Organic matter source in the freshwater tropical lakes of southern India

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In this article, sediment texture, calcium carbonate, organic matter (OM), total organic carbon (TOC), total nitrogen (TN) and C/N ratio analysis of lake floor sediments of the Berijam and Kukkal lakes located nearly 2000 m amsl in the Palani Hills, Tamil Nadu, India are presented. This study was carried out to decipher the spatial distribution, origin of OM and the relationship among the components. TOC, TN% and C/N ratio of the Berijam lake sediments indicate a mixed source of OM (terrestrial and *in situ* lake algae and other biota), while for the Kukkal lake it is due to algae, aquatic weeds and plant detritus that grow along its margins. The lake margins and lake-bed morphology control the distribution of sediment particulate matter and texture.

Keywords: Algae, freshwater lakes, organic matter, particulate matter, PCA analyses, sediment texture.

PLANT detritus and sediments are an integral part of the lake system, that influence the nutrient budget and reflect upon the ecology, trophic status and rate of evolution of lakes[1,2]. Lake floor sediments play a significant role as a trap and offer a surface for sediment deposition. They act as a natural regulator for biological processes in the lakes[3,4]. They are also a source of nutrients to the water column that lead to benthic–pelagic mixture, which influences the principal productivity[3,4]. Spatial changes in the floor sediment types often carry signatures of variations in the hydrological processes that operate within the lakes and the local sediment sources[5,6]. Sediments produced due to the physical and chemical erosion of rocks in the catchment area are transported by streams and deposited in the lakes. There is relatively little information published about the lake floor sediment characteristics[5,6]. Further, information pertaining to contributions from the catchment area and distribution pattern of sediments in the lake, origin and source of total organic carbon (TOC) is scarce[3,4]. The primary source of organic matter (OM) and TOC in lake sediments is often considered to be derived from the particulate detritus of plants and only a small percentage is from animals and other sources[7,8]. Lakes are also major sinks for carbon and hence it is important to know the origin of OM and TOC in the lakes and to categorize major biogeochemical processes that operate within the lake systems[8].

In this study, we present data on OM, TOC, total nitrogen (TN), C/N and texture of lake floor sediments collected from two lakes, Berijam and Kukkal, Palani Hills, Tamil Nadu, India[9], to identify the source of OM and understand the spatial distribution and interrelation among various parameters.

Study area

Berijam lake (10°11′00″N: 77°23′44″E) and Kukkal lake (10°16′N: 77°22′E) are located respectively at an altitude of ~2165 (ref. 9) and ~1887 m amsl in the Palani Hills, about 21 and 33 km from Kodaikanal town. The Palani Hills are an eastward extension of the Western Ghats range in southern India (Figure 1). Both are freshwater lakes having zig-zag lake margins (Figures 1 and 2). The Berijam lake has an catchment area of 77.8 sq. km with a maximum length of 3 km and a surface area of 24 ha; it has a capacity of 77 million cubic metres of water. By comparison, Kukkal lake is small, with a maximum length of ~1 km, covering an area of 18 ha and can hold ~30–35 million cubic metres of water. The underlying bedrock for both the lakes is Precambrian charnockite in association with hornblende–biotite gneiss, granite and quartzite covered by red vertisols and laterite. Amaravathi, Kudhiraiyar, Palar, Porandalar, Vardhamanadhi, Manjalar and Maruthanadhi are the watersheds that cover the Berijam lake and for the Kukkal lake, it is Kudiraiyar. The area receives mean annual rainfall of 1690 mm from both the SW and NE monsoon, with contribution from the former being dominant. The dry season is from December through March. The summer and winter temperatures vary between 19.8°C (max) and 11.3°C (min), as well as 17.3°C (max) and 8.3°C (min) respectively. Both lakes are surrounded by the Shola forests. The soil is clay to clay-loam, black in colour due to the accumulation of humus[10], and acidic in nature with high percentage of iron and alumina.

Materials and methods

In the present study, 30 lake floor sediment samples (15 samples from each lake) were collected using a scoop

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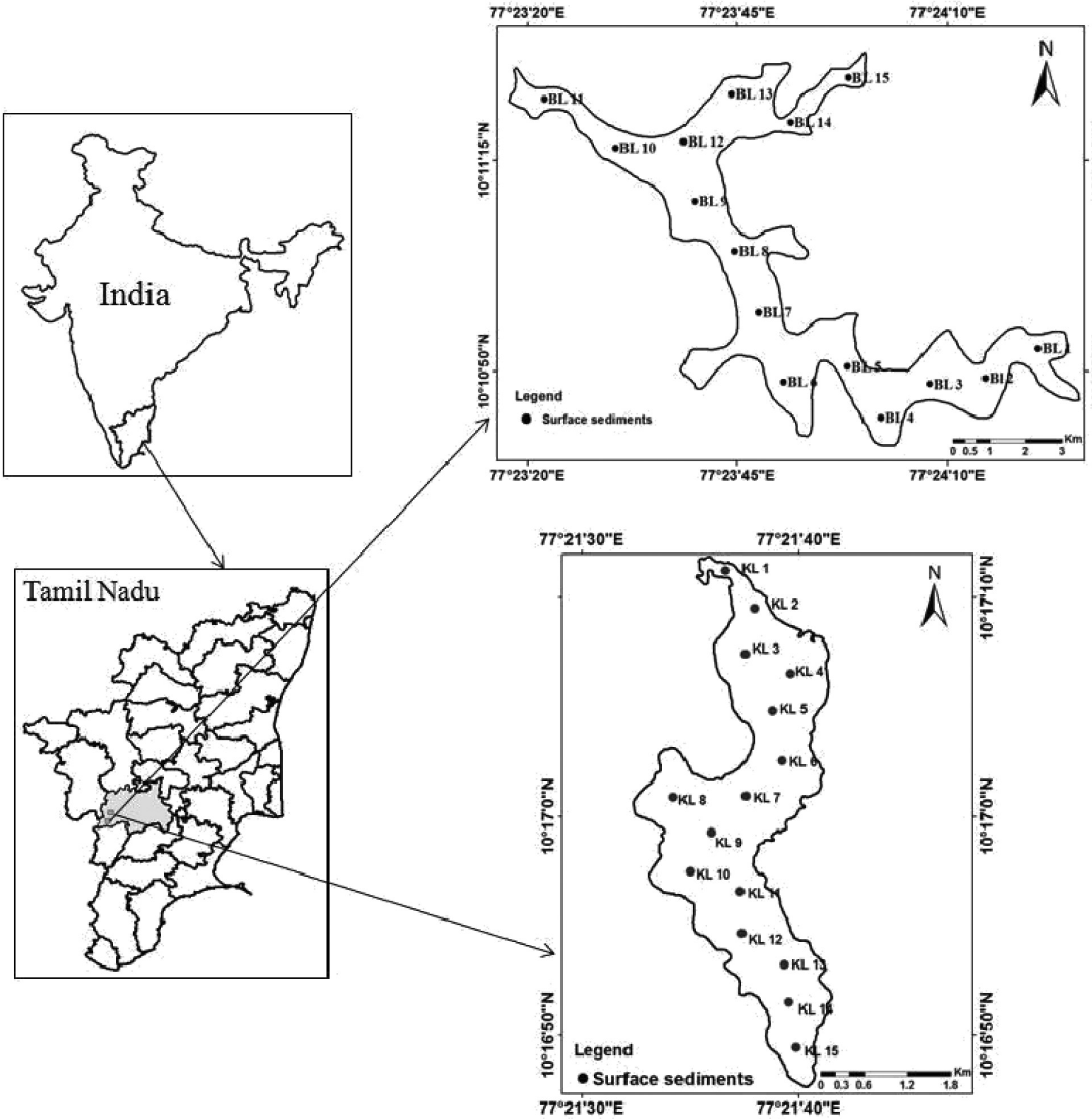

Figure 1. Location map of the Berijam and Kukkal lakes with stations marked where sediments were sampled.

from a water depth of 1–7 m in Berijam lake and 1–6 m in Kukkal lake during 2012. Locations of the samples were recorded using global positioning system (Figures 1 and 2). The sediment samples were immediately transferred to pre-cleaned polyethylene bags, stored and dried at 50°C for sediment and geochemical analysis. Textural studies on the sediments collected were performed for sand, silt and clay distribution adopting the method of Ingram[11] (Figure 3). Sediment samples for TOC and TN determinations were first decarbonated using 1 M hydrochloric acid, washed and freeze-dried. The samples were then analysed in a Thermo Scientific Flash 2000 CHNS-O analyzer at the Department of Geology, Anna University (Table 1). OM and $CaCO_3$ were determined by titration following the method of Gaudette *et al.*[12], and Loring and Rantala[13]. Using the ArcGIS 9.3 (ESRI software Inc.), data were then contoured to understand distribution pattern of the sediments. The interpolated data in the maps were created using the inverse distance weighting (IWD) method (Figures 4 and 5). Table 2 presents the correlation matrix of various factors such as sediment texture, $CaCO_3$, OM, TOC, TN and C/N is presented (Table 2). Principal component analysis (PCA) was conducted using compositional pattern, examining sediment systems to identify the factors influencing them (Figure 6).

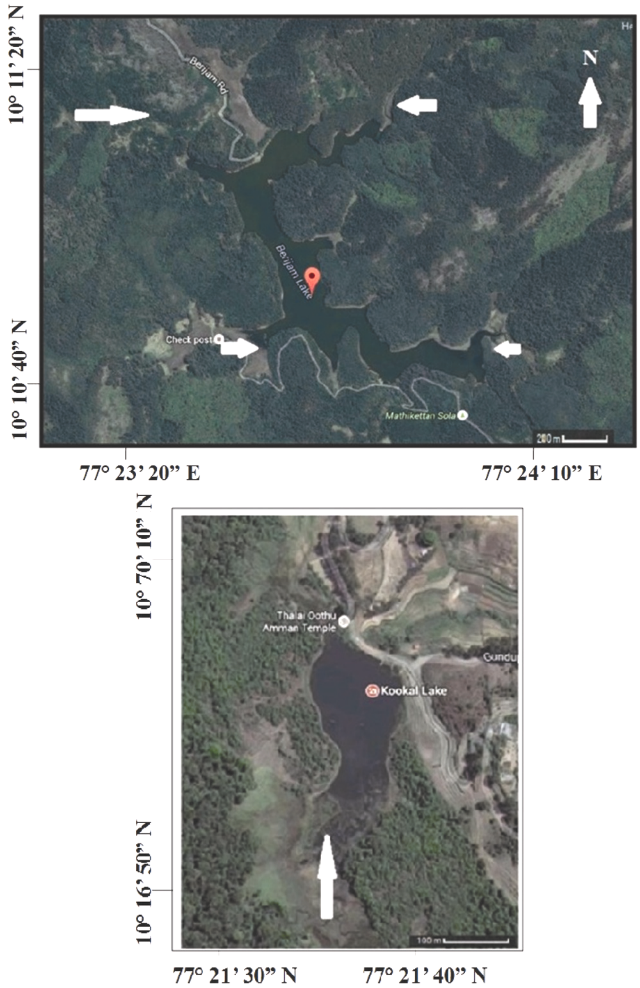

Figure 2. Google maps of the Berijam and Kukkal lakes showing prominent inlets into the lakes.

Results

In the Berijam lake, sediments are dominantly sandy near the lake margins and silty clay in the deeper part of the lake basin (Figure 3). The central part of the NW arm of the lake has low sand content (14.52%) at BL 12, while high sand content is observed towards the northern part of the lake to a maximum of 41.14% at BL 10 (Figure 4 *a–e*). Towards the southeastern side of the lake (BL 4), low silt (5.13%) content is observed, while high silt content (30.36%) is observed at the northern region of the lake (BL 12). Clay percentage varies from 68.52 to 32.12, and is mixed with sand and silt. Textural classification of the Berijam lake floor sediments following Shepard[14] points to the predominance of sandy clay (Table 1 and Figure 3).

The electrical conductivity is low (7.5 ms/cm) and pH of the Berijam lake water is mildly alkaline (slightly above 7.5). $CaCO_3$ content is low (0.4% at BL 12 to 2.7% at BL1 and BL9), indicating that carbonates are negligible and that the carbon produced in the lake is organic. OM concentration varies from 9.75% (BL 7) to 7.07% (BL 3). High values of TOC (5.67%) and TN (0.56%) are observed at the stations BL 7 and BL 8 in the central area of the lake (Table 1). Lower values of TOC (4.11%) at BL 3 and TN (0.40%) at BL 3 and BL 12 are noticed in the southeastern part of the lake. C/N ratio of 12.22 is observed at BL 6. The correlation matrix of silt with TOC (0.45) reveals a mild positive association (Table 2). OM with TOC (0.9), TN (0.75) and C/N (0.51) shows a good correlation. Similarly, TOC with TN (0.87) and C/N (0.5) shows a positive relationship.

In the Kukkal lake sediments, sand content ranges from 3.4% (KL 12) to 80% (KL 6) and silt ranges from 7% (KL 6) to 82% (KL 11). Clay content varies from 6% (KL 15) to 21% (KL 8, KL 9 and KL 10). Textural classification of the Kukkal lake floor sediments is silty sandy to

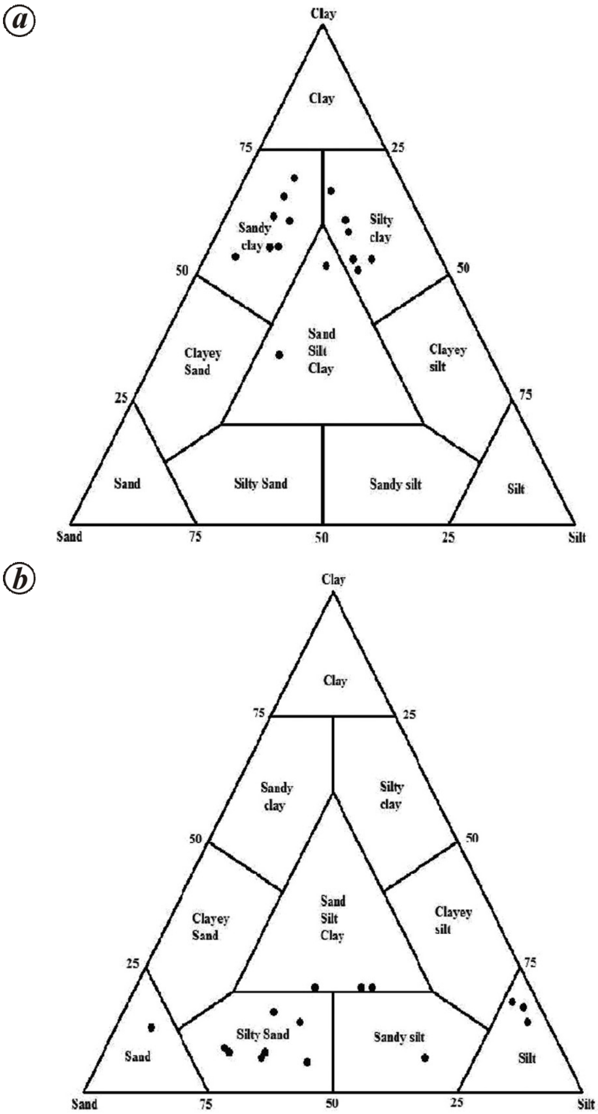

Figure 3. Ternary plot showing relative percentage of sand, silt and clay particles of (***a***) Berijam lake and (***b***) Kukkal Lake floor sediments.

Table 1. Textural and chemical parameters of Berijam and Kukkal lakes, Palani Hills, Tamil Nadu, India

	Latitude	Longitude	Sand%	Silt%	Clay%	$CaCO_3$%	OM%	TOC%	TN%	C/N	Sediment type
Berijam Lake											
BL 1	10°10′57.9	77°23′34.6	33.89	11.71	54.40	2.70	7.26	4.22	0.44	**9.60**	Sandy clay
BL 2	10°10′58.8	77°24′37.6	28.39	10.33	61.28	2.20	8.41	4.89	0.41	11.92	Sandy clay
BL 3	10°10′57.10	77°25′34.7	26.47	13.77	59.76	2.60	**7.07**	**4.11**	**0.40**	10.28	Sandy clay
BL 4	10°10′58.9	77°26′37.7	39.55	**5.13**	55.32	1.00	8.03	4.67	0.41	11.42	Sandy clay
BL 5	10°10′57.11	77°28′34.8	25.15	10.85	64.00	0.80	9.17	5.33	0.46	11.56	Sandy clay
BL 6	10°10′58.10	77°29′37.8	32.04	13.44	54.52	1.00	9.36	5.44	0.45	**12.22**	Sandy clay
BL 7	10°10′57.12	77°30′34.9	24.02	25.18	50.80	1.60	**9.75**	**5.67**	0.49	11.58	Sand–silt–clay
BL 8	10°10′58.11	77°23′37.9	18.33	28.31	53.36	0.90	9.36	5.44	**0.56**	9.67	Silty clay
BL 9	10°10′57.13	77°23′34.10	18.99	26.65	54.36	**2.70**	8.22	4.78	0.41	11.60	Silty clay
BL 10	10°10′58.12	77°23′37.10	**41.14**	26.74	**32.12**	1.40	9.36	5.44	0.47	11.63	Sand–silt–clay
BL 11	10°10′57.14	77°23′34.11	16.95	17.09	65.96	2.60	8.82	5.13	0.47	10.98	Silty clay
BL 12	10°10′58.13	77°23′37.11	**14.52**	**30.36**	55.12	**0.40**	7.60	4.42	**0.40**	11.14	Silty clay
BL 13	10°10′57.15	77°23′34.12	16.33	23.47	60.20	2.00	9.66	5.62	0.54	10.38	Silty clay
BL 14	10°10′58.14	77°23′37.12	21.20	10.28	**68.52**	1.60	8.73	5.07	0.48	10.47	Sandy clay
BL 15	10°10′57.16	77°23′34.13	17.01	24.23	58.76	0.80	9.29	5.40	0.55	9.81	Silty clay
	Average		**24.93**	**18.50**	**56.57**	**1.62**	**8.67**	**5.04**	**0.46**	**10.95**	
Kukkal Lake											
KL1	10°17′09.3	77°21′38.8	66.80	25.20	8.00	**2.90**	9.11	4.55	1.20	3.79	Silty sand
KL2	10°10′58.8	77°23′37.6	59.60	32.40	8.00	2.40	10.12	0.94	**1.46**	0.64	Silty sand
KL3	10°09′57.10	77°24′34.7	67.20	23.80	9.00	1.80	6.88	3.61	1.34	2.70	Silty sand
KL4	10°09′58.9	77°24′37.7	60.80	32.20	7.00	1.50	8.70	2.67	1.16	2.30	Silty sand
KL5	10°08′57.11	77°25′34.8	28.00	65.00	7.00	1.10	8.90	0.94	1.42	0.66	Sandy silt
KL6	10°08′58.10	77°25′37.8	**80.00**	7.00	13.00	1.90	4.86	12.66	1.38	9.17	Sand
KL7	10°07′57.12	77°26′34.9	53.80	30.20	16.00	1.10	2.23	7.10	0.96	7.37	Silty sand
KL8	10°07′58.11	77°26′37.9	33.80	45.20	**21.00**	1.80	14.37	5.56	1.20	4.64	Sand–silt–clay
KL9	10°06′57.13	77°27′34.10	31.60	47.40	**21.00**	2.10	12.55	8.81	0.91	9.63	Sand–silt–clay
KL10	10°06′58.12	77°27′37.10	43.20	35.80	**21.00**	2.40	13.56	7.71	0.88	8.76	Sand–silt–clay
KL11	10°05′57.14	77°28′4.11	4.00	**82.00**	14.00	1.60	14.16	1.84	1.00	1.84	Silt
KL12	10°05′58.13	77°28′37.11	3.40	79.60	17.00	1.10	12.95	8.10	0.88	9.17	Silt
KL13	10°03′57.15	77°29′34.12	5.00	77.00	18.00	0.60	**14.57**	**12.78**	1.17	**10.97**	Silt
KL14	10°10′58.14	77°29′37.12	49.60	36.40	14.00	0.80	10.32	9.18	0.91	10.12	Silty sand
KL15	10°02′57.16	77°30′34.13	52.20	41.80	6.00	0.20	13.76	5.58	0.65	8.57	Silty sand
	Average		**42.6**	**44.07**	**13.3**	**1.55**	**10.47**	**6.14**	**1.10**	**6.02**	

silt clay (classification as proposed by Folk[15], Table 1). pH of the Kukkal lake water is mildly alkaline (above 7.5) and electrical conductivity is low (7.2 MS/cm). Calcium carbonate percentage is low (0.20) at KL 15 and high (2.9%) at KL 1, while OM concentration varies from 2.23% (KL 7) to 14.57% (KL 13). Overall, the distribution of OM reveals a general increase from stations KL 1 towards KL 15 (i.e. from the southeastern region to the north of the lake). Enhanced values of TOC (12.78%) at KL 13 and TN (1.46%) at KL 2 (Table 1) are observed at the southern and northern ends of Kukkal lake. C/N ratios vary from 0.64 (KL 2; northern part of the lake) to a higher value 10.97 (KL 13; towards the southern area). The correlation matrix of silt with OM (0.65) indicates a positive link, while clay with TOC (0.58) and C/N (0.58) indicates a positive association (Table 2), and TOC with C/N (0.9) shows a strong positive relationship.

Discussion

Based on spatial distribution of the sediments and their texture, it is observed that finer materials have been transported in the run-off, thus leaving the coarser sediments on the lake floor[16] and lake margins (Figure 4 *a–h*). Closer to the source area near the lake margins the sediment texture is more sandy; in the area farthest from the lake margins, deeper lake sediments are clay-rich. The southern and northern margins of the Berijam and Kukkal lakes reflect the confluence of the stream fluxes into the lakes (Figures 4 and 5). This is due to the varying lake depth, and inclination of the lake floor towards the northeastern and northwestern arms of the Berijam lake, and central and western sides of the Kukkal lake. OM concentration shows a close link with the fine sediments. pH of the Berijam and Kukkal lake waters being above 7.2 and the low electrical conductivity indicate negligible carbonate content in the water, thereby signifying autochthonous nature of organic carbon.

Carbon and nitrogen

Carbon and nitrogen are two principal mechanisms of OM and TOC, both of which depend on parameters such as sediment texture, rate of microbial degradation, terrestrial

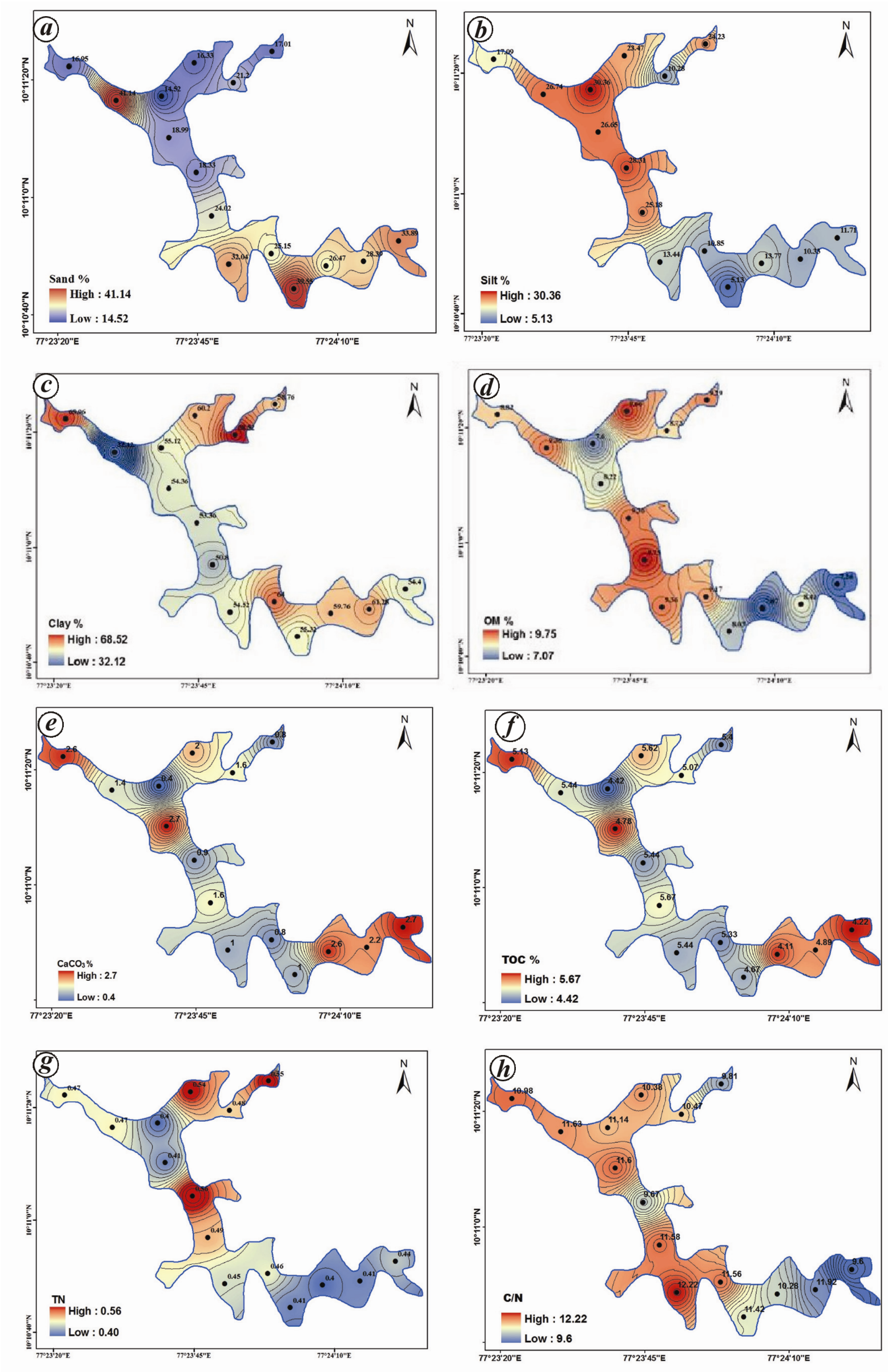

Figure 4 *a*–*h*. Spatial distribution map of sand, silt, clay, $CaCO_3$, OM, TN and C/N ratio of the Berijam Lake.

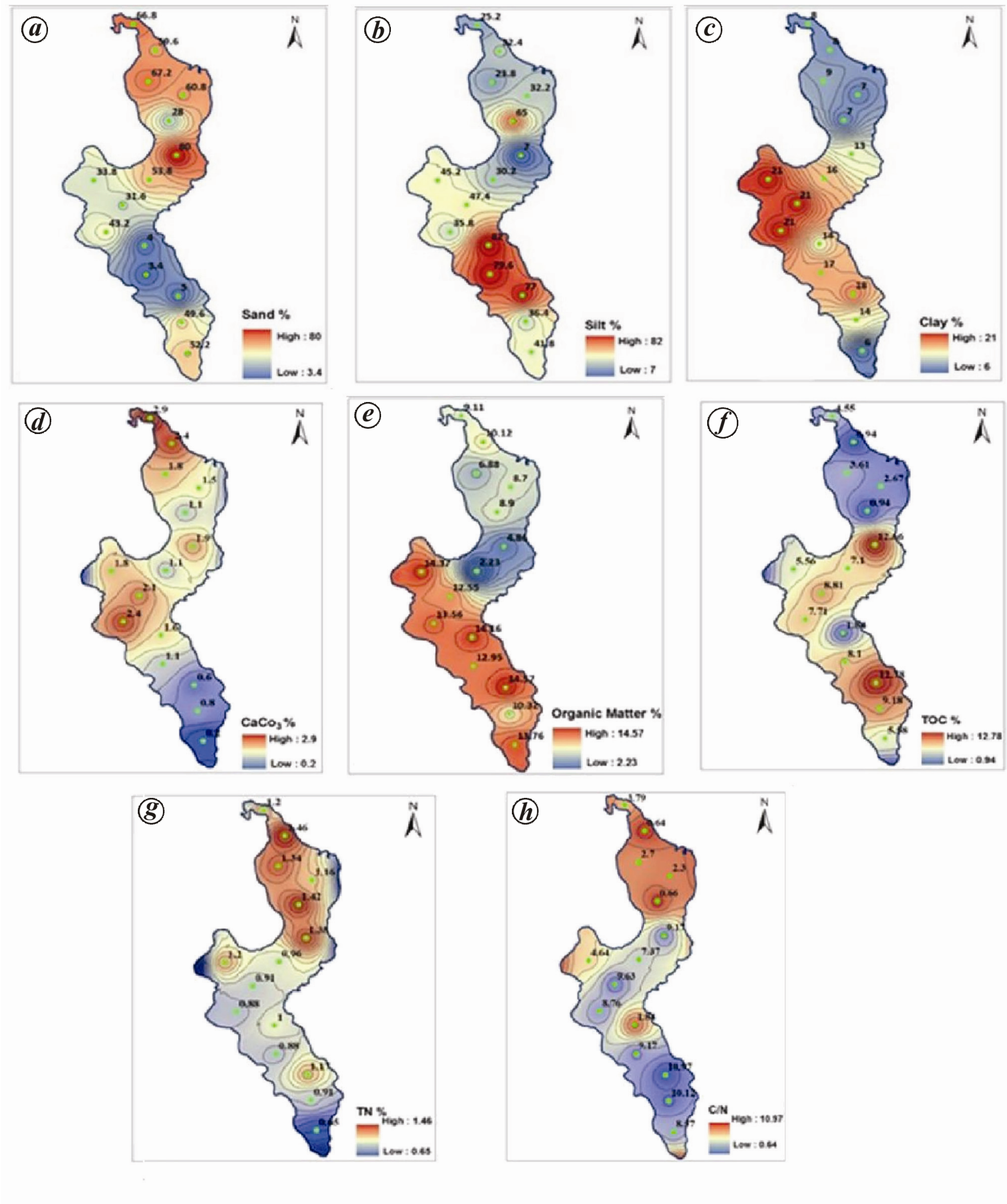

Figure 5 ***a–h***. Spatial distribution map of sand, silt, clay, $CaCO_3$, OM, TN and C/N ratio of Kukkal lake.

input, water column, suspended particles and productivity[4]. TOC and TN concentrations serve as a primary proxy for aquatic and terrestrial organic inputs into the ecosystem[17]. The C/N ratio of algae falls between 4 and 10, whereas terrestrial OM has C/N ratio greater than 20 (refs 8, 18–20). However, the use of C/N ratios to differentiate changes in sources of OM has also been questioned[21,22], because the C/N ratio of terrestrial OM decreases during post-depositional changes but that of algae increases[22,23]. Higher plant OM corresponds to low nitrogen content and thus a high C/N ratio is characteristic of terrigeneous OM contribution[17]. Thus, sediment

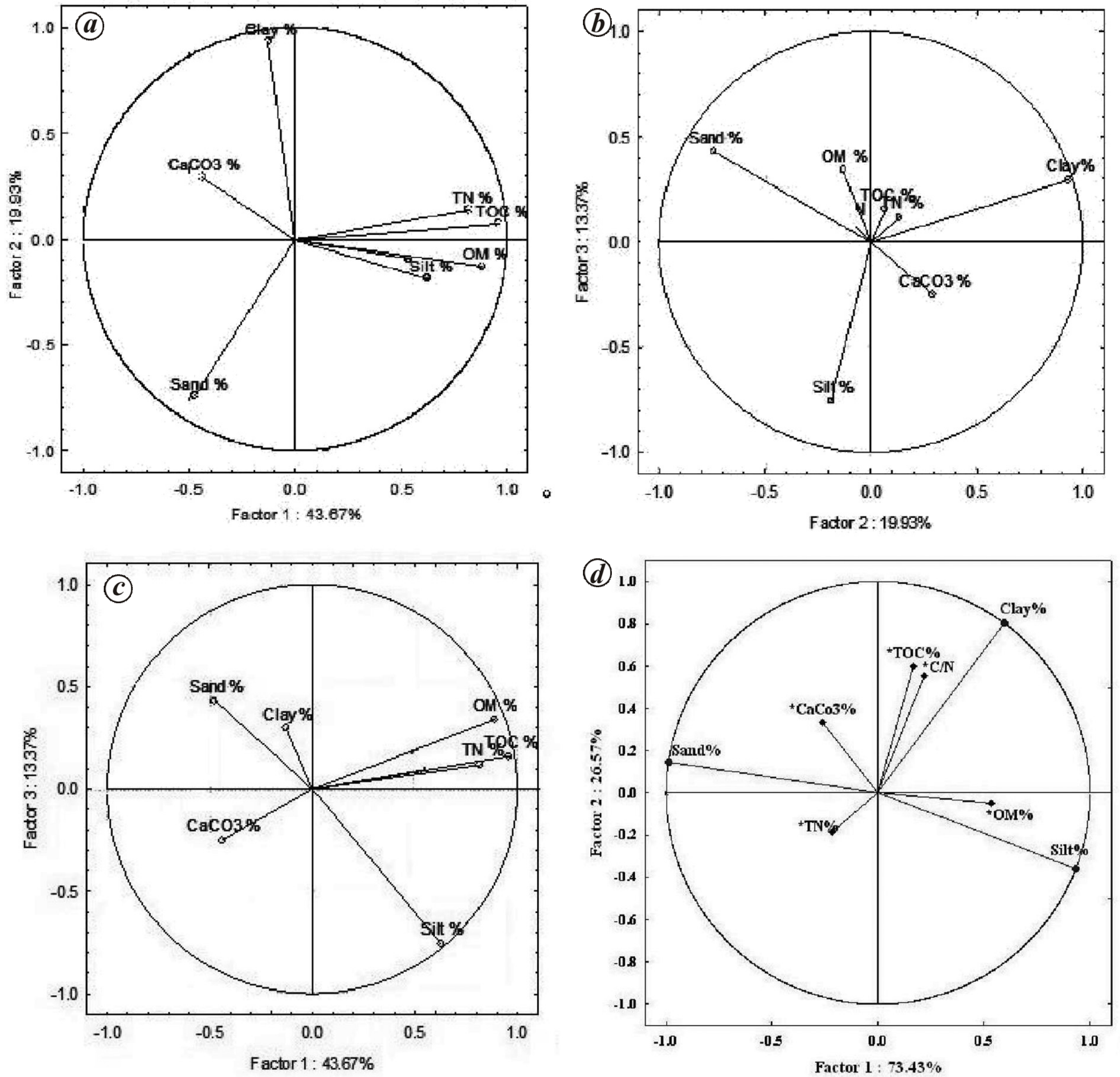

Figure 6 *a–d*. Principal component analysis of Berijam and Kukkal lakes. (***a***) Factor 1 vs factor 2, (***b***) factor 2 vs factor 3, (***c***) factor 1 vs factor 3 of Berijam lake, and (***d***) factor 1 vs factor 2 of Kukkal lake.

granulometry supported by C/N ratio suggests the settling strength of OM that is in association with fine particulates.

In this study C/N ratio variation has been applied to determine sources of OM[20,21]. The study shows that OM and TOC are closely associated with fine sediment, especially clay. A C/N ratio of 12.22 for the Berijam lake sediments points to a mixed source of TOC, although dominated by terrestrial source, while a C/N ratio of 10.97 for the Kukkal lake indicates a prevailing lake algal, aquatic weed and plant source of OM with minimal terrestrial contribution. The percentage of terrestrial OM is reduced because of low particulate matter[23], reduced discharge of streams flowing directly into the lake and also due to reforestation. This also points to the fact that the lake inward-bound streams are not a significant source of OM. Sediment loads decrease because of increasing forest cover[23].

Natural OM is less diluted compared to the input of nitrogen. TOC and nitrogen concentration in the Berijam and Kukkal lake bed sediments reflects the lake water column yield, microbial degeneration and terrestrial inputs. The Berijam lake sediments show a positive relationship between TOC, OM, TN and C/N, indicating an *in situ* source of OM. A positive correlation is also observed between silt and OM, clay, C/N and TOC in the Kukkal lake, which suggests the binding of OM with fine fractions.

Table 2. Correlation matrix of geochemical and textural parameters

	Sand%	Silt%	Clay%	$CaCO_3$%	OM%	TOC%	TN%	C/N
Berijam lake								
Sand%	1.00							
Silt%	–0.49	1.00						
Clay%	–0.53	–0.47	1.00					
$CaCO_3$%	0.03	–0.19	0.16	1.00				
OM%	–0.15	0.32	–0.15	–0.36	1.00			
TOC%	–0.40	0.45	–0.03	–0.31	**0.90**	1.00		
TN%	–0.37	0.39	0.00	–0.27	**0.75**	**0.87**	1.00	
C/N	–0.19	0.27	–0.07	–0.20	**0.51**	**0.52**	0.03	1.00
Kukkal lake								
Sand%	1.00							
Silt%	–0.98	1.00						
Clay%	–0.47	0.27	1.00					
$CaCO_3$%	0.36	–0.42	0.09	1.00				
OM%	–0.67	**0.65**	0.35	–0.13	1.00			
TOC%	–0.07	–0.07	**0.58**	–0.23	0.02	1.00		
TN%	0.31	–0.26	–0.33	0.42	–0.40	–0.28	1.00	
C/N	–0.16	0.03	**0.58**	–0.36	0.17	**0.92**	–0.60	1.00

Positive values above 0.5 are marked in bold.

Principal component analysis

Using the loading plots of PCA parameters such as OM, TOC, TN, C/N ratio and sediment textural data help in understanding the distribution, mobility and binding behaviour of OM. PCA analysis of the Berijam lake surface sediments shows an overall variance of 76.97% with factors 1, 2 and 3 (43.67%, 19.93% and 13.37% respectively) in grain size, OM and TOC respectively (Figure 6 *a*–*c*). Factor 1 vs factor 2 exhibits a positive correlation; factor 2 vs factor 3 shows a positive loading with total TOC and TN with clay, while factor 1 vs factor 3 shows positive associations of OM, TOC and TN. PCA of Kukkal sediments accounted for 73.4% variance for factor 1 and 26.5% for factor 2. Factor 1 vs factor 2 shows a positive correlation between $CaCO_3$ and sand component, and of clay with TOC and C/N; the silt fraction shows a negative loading with OM. TN shows no factor loading with any parameter, indicating an alteration of OM by biochemical process. Therefore, in this study, it is observed that OM and TOC are positively correlated, interconnected and bound to the fine clay fractions. This is because OM is locally sourced. Thus, three major factors interact at different scales and manage the sediment distribution within the lake floor: (i) morphology of the lake margin and depth of the water column in the lake; (ii) lake water volume and wave regime, and (iii) sediment flux. These factors result in the sediment distribution pattern on the lake floor.

Conclusion

In this study, the characteristics of the lake floor sediments collected from the Berijam and Kukkal lakes of Palani Hills, including calcium carbonate, OM, TOC, TN and C/N ratios are presented. The sediments are predominantly coarse detritus near the confluence of the streams and lakes. Fine silt and clay are deposited in the deeper parts of the lakes. OM and TOC are positively correlated with fine fractions. C/N ratio indicates that OM is largely produced by the lake algae in the Kukkal lake, while there is a mixed resource of OM in the Berijam lake.

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