogenic minerals, various biogenic organic matters are also reported in the

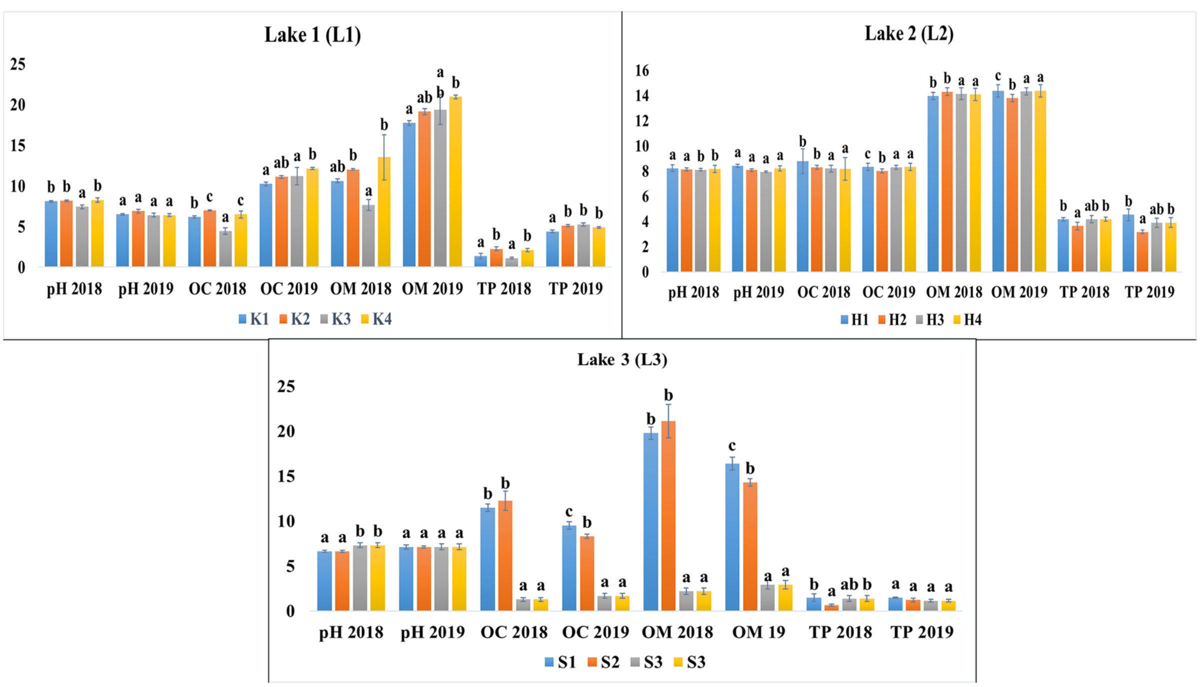

Fig. 2 Sediment physicochemical parameters showing the major variations with respect to different sites in the selected three lakes (OC: organic carbon; OM: organic matter; TP: total phosphorous). Note: different alphabetical letters specify significant differences among different sites of the selected lakes at $p<0.05$

sediment of the lake. Therefore, mineralogical analysis using FTIR provides the "fingerprint" of geogenic and biogenic mineral constituents in the lake sediments. The distinct mineral composition reported in the bottom sediments of selected three lakes is described below.

Lake 1 (L1) sediments

Sediment analysis of the year 2018 reports the presence of geogenic minerals such as quartz, kaolinite, and montmorillonite along with biogenic minerals such as calcite and biogenic silica. Biogenic organic matters reported in the lake belong to amides, carboxylic group, and humic compounds (site K1). On sites K2, K3, and K4 along with all these minerals biogenic silica was reported. Sediment analysis for the next consecutive year 2019 reports the presence of the same trend of the geogenic minerals quartz, kaolinite, and montmorillonite and biogenic minerals like biogenic silica and calcite (site K1). Biogenic organic matters are mainly amides, carboxyl, and humic compounds along with organic matter reported at the sites K1, K2, K3, and K4.

Lake 2 (L2) sediments

Geogenic sediments reported are quartz, kaolinite, and montmorillonite. Biogenic minerals reported are calcite and biogenic silica, along with the biogenic organic matter which constitutes total organic carbon, amides, carboxyl group, and humic compounds followed by organic compounds, in sites H1, H3, and H4 whereas in site H2 all above-mentioned minerals were present except organic compounds in 2018. In the next consecutive year, 2019, geogenic minerals reported are quartz, kaolinite, and montmorillonite, and biogenic minerals reported are biogenic calcite, carbonate, and silica at sites H1, H2, H3, and H4. Biogenic organic matters are mainly amides, carboxyl, and humic compounds along with organic matter.

Lake 3 (L3) sediments

Geogenic minerals reported in the year 2018 are quartz and montmorillonite while biogenic minerals reported are calcite and biogenic silica along with the biogenic organic matter, i.e., total organic carbon, amides, carboxylic, humic compounds, organic matter (sites S1, S2, and S3). Biogenic carbonate was reported on sites S1 and S3 and geogenic kaolinite was reported only on site S3. Geogenic minerals reported during the year 2019 are quartz, kaolinite, and montmorillonite, and biogenic minerals reported are biogenic silica along with biogenic organic matter, i.e., amides, carboxylic groups, humic compounds, and organic matter reported on site S3. At site S2, calcite and total organic carbon were also reported in addition to the above-mentioned minerals. At site S1, additional organic compounds such as total organic carbon, cellulose, hemicellulose, and lignin were also reported, the main reason being the site was close to the littoral area where the decomposition of aquatic flora was prominent. On the other hand, at site S4, all the above-mentioned minerals were present, including calcite, while biogenic silica was not reported. The observed FTIR data of the selected three lakes along with the geogenic and biogenic minerals and biogenic organic compounds are summarized in Table 3.

Calcite may be geogenic or biogenic in nature (Chu et al., 2008)

The peak absorption frequencies in the FTIR spectra give a clear richness of the quality of lake sediments during the year 2018 and 2019 (Fig. 3).

Findings of the mineralogical analysis from FTIR

Freshwater lake sediment is characterized by a high content of biogenic silica and carbonate mineral content as seen in the selected three lakes (Ravishankar et al., 2010; Meyer-Jacob et al., 2014; Petrovskii et al., 2016). The FTIR study confirms the presence of biogenic organic matter, cellulose, and hemicellulose compounds in the lake (L3). This was due to the dumping of the uprooted invasive macrophytes *Eichhornia crassipes* on the shoreline of the lake (Punning et al., 2007). SOC is characterized as a complex mixture of residuals of organic matter involving a number of chemical compounds and is described by very complex spectra (Rosén et al., 2010). Inorganic carbon is found in bottom lake sediments as carbonate minerals (Petrovskii et al., 2016). Lake sediment composition is influenced by in-lake and shoreline vegetation cover as degradation of dead and decaying plant biomass is a major source of organic matter and biogenic minerals in the sediment.

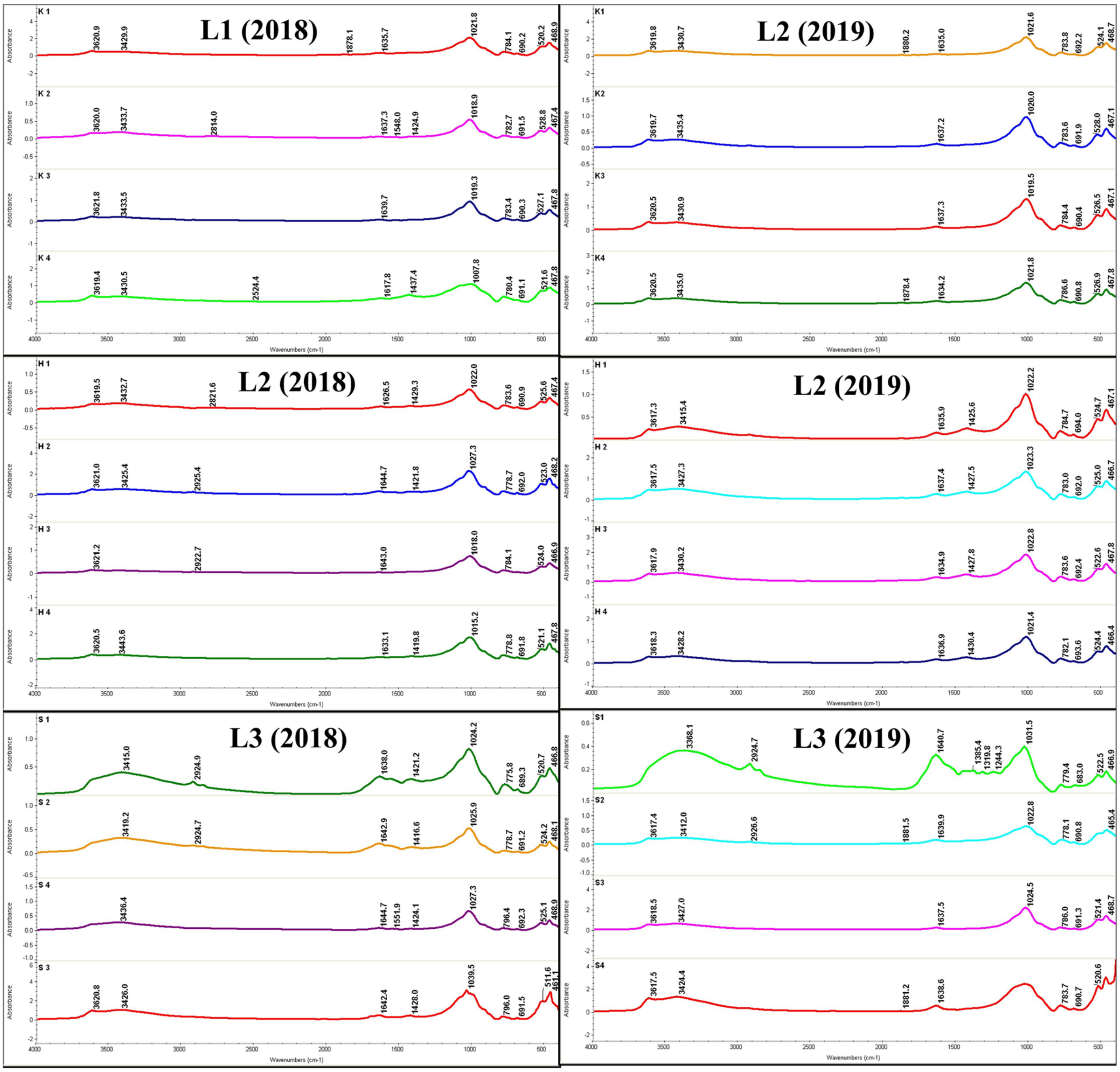

Fig. 3 Stack graph of the FTIR spectra of lake sediments of the selected three lakes

Along with geogenic and biogenic minerals, biogenic organic matter is also reported in the FTIR spectra. They mainly constitute organic matter, total organic carbon, amides, carboxylic group, humic compounds, cellulose, hemicellulose, and lignin. Their deposition in lake sediment is undoubtedly an important component of the local, regional, and even global biogeochemical cycle in the lakes (Chen et al., 2019). Organic matter, total organic carbon, cellulose, hemicellulose, and carboxylic compounds play a major role in the carbon cycle. Lignin concentration in the lake sediment directly correlates with organic carbon concentration; therefore, it also plays a major role in the carbon cycle and amides in the nitrogen cycle. Organic and inorganic carbon in lakes later consists of lithogenic carbonate entering mainly through endogenic carbonate, which is biogenic in origin (Anas et al., 2015).

Major geogenic minerals like quartz, kaolinite, montmorillonite, and calcite are common among all three selected lakes because of the same geological location, i.e., all three lakes are located in the Central

Gangetic Plain of Uttar Pradesh. Geogenic mineral constituents of the selected lakes show negligible variations when compared between the years 2018 and 2019 in comparison to the biogenic-originated compounds as they depend on the productivity of the lake ecosystem.

The results highlight the importance of studying annual fluctuations and spatial variations in geogenic and biogenic mineral particle fluxes in lakes. Such investigations provide valuable insights into the annual dynamics of minerals within lakes, contributing to a more comprehensive understanding of their behavior and distribution. It is also concluded that in-lake mixing processes are ineffective in leveling out spatial variations in the concentration of geological minerals within the lake. The geominerals stored in sediments mainly reflect the catchment's bedrock, soil, and land cover whereas biogenic mineral depicts the productivity of the lakes (Thorpe and Horowitz, 2020).

XRD analysis of the sediments

The XRD diffractogram of the sediment samples is evaluated, and the "2θ" values of samples are compared with available literature and standard values from the Joint Committee on Powder Diffraction Standards (JCPDS) data.

Lake 1 (L1) sediments

In the XRD sediment analysis for the year 2018, geogenic minerals such as mica, quartz, calcite, and albite were reported. Major peaks were reported for the mica and quartz. In the year 2019, a major peak of the quartz is observed.

Lake 2 (L2) sediments

XRD sediment analysis of the year 2018 reports the presence of geogenic minerals like mica, kaolinite, quartz, albite, and calcite. Minerals that reported major peaks are quartz and mica. XRD sediment analysis of the year 2019 exhibits the same pattern and reports the presence of geogenic mica, quartz, calcite, and albite. Minerals that observed major peaks are kaolinite, chlorite, paratacamite, quartz, albite, calcite, hematite, magnetite olivine, and pyrite.

Lake 3 (L3) sediments

XRD sediment analysis of the year 2018 reports geogenic minerals like mica, kaolinite, quartz, and albite. Major peaks were observed for the minerals like mica and quartz. XRD sediment analysis of the year 2019 reports the presence of mica, quartz, and albite. The XRD patterns observed in the results show kaolinite and quartz as the major component of lake sediments and various other minerals as the minor components. They are known to crystallize in anorthic and hexagonal systems, i.e., triclinic systems. These XRD results correlate with the FTIR result of the selected sediment samples as the occurrence of the geogenic minerals reported in XRD in the sediment samples is confirmed by the FTIR analysis (Cannane et al., 2013). Further, the results of XRD analysis indicated the presence of several geogenic minerals, like quartz, kaolinite, aragonite, hematite, illite, and calcite in the sediments. The study found that the dominant mineral is quartz along with other rock-forming minerals like feldspar, mica, and chlorite and with traces of calcite and dolomite. The main reason behind the absence of some geogenic and biogenic minerals in the XRD analysis, which are recognized by FTIR, is mainly caused by disorders and loss of the crystalline nature of the minerals. At the same time, few minerals are reported only in XRD diffractograms which indicate their crystalline order even though they are present in exceedingly small amounts. Thus, from all these observations, the decreasing trend is the main reflection that shows a lowering of the crystalline nature of the respective minerals. The loss of crystalline nature results in the non-appearance of minerals in the XRD study despite their presence in the FTIR analysis (Ramasamy et al., 2009).

Findings of the mineralogical analysis from XRD

The mineral composition suggests that the lake sediment generally inherits the geogenic terrigenous mineral composition that enters the lake with runoff water from the lake catchment. The predominant authigenic minerals include biogenic illite, chlorite, and quartz minerals (Strakhovenko et al., 2020). Consequently, the main mineral composition of the sediment is kaolinite, chlorite, paratacamite, quartz, albite, calcite, hematite, magnetite, olivine, and pyrite in the selected lakes.

Pyrite reported in L2 in the year 2019 might have also reflected the catchment development due to a changing land cover. Pyrite is thought to have been inherited from parent bedrock rather than being formed within the sediments (Ohfuji and Rickard, 2005). So, the variation in pyrite contents is mainly due to a change in land cover (from exposed bedrock to vegetated areas) or modification in the particles that reached the lake because of size-dependent transportation caused by vegetation. Anthropogenic sources of quartz in L1 are available through fish feed and from water purification reagents (Jia et al., 2015). The recurrent occurrence of the most plentiful quartz mineral in lake sediments is mainly because of its hardness and chemical structure which make it difficult to weathering and erosion. Therefore, it is the main component of the sediment samples. The occurrence of the geogenic minerals reported in the XRD analysis of the sediment samples is confirmed by the FTIR analysis.

The most plentiful mineral in the samples is quartz because of its thermodynamic resistance to weathering. Quartz can be of eolian origin, or it can be a residue after dissolution of limestones containing a small amount of quartz. Quartz has an extremely low cation exchange capacity (CEC) since it has an almost insignificant amount of charge. When compared to other soil minerals, quartz has an almost diluting effect on the overall value of CEC. Minor variations in mineral concentration reflect the constant input of terrigenous material in the lakes over the years (Siročić et al., 2020).

XRD spectra of the three lakes for the year 2018 and 2019 are given in Fig. 4.

Elemental analysis of the sediments using energy-dispersive X-ray spectroscopy (EDS)

Sediment samples were analyzed for total carbon (C) and total nitrogen (N), phosphorous (P), calcium (Ca), silica (Si), aluminum (Al), iron (Fe), manganese (Mn), magnesium (Mg), sodium (Na), potassium (K), and the trace elements zirconium (Zr), strontium (Sr), rubidium (Rb), titanium (Ti), barium (Ba), sulfur (S), lead (Pb), and zinc (Zn). C, N, and P are mainly responsible for the formation of biological materials, Ca for calcium carbonate, Fe for iron oxides, Mn for manganese oxides, and Al and Si are for silica (biogenic SiO_2, quartz) and aluminosilicates. Concentration ratios for organic carbon, calcium, iron, and manganese were determined to clarify spatial differences in the particle composition. Changes in an element's concentration in sedimentary material can then be stated in relation to that element's concentration in sediment (Wieland et al., 2001).

Elemental constituents present in the composite sediment samples collected in the years 2018 and 2019 were analyzed to understand the elemental chemistry of the sediment as shown in Fig. 5. The results obtained from EDS spectra revealed the heterogeneous composition of the sediment samples of the selected lakes. Computer-controlled elemental analysis of the sediments through EDS provides compositional information about the sediment particles and allows evaluation of an abundance of the relative minerals (Pirrie et al., 2004).

Elemental analysis of the selected three lakes in the years 2018 and 2019 correlates with the minerals reported in the FTIR and XRD analysis. The main elements responsible for the formation of quartz, feldspar, and mica reported in the FTIR and XRD analysis correlate with the presence of silicon (Si) and oxygen (O) with aluminum (Al), potassium (K), and several other trace elements in the EDS analysis. For the formation of calcite ($CaCO_3$) reported in the FTIR and XRD, the main elements responsible are carbon (C), oxygen (O), calcium (Ca), and magnesium (Mg) reported in EDS. Iron (Fe) and sulfur (S) are responsible for the formation of pyrite (FeS_2) and other metal sulfides. Hematite (Fe_3O_4) and magnetite (Fe_3O_4) reported in lake 2 are represented by the presence of iron (Fe) and oxygen (O) elements in the EDS analysis. These elements interact with geological and environmental factors, shaping the unique characteristics of lake sediments and contributing to the overall composition of the lake ecosystem.

No major elemental changes in L2 and L3 lakes were reported between 2018 and 2019, whereas in lake L1 increase in elemental constituents was reported along with an increase in carbon content in the lakes which correlates with the physicochemical analysis. The likely reason could be the fishing activities in lake L1. Geomineral study of the sediments reveals a history of anthropogenic lake pollution, particularly from intense aquaculture practices that left nutrients and trace elements in the sediment, such as the direct introduction of chemical fertilizers, pesticides, and animal feed into the lake (Zhang et al.,

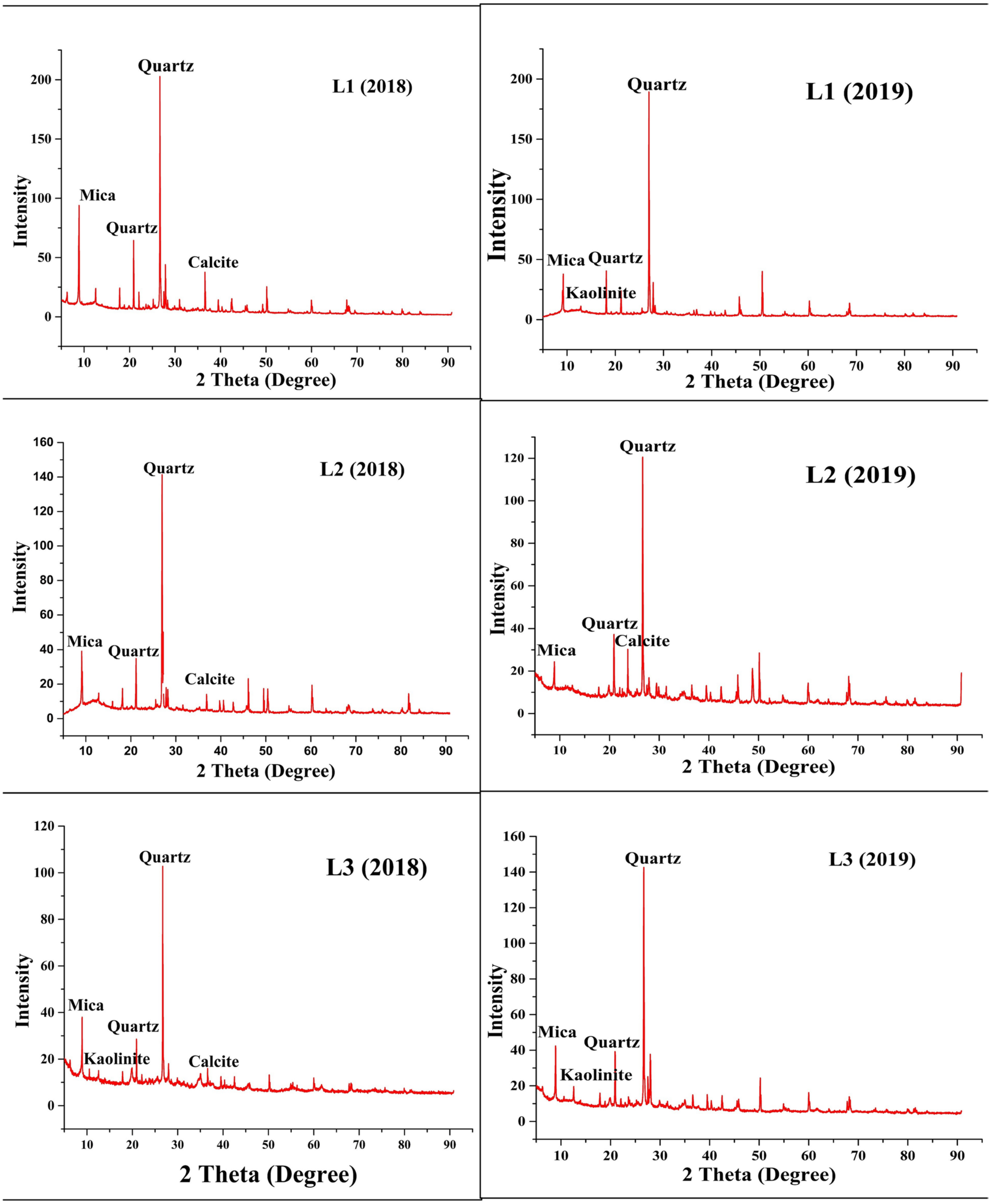

Fig. 4 XRD spectra of the lake sediments during the year 2018 and 2019

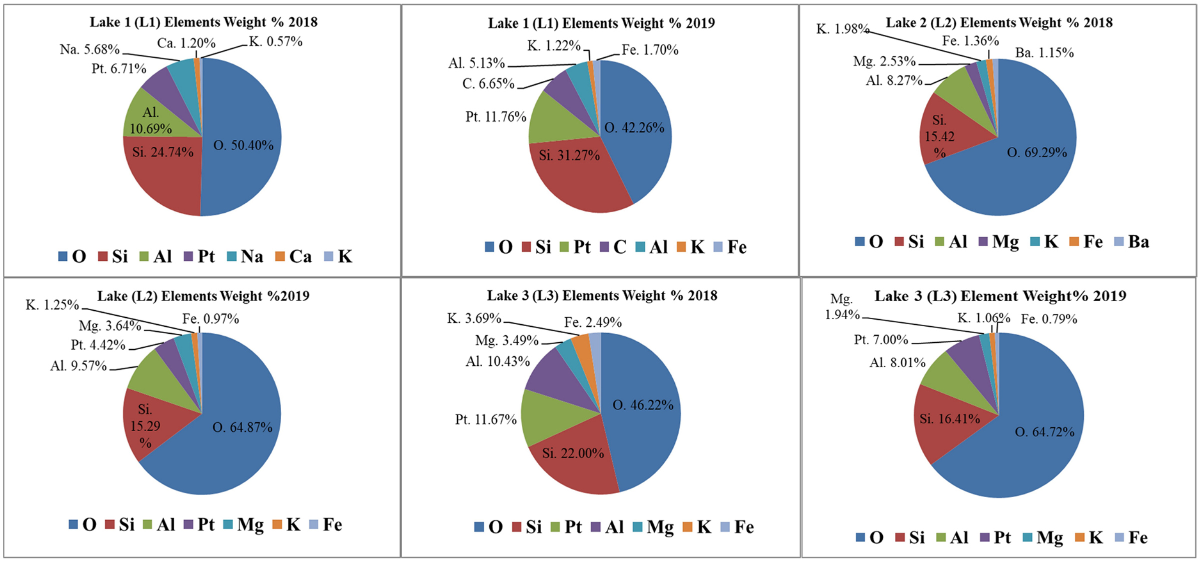

Fig. 5 Weight percent of the elements present in the lake sediments during the year 2018 and 2019

2019). Hence, anthropogenic activities in the lake ecosystem change the elemental constituents of the sediments. A pie chart showing the weight percent of the elements present in the lake sediment of lakes L1, L2, and L3 during the years 2018 and 2019 is given in Fig. 5.

The fluxes and composition of trapped elements in the sediment particles were found to vary annually with fluctuations in the main biogenic components (organic matter, calcium carbonate, biogenic silica, silicates) and spatially due to the various in-lake processes, like photosynthesis which is directly linked with lake productivity, respiration, decomposition, nutrient cycles, eutrophication, and carbon sequestration reported in all the selected lakes. The mineral composition of the lake sediment was influenced by the water and sediment chemistry (Lein et al., 2013). The aquatic biota plays an important role in the formation of bottom biogenic sediments (Strakhovenko et al., 2020). Understanding these linkages is vital for managing and preserving lake ecosystems. Changes in sediment nutrient loads, mineralogy, and elemental composition can have cascading effects on the water quality, aquatic life, and overall health of the freshwater ecosystem. Monitoring these interactions helps inform effective strategies for maintaining a balanced and sustainable lake environment.

Depending on the biotic species and environmental factors, the types of minerals and concentration of the nutrients vary. This biodeposition may play a crucial role in controlling the water and sediment column processes of the various lacustrine components. Sediment minerals play key roles in nutrient cycling in lakes. The geological allochthonous and autochthonous minerals contributing to the mineral budget of the sediment are less well known. Wind-blown dust (air deposition), biogenic organic matter, biogenic silica, and carbonates are the chief elements of lake sediments and the precursor of the lake biogenic cycle.

Once ecosystem development reached a threshold, characterized by a stable level of organic deposition in the sediments, subsequent elemental changes were minimal. The geochemical methods utilized in this work, especially when performed on the clay-sized fractions, showed bulk, micro, and elemental scale differences that indicated mineral, organic, and elemental evolution of the sediments. EDS spectra of the selected lake sediments are given in Fig. 6. The results of elemental study revealed the heterogeneous composition of the lake sediments with distinct signatures of elemental constituents. The mineral composition suggests that the lake sediment generally inherits the geogenic terrigenous mineral composition that enters the lake with runoff water from the lake catchment.

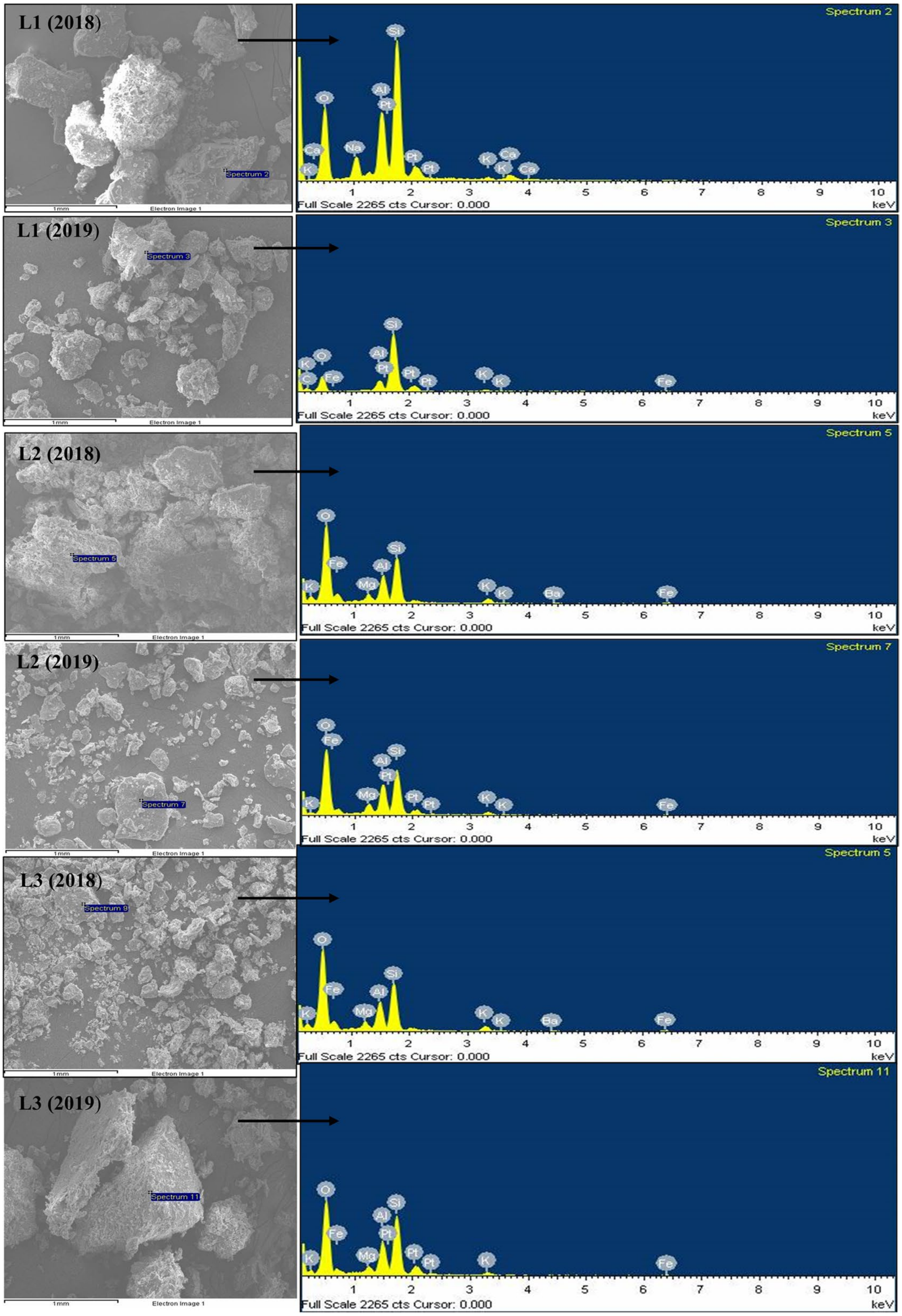

Fig. 6 Energy-dispersive X-ray spectroscopy (EDS) spectra of the lake sediments during the years 2018 and 2019

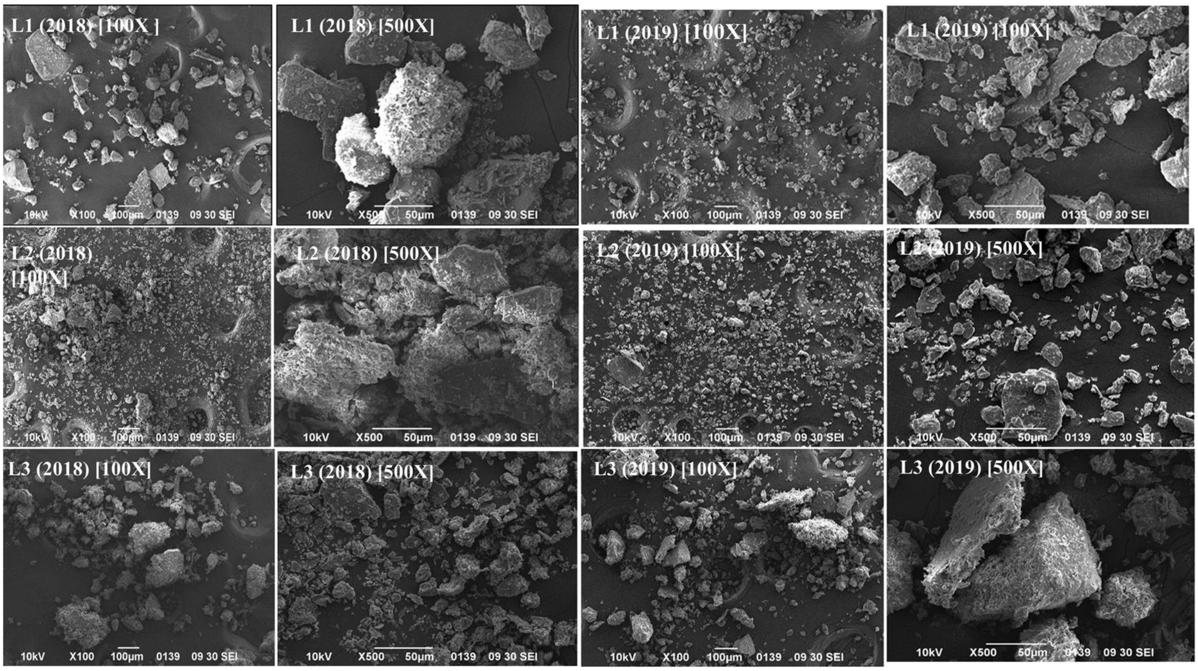

Fig. 7 Scanning electron microscope (SEM) images of the sediments collected from the selected lakes

SEM analysis of the sediments of the selected lakes

The SEM photomicrographs of the sediments taken at 100× and 500× resolutions reveal sediments with varying particle sizes and different morphology (Krinsley et al., 1998; Strakhovenko et al., 2020). The sediment samples present complex aggregates, with symmetrical and spheroidal forms. The pretreatment of the sediment samples does not alter the sediment morphology as the sediment samples were made uniformly to remove sediment agglomerations and debris. The analyses of SEM results of the sediments are grounded on morphology and mineralogy characterization of sediment minerals (Saikia 2009; Oliveira et al., 2014; Saikia et al., 2015a, b; Pérez-Sirvent et al., 2016; Xie et al., 2018).

SEM is helpful in the interpretation of diverse sedimentary lacustrine environments and is well recognized as it offers an understanding of the history of deposition and transportation of clastic sediments (Chen et al., 2019; Saha et al., 2020). It is the first study of the tropical lakes in the Ganga Basin with varying catchments that discloses a noticeable dissimilarity in the morphological patterns on the surface of the lake sediments. Morphological variations were reported in terms of the shape, size, and amorphous nature of the sediment of the selected lakes. This is caused due to the different catchment characteristics and severity of anthropogenic stressors. A negligible yearly variation was reported in the lakes between the years 2018 and 2019 as seen in Fig. 7. Hence, the temporal variations in the morphology of the lake sediments are negligible in the selected three lakes. Anthropogenic activities like aquaculture as reported in lake L1 do not cause major changes in the sediment morphology as reported in the SEM images (Fig. 7). A long-term study may provide deeper insights into the morphological changes in the lake sediments as it takes a longer timescale for the morphological changes to be manifested in the sediments.

Conclusion

Anthropogenic activities such as mining, dredging, changes in land use, wastewater discharge, and aquaculture operations have a significant impact on the mineral and elemental composition of lake sediments. It affects the physicochemical parameters, biogenic minerals, and elemental concentration in the lakes whereas the morphology of the lake sediment remains largely unaffected by these disturbances. Geogenic minerals remain constant in the temporal analysis of the lake whereas the biogenic minerals are dependent on the in-lake processes. Mineral in lake sediments reported in the study are mainly of allochthonous origin and therefore contain more quartz, feldspar, and mica than fine mud, which is composed mainly of carbonate minerals and clays. Biogenic silica and carbonate or calcite formation in the lake is an important process linking geogenic and biogenic minerals in freshwater ecosystems as redeposition of the sediment mineral is controlled by the hydrodynamical characteristics of the lakes.

The distribution of minerals in the lake is impacted by in-lake particle dynamics, including episodic biogenic silica whose main sources are diatoms and planktons, production events, calcium carbonate ($CaCO_3$) precipitation events, and nutrient and elemental concentration in lakes. Concentrating sediment has a considerable impact on the distribution of nutrients and elements within lakes, which are related to organic matter, silica content, and carbonate matter. This cycle involves the whole geosystem of the lacustrine environments including biotic, abiotic, and anthropic factors, which directly influence the formation and alterations of the minerals in the lake sediment. The results emphasize the significance of studying annual fluctuations and spatial variations in mineral particle fluxes. These investigations offer valuable insights into the yearly dynamics of minerals within lakes, contributing to a more comprehensive understanding of their behavior and distribution. Furthermore, it is concluded that in-lake mixing processes are insufficient in homogenizing spatial variations in the concentration of geological minerals within the lake.

The findings of this study show that a thorough understanding of sediment particle dynamics in lakes requires knowledge of annual temporal oscillations and catchment characteristics. Differences in sediment nutrients and mineral fluxes are due to different anthropogenic pressures, lake productivity, and the biotic status of the lakes. It is also concluded that catchment and biotic deposit variations in the lakes cannot be evened out by in-lake mixing mechanisms due to variations in the terrigenous and pelagic deposits of the lake. In the selected lakes, major variation was reported in the autochthonous biogenic sediments in comparison to the allochthonous geogenic sediments. These findings are of immense importance in the characterization and identification of minerals in sediments, offering insights into their structural properties, composition, and potential environmental implications.

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Author contribution Divya Dubey: Project administration, Methodology, Data curation, Interpretation of FTIR and XRD, SEM and EDS data, writing-review and editing of original draft Saroj Kumar: Review, Formal analysis Venkatesh Dutta: Conceptualization, Supervision, Methodology, Validation, Writing-review and editing, Finalization of the manuscript.

Data availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Consent to participate We declare that we have no human participants, human data, or human tissues in this study.

Consent for publication All the authors agree with the publishing of this research article.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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