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Research Article

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Trophic Status Analysis and Nutrient Source Allocation in Urban Lakes of Dhaka, Bangladesh: A Comprehensive Approach to Eutrophication Monitoring

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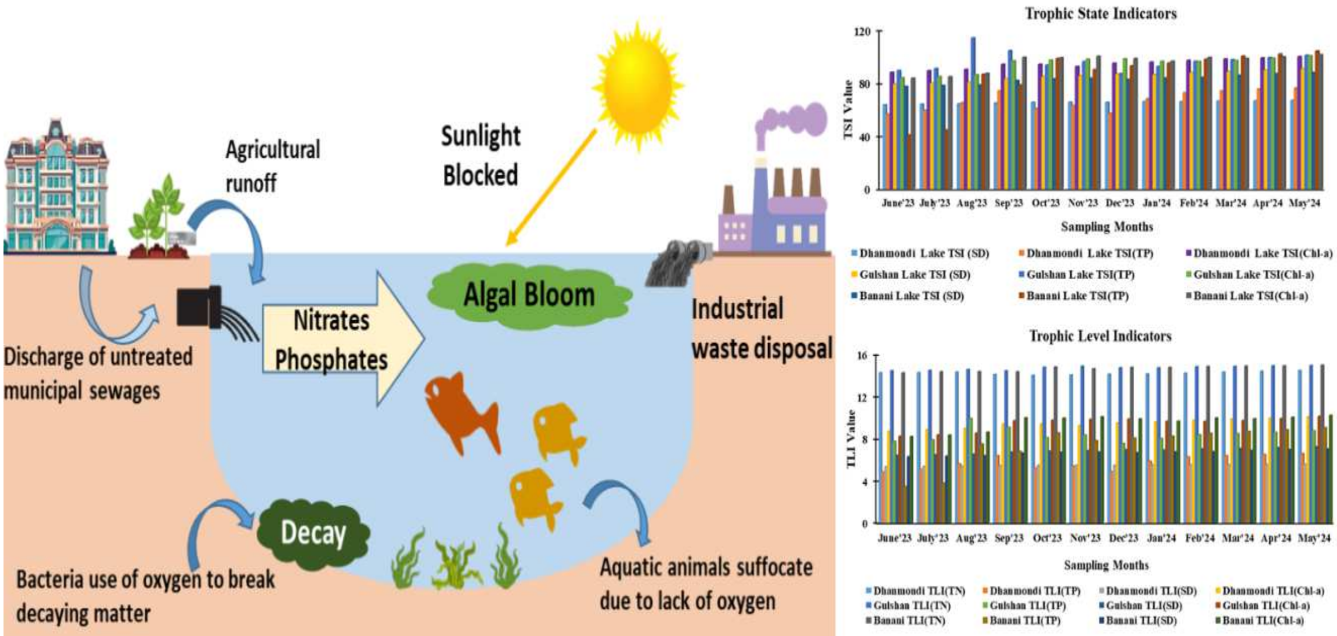
Graphical Abstract



Abstract

Urban lakes are vital to ecosystems, providing essential services and recreational spaces in densely populated megacities. However, rapid urbanization and anthropogenic activities, particularly eutrophication driven by macronutrient accumulation, severely threaten these water bodies. This study underscores the critical need for continuous trophic state monitoring to sustain fish, wildlife, and plant ecosystems. The trophic status of Dhanmondi, Gulshan, and Banani Lakes in Dhaka City, Bangladesh, was assessed using Carlson's Trophic State Index (CTSI) and Burn's Trophic Level Index (BTLI), based on Chlorophyll a (Chl-a), Total Phosphorus (TP), Secchi Disc Depth (SD), and Total Nitrogen (TN). Water samples from five sites per lake were analyzed for physicochemical parameters from June'23 to May'24, revealing monthly and seasonal variations. The study revealed that Dhanmondi Lake's CTSI ranged from 69.3 to 79.5 (June'23 to March'24), indicating initial "Eutrophic" conditions progressing to "Hypereutrophic". Gulshan Lake consistently showed "Hypereutrophic" conditions, with CTSI values between 84.1 and 97.3. Banani Lake was "Eutrophic" in June & July'23, transitioning to "Hypereutrophic" from August'23 to May'24 (84.1-97.7). The Trophic Level Index (TLI) showed the "Hypereutrophic" status with a progressive monthly escalation for all the lakes. The Water Quality Index (WQI) categorized the lakes as "Poor" to "Very Poor" from June to August'23, becoming "Unsuitable" from September'23 to May'24, indicating significant anthropogenic stress. Principal Component Analysis (PCA) identified nutrient infiltration, soil erosion, waste discharge, and organic residue accumulation as key pollution drivers. The study advocates for a multi-sectoral strategy to regulate nutrient loading and mitigate eutrophication, emphasizing best management practices for urban lake conservation.

Keywords: *Secchi disc, transparency, Hypereutrophic, Total Nitrogen, Total Phosphorus, Chlorophyll-a.*

Introduction

Lakes are vital freshwater resources supporting diverse human activities globally, including drinking water, hydropower, flood control, agriculture, industry, and recreation (Lehner et al., 2011; Jargal et al., 2023). But lakes, worldwide, are facing a deterioration in water quality as well as ecological function, particularly in developing countries like Bangladesh, increasing the demand of freshwater (Liu et al., 2012; Xiangcan, 2003; Ding et al., 2020; James et al., 2009; Ding et al., 2021). The worsening condition of lakes, ponds, and other aquatic ecosystems frequently leads to eutrophication (excessive phytoplankton and aquatic plant growth) due to elevated nitrogen and phosphorus levels (Abell et al., 2011; Jin et al., 2016). According to the United Nations Environmental Protection (UNEP), 30-40% of global lakes and reservoirs exhibit varying degrees of eutrophication (Farley, 2012). This issue is largely driven by human activities, increased land use and fertilizer application acting as major nutrient sources (Xing et al., 2013). Natural events like floods and heavy runoff further contribute to nutrient influx exacerbating eutrophication (Yang et al., 2008). This process degrades water quality that leads to increased turbidity, cyanobacterial blooms, biodiversity loss, health risks, oxygen depletion, and unpleasant tastes and odors (Havens, 2008).

Urban lakes, particularly in metropolitan areas like Dhaka, Bangladesh, face significant pollution from municipal waste and domestic discharge, comprising diverse organic and inorganic pollutants (Islam et al.,2018). The lakes in this megacity are considered essential ecological regions, serving as recreational areas for the city's densely populated residents (Alam & Rabbani, 2007; Nabila et al.,2022). Despite Bangladesh ranking fourth in inland fisheries production, insufficient management of lakes and ponds poses challenges such as fish mortality and increased prevalence of diseases (Ferdousi et al., 2015). Covering merely 10-15% of water bodies, the lakes of Dhaka city, specifically Gulshan Lake, Banani Lake, and Dhanmondi Lake, are experiencing increasing degradation from industrial effluents, municipal wastes, runoff, sewage, and harmful substances (Hashan & Moniruzzaman, 2022). This results in negative impacts in their usability and severely restricts local socioeconomic development, such as higher water treatment costs, difficulties meeting disinfection by-product standards, and aesthetic degradation (Miah et al., 2017; Islam et al., 2014; Chislock et al., 2013). Some of the ecological consequences include increased phytoplankton biomass, toxic algae, macroalgae proliferation, reduced water transparency, hypoxia, altered species dominance and so on (Paerl et al., 2011). In order to manage this devastating drawback, effective eutrophication management is essential for conserving water bodies (Cunha et al., 2013). Furthermore, predicting lake eutrophication provides valuable insights into future trends in the health of lake ecosystems (Zhang et al., 2018; Dodds, 2007; Cui et al., 2019; Jennings et al., 2009). To accurately assess this phenomenon, it is necessary to classify water resources into different trophic states and perform quantitative analysis. Various criteria, such as the trophic state index, to measure the trophic status of lakes are commonly used by the researchers due to their ability to evaluate comprehensively and quantify the trophic status of aquatic ecosystems while providing essential insights through established relationships and weighted indicators. (El-Serehy et al., 2018).

Carlson's Trophic State Index (CTSI) is widely used to categorize lakes into four trophic states: oligotrophic, mesotrophic, eutrophic, and hypereutrophic. This classification is based on chlorophyll-a (chl-a) levels, total phosphorus (TP) concentrations, and Secchi disc depth, as established by Carlson et al. (1977). This index is a common tool for researchers and government agencies to indirectly estimate algal biomass and assess eutrophication levels in lake ecosystems (Sruthy et al.,2021). Aizaki et al. (1981) explored the applicability of Carlson's index to Japanese lakes by examining its relationship with parameters indicative of lake trophic status. Burns et al. (2005) modified Carlson's index, and named it Trophic Level Index (TLI). This modification maintains consistency with TSI's input variables (total phosphorus, chlorophyll-a, and Secchi Depth), while also integrating total nitrogen (TN) (Burns et al., 2005). Phosphorus, a primary limiting nutrient in algal growth compared to nitrogen, justifies its integral role in Carlson's trophic state index (Havens, 2008). Increased nitrogen concentrations are often linked to enhanced primary productivity and the possibility of ecological disruptions (Diaz and Rosenberg, 2008; Aleksandrov, 2010). Chlorophyll-a, the green photosynthetic pigment inherent in algae, stands as a valuable indicator for evaluating the density of phytoplankton biomass (Opiyo et al., 2019). The Secchi depth, assessing transparency, is primarily affected by factors such as algal density (Opiyo et al., 2019). In addition to that, according to Nasirian (2007), the Water Quality

Index (WQI), developed by Horton (1965), is a crucial mathematical tool that merges different water quality parameters into a single value. It offers a thorough evaluation for water uses like drinking, recreation, and the support of aquatic life (Abedin et al., 2023). WQI serves as a distinctive rating system that helps in selecting appropriate recovery strategies to address water quality issues (Islam et al., 2021).

However, Studies on the trophic status of Urban Lakes in Dhaka, particularly in Dhanmondi, Gulshan, and Banani are scarce. Immediate focus is needed for restoration and conservation due to increasing nitrate and phosphate levels, along with declining water transparency. Effective management is crucial to maintain a balance between socio-economic use, recreational activities, and the ecological health of these valuable lakes. So, the purpose of this study comprises the following primary objectives: (1) To evaluate the Trophic State Index (TSI) and Trophic Level Index (TLI) in urban lakes, (2) To provide insights into the current nutrient enrichment levels and their impacts on the water quality, (3) To investigate spatial and temporal variations in TSI and TLI, (4) To identify and quantify the primary sources contributing to the nutrient overload in these aquatic ecosystems. The findings of this study will provide valuable insights for addressing eutrophication in urban water bodies globally, fostering more effective management strategies. This work aims to develop a robust framework for assessing and mitigating nutrient pollution in urban lake ecosystems, including strategic recommendations for improving lake management practices.

Materials and Method

Study area

The study was carried out over one year, from June 2023 to May 2024, at Gulshan Lake, Dhanmondi Lake, and Banani Lake in Dhaka city, Bangladesh (Fig. 1). Dhanmondi Lake is situated in the middle of Dhaka City (23˚43'N latitude and 90˚26'E longitude) spans approximately 3 kilometers in length and varies in width from 35 meters to 100 meters. It has a maximum depth of 4.77 meters, encompassing an estimated total water area of 37.37 ha (Razzak et al.,2012). Gulshan Lake (23°48′ N latitude and 90°25′ E longitude) is designated as one of the eight Ecologically Critical Areas declared by the Department of Environment, Bangladesh (Islam et al., 2014). The lake extends over a length of 3.8 km and covers an area of 2.89 meters. With an average depth of 2.5 meters, the lake has a volume of approximately 12×10^5 m^3. Banani Lake in Dhaka City, located at 23˚48' N latitude and 90˚025' E longitude, has an average depth of two meters and covers an area of 32.7 hectares (Uddin et al.,2023).

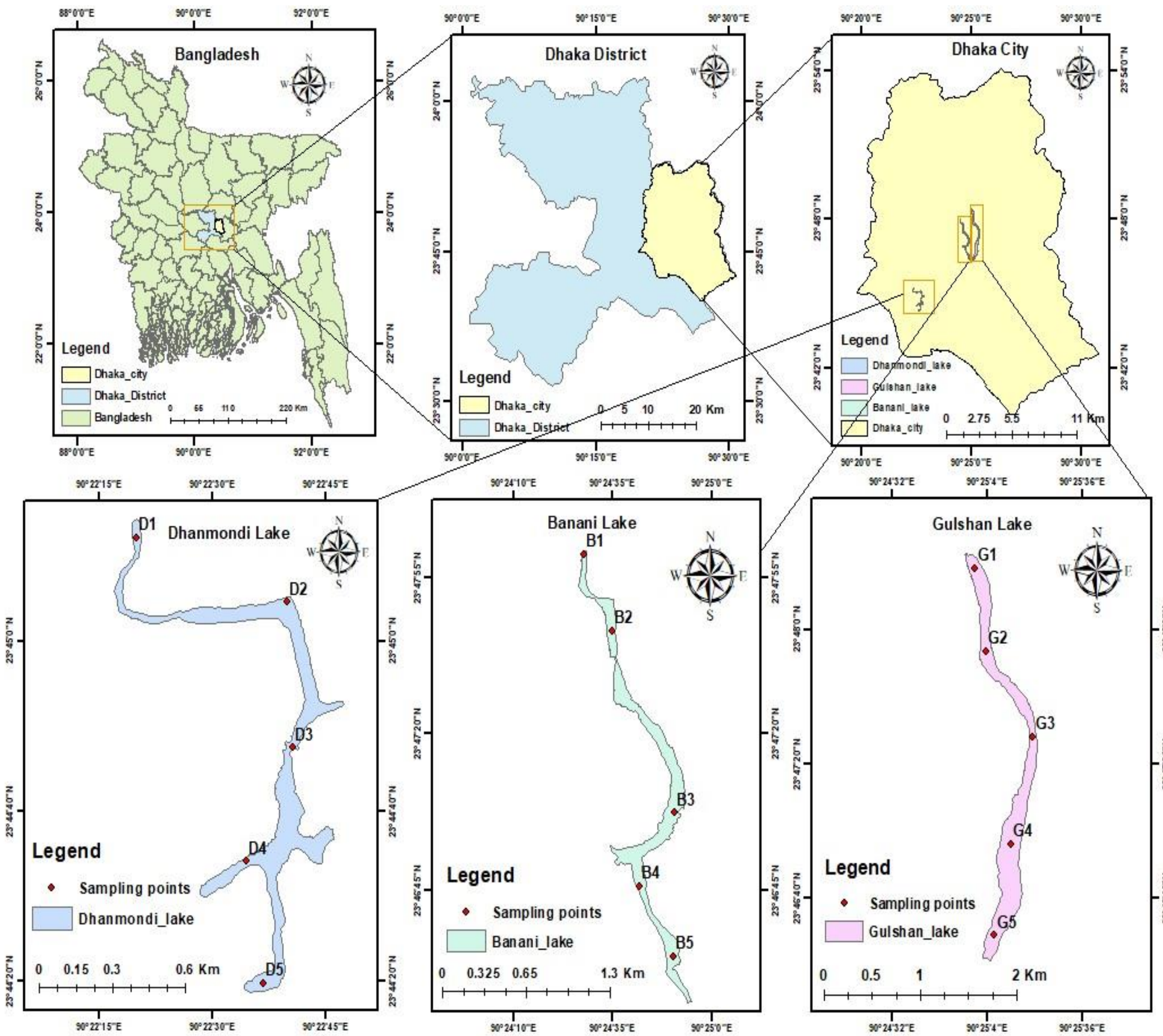


Fig. 1 Map showing the study area

Sample collection and Analysis

Monthly sampling of water was carried out at five separate points of each lake as illustrated in Fig. 1. The periods from June 2023 to September 2023 were categorized as Monsoon, October 2023 to January 2024 as Post-Monsoon, and February 2024 to May 2024 as Pre-Monsoon seasons. Water samples, collected in 1000 ml pre-treated plastic bottles with 10% concentrated nitric acid, were rinsed thrice with sample water at each station before immersion (APHA, 1998). Bottles were sealed securely, labeled with identification numbers, and acidified with 2 ml concentrated nitric acid per 1000 ml. Stored in an ice bath, samples were transported to the lab on the same day, remaining frozen at 4°C to prevent contamination until analysis (Ahsan et al., 2018; Kazi et al., 2009). Water parameters (pH, Temperature, DO, EC, TDS) were assessed using a multi-parameter (Model: HI 9829). Total Alkalinity and BOD were determined via titrimetric methods, while Hardness was measured using the EDTA method (APHA 2012). Total Phosphorus and Total Nitrogen concentrations were analyzed following standard methods from the APHA 2017. Water Transparency was determined with a 20cm Secchi disc, and Chlorophyll-a was estimated using the 90% Acetone method, measured spectrophotometrically at 630, 645, and 665 nm wavelengths, with concentration determined using the equation of Jeffrey et al., 1975.

Trophic Status Indices

Trophic State Index (TSI)

Carlson (1977) introduced the Trophic State Index (TSI) as a method to categorize lakes into four primary classes: oligotrophic, mesotrophic, eutrophic, and hypereutrophic. Designed specifically for lakes with minimal rooted aquatic vegetation and low non-algal turbidity, Carlson's TSI model is valuable for comparing lakes within a region and monitoring changes in trophic status over time (EPA 2007). It utilizes algal biomass with three variables: chlorophyll-a (Chl-a), Secchi disc depth (SD), and total phosphorus (TP) (Carlson et al., 1977). CTSI is calculated by averaging TSI values from these indicators using the following equations (Eq. 1-4):

$$TSI(Chl\text{-}a)=9.81 \ln \text{Chlorophyll-a } (\mu g/L) + 30.6 \quad (1)$$

$$TSI(SD)=60-14.4 \ln \text{Secchi depth(meters)} \quad (2)$$

$$TSI(TP)=14.42 \ln \text{Total Phosphorous}(\mu g/L)+4.15 \quad (3)$$

Where, Chl-a represents chlorophyll-a concentration (µg/L), SD is the Secchi disk depth (meters), TP denotes total phosphorus concentration (µg/L).

$$CTSI=[TSI(TP)+TSI(Chl\text{-}a)+TSI(SD)]/3 \quad (4)$$

Here, LN signifies the natural logarithm, and TSI refers to the Trophic State Index. The range of Carlson's Trophic State Index values and the corresponding lake classifications are presented in Supplementary Table S1.

Trophic Level Index (TLI)

Burns et al. (1999) developed the Trophic Level Index (TLI) by modifying Carlson's (1977) Trophic State Index to better assess the trophic status of New Zealand lakes, incorporating total nitrogen (TN) as a crucial parameter (Burns et al, 1999; Carlson et al., 1977). Recognizing the importance of TN in these ecosystems, the New Zealand Ministry for the Environment published the "Monitoring Protocols of the Trophic Levels of New Zealand Lakes and Reservoirs" in 2000, further validating the TLI's comprehensive approach to evaluating lake eutrophication (Burns et al, 2000). Burns Trophic Level Index (BTLI) utilizes chlorophyll-a concentration (Chl), Secchi Depth (SD), total phosphorus (TP), and total nitrogen (TN). The numerical values of BTLI for lake water were calculated using the following equation (Eq. 5-9) proposed by Burns et al. (2005).

$$\text{TL nitrogen}=3.61+3.01 \log(\text{N Total}) \quad (5)$$

$$\text{TL phosphorus} = 0.218 + 2.92 \log(\text{P total}) \quad (6)$$

$$\text{TL transparency} = 5.10 + 2.27 \log(1/\text{ Secchi disc depth} - 1/40) \quad (7)$$

$$\text{TL chlorophyll-a}= 2.22 + 2.54 \log(\text{Chl-a}) \quad (8)$$

$$\text{BTLI} =(\text{TL nitrogen + TL phosphorus + TL transparency + TL chlorophyll-a})/4 \quad (9)$$

Where, N total, P total, Chl-a are Total Nitrogen, Total Phosphorus, Chlorophyll-a respectively. Supplementary Table S1 outlines the range of Burns Trophic Level Index values and the corresponding classification of lakes.

Water Quality Index (WQI)

For WQI calculation, 13 parameters were selected (Temperature, Electric Conductivity, pH, Total Hardness, Total Alkalinity, DO, BOD, Turbidity, Transparency, Nitrates, Phosphate) as outlined in Table 2. The weighted arithmetic index method (Brown et al., 1972) was employed for WQI calculation, utilizing the equation described by Devendra (1983) and Tyagi et al. (2013) are as follows (Eq.10-12):

Quality rating or sub index (qn) was calculated by the following expression (Eq.10):

$$q_n = 100[V_n - V_{10}]/[S_n - V_{10}] \quad (10)$$

Where, qn = Quality rating for the n^{th} water quality parameter, Vn = Estimated value of the n^{th} water quality parameters of collected sample, S_n= Standard permissible value of the n^{th} water quality parameter, V10 = Ideal value of the n^{th} water quality parameter in pure water

Unit weight was calculated (Eq.11) by a value inversely proportional to the recommended standard value Sn of the corresponding parameter.

$$W_n=K/S_n \quad (11)$$

Where, Wn = Unit weight for n^{th} water quality parameter, K = Constant for proportionality.

The overall WQI was calculated (Eq.12) by aggregating the quality rating with the unit weight linearly.

$$WQI=\sum q_n \times W_n / \sum W_n \quad (12)$$

Where, qn = Quality rating for the n^{th} water quality parameter, Wn = Unit weight for n^{th} water quality parameter

WQI scores are classified into various categories, from excellent to Unsuitable, as presented in Supplementary Table S1.

Statistical Analysis

The measured parameters data underwent statistical assessment via IBM SPSS version 26, employing principal component analysis (PCA) and Pearson correlation matrix to identify variable relationships and predict contamination sources (Abedin et al., 2023; Islam et al., 2018). PCA guided variable selection for the PMF model. Sampling points were mapped using ArcGIS version 10.8.

Results and Discussions

Seasonal variations in the Physiochemical and Biological Parameters of lake water

The suitability of a body of water for an aquatic environment is highly dependent on its temperature (Kabir et al., 2020). The water temperatures of the studied lakes showed very little variation between the pre-monsoon and monsoon seasons, with Banani Lake having the lowest water recorded during the post-monsoon (23.42°C) (Table 1). The suitable water temperature for fish culture falls within the range of 24°C to 32°C (Mramba & Kahindi, 2023). Thus, apart from the post-monsoon season, the findings indicate that the temperature is optimal for fish cultivation.

The pH levels in the three lakes have reached their highest point during the pre-monsoon season. In Banani Lake, the pre-monsoon season had the highest pH value of 7.54, whereas at Gulshan Lake, the pH value dropped to 6.92 during the post-monsoon season. The pH levels in the lakes exhibit minimal temporal fluctuation, consistently maintaining values within the acceptable range for surface water quality in irrigation (pH: 6.5-8.5) or aquaculture (pH: 6.5-9.0) per ECR, 1997 standards (Table 1).

The EC levels in Gulshan and Banani lakes were found to be above the standard range of 500-700 µs/cm, which can have a detrimental effect on the aquatic ecosystem (ECR,1997). The EC levels in Dhanmondi lake were within the acceptable range, but during the pre-monsoon season, the it was higher compared to the monsoon and post-monsoon seasons which is shown in Table 1.

The TDS content in Gulshan Lake water was found to be higher compared to Dhanmondi and Banani Lake, although the three lakes were within the standard limit (ECR,1997). The pre-monsoon season in Gulshan Lake recorded the highest total dissolved solids (TDS) concentrations, reaching 491.16 ppm (Table. 1).

Table 1 Water quality parameters of Dhanmondi, Gulshan, Banani lakes during the study period

Parameters	**Seasons**	**Lakes**			**Standard Value**
		Dhanmondi	**Gulshan**	**Banani**	
Temperature (°C)	Monsoon	28.19±0.91	28.4±1.12	28.3±0.79	25°-30°C, (EPA,2017)
	Post-Monsoon	23.68±2.56	23.42±2.31	23.47±2.36	
	Pre-Monsoon	27.8±1.86	28.3±1.85	27.8±1.58	
pH	Monsoon	7.31±0.21	7.23±0.25	7.28±0.21	6.5-8.5, (DoE, 2001)
	Post-Monsoon	7.04±0.24	6.92±0.27	7±0.26	
	Pre-Monsoon	7.4±0.17	7.38±0.18	7.54±0.28	
EC (µs/cm)	Monsoon	321.25±13.6	564.25±16.1	511.75±15.8	500-700, (ECR,1997)
	Post-Monsoon	311.08±79.4	647.33±257.23	599.5±189.72	
	Pre-Monsoon	508.08±70.4	882.33±72.08	844.66±77.83	
TDS (ppm)	Monsoon	153.08±10.5	275.08±15.24	261.08±12.97	1000, (ECR,1997)
	Post-Monsoon	144.75±31.3	304.25±87.64	300.08±116.9	
	Pre-Monsoon	246.08±44.1	491.16±32.79	466.75±37.48	
Transparency (cm)	Monsoon	74.92±2.7	23.85±2.83	27.17±3.47	>40, (Santhosh,2007)
	Post-Monsoon	68.5±1.14	16.75±1.09	20.12±0.75	
	Pre-Monsoon	64.42±1.66	13.27±1.15	16.32±1.82	
Hardness (ppm)	Monsoon	79.94±3.47	142.4±14.14	103.82±8.78	200-500, (ECR,1997)
	Post-Monsoon	89.78±15.0	167.26±12.66	135.6±9.78	
	Pre-Monsoon	136.16±18.1	161.02±6.06	159.83±23.02	
Alkalinity (ppm)	Monsoon	90.32±4.79	151.09±6.96	123.76±7.07	150, (EQS,1997)
	Post-Monsoon	106.88±8.8	212.79±56.63	168.22±26.93	
	Pre-Monsoon	98.13±5.71	172.89±28.13	140.74±6.37	
NO_3- (mg/L)	Monsoon	3.3±0.19	3.52±0.15	3.98±0.16	10, (EPA,2017)
	Post-Monsoon	2.95±0.1	4.86±0.22	4.94±0.28	
	Pre-Monsoon	3.6±0.3	5.54±0.23	5.38±0.22	
PO_4- (mg/L)	Monsoon	0.1±0.04	1.29±0.85	0.19±0.2	0.005-0.20, (EPA,2017)
	Post-Monsoon	0.07±0.01	0.48±0.09	0.55±0.16	
	Pre-Monsoon	0.13±0.01	0.71±0.09	0.85±0.16	
Chl-a (mg/L)	Monsoon	0.46±0.14	0.41±0.3	0.48±0.42	0.06-0.59, (EPA,2017)
	Post-Monsoon	0.68±0.08	0.93±0.07	1.02±0.15	
	Pre-Monsoon	1.03±0.12	1±0.18	1.17±0.13	
DO (mg/L)	Monsoon	6.8±0.24	4.51±0.37	5.51±0.15	>5-6, (ECR,1997)
	Post-Monsoon	6.27±0.28	5.02±0.08	5.15±0.17	
	Pre-Monsoon	5.67±0.56	5.3±0.04	4.89±0.06	
BOD (mg/L)	Monsoon	7.62±0.44	17.37±0.17	13.02±0.83	<6, (DoE,2001)
	Post-Monsoon	8.53±0.5	18.42±0.86	15.64±0.53	
	Pre-Monsoon	9.85±0.51	20.03±0.12	17.31±0.45	
Turbidity (NTU)	Monsoon	8.12±0.78	50.71±9.5	34.05±9.55	10, (EQS,1997)
	Post-Monsoon	14.61±10.8	39.72±19.18	24.58±5.39	
	Pre-Monsoon	10.9±3.7	71.67±57.27	73.97±37.66	

During the monsoon season, Dhanmondi Lake had the highest transparency (74.92 cm), whereas Gulshan Lake had the lowest transparency (13.27 cm) during the pre-monsoon season. Throughout the entire study period, Banani and Gulshan Lake had substantially lower limits of Secchi disc visibility than Dhanmondi Lake (Table 1). Hence, in contrast to Gulshan and Banani Lakes, Dhanmondi Lake was far more suitable for aquatic life. The study revealed that transparency met the standard limit (>40 cm) only in Dhanmondi Lake (Santhosh, 2007).

The hardness of the studied lakes' water showed a noticeable increase during the pre-monsoon season compared to the monsoon and post-monsoon season, with the highest concentration in Gulshan Lake (161.02 mg/L). Importantly, the total hardness values in all the lakes remained within the acceptable limits set by ECR 1997.

In Gulshan Lake, the alkalinity is notably higher compared to Dhanmondi and Banani lakes, reaching its peak concentration (212.79 mg/L) during the post-monsoon season. Table 1 shows Alkalinity levels in Dhanmondi Lake and Banani Lake, except for the post-monsoon season, remained within EQS (1997) limits, while Gulshan Lake exceeded the recommended threshold.

An excessive amount of nitrates in water can have a serious effect on water quality, despite their importance as essential nutrients. High levels of nitrate, particularly when combined with phosphorus, can accelerate eutrophication, causing substantial growth in aquatic organisms (Kabir et al., 2020). There was minimal variation in nitrate content across all lakes, with slightly elevated values noted in the pre-monsoon season. In the post-monsoon season, Dhanmondi Lake had the lowest concentration of NO_3- (2.95 mg/L), while Gulshan Lake recorded the highest concentration (5.54 mg/L) during the pre-monsoon season. These findings are within the acceptable range according to EPA, 2017 (Table 1).

As a limiting factor in algal growth, phosphate determination is essential to evaluate surface water biological productivity ((Havens & Nürnberg, 2004)). For fish culture, the recommended total phosphorus (TP) level is 0.06 mg/l, while the optimal range for plankton production falls between 0.05-0.07 mg/l (Mramba & Kahindi, 2023). In the monsoon season, Gulshan Lake recorded the highest phosphate value of 1.29 mg/L, while Dhanmondi Lake had the lowest value of 0.07 mg/L. (Table 1). The phosphate level in Dhanmondi Lake meets the permissible limit set by the EPA, 2017. However, the limit was exceeded in Gulshan and Banani Lakes.

Chlorophyll-a is a reliable indicator for overall algae concentration in lakes. The current study indicated seasonal variations in chlorophyll-a values, reaching the lowest at 0.41 mg/L during the monsoon and progressively increased, reaching its peak at 1.17 mg/L in the pre-monsoon season for Banani Lake, as depicted in Table 1. Monsoon Chlorophyll-a concentrations in all lakes stayed within the acceptable range (0.06-0.59 mg/L) per EPA, 2017 guidelines. However, in post-monsoon and pre-monsoon seasons, the concentration exceeded permissible limits.

Insufficient dissolved oxygen levels pose a threat to fish and aquatic organisms' survival (Islam et al., 2021). The study noted higher dissolved oxygen concentrations during the monsoon season compared to the post-monsoon and pre-monsoon seasons across all studied lakes. The findings reveal significantly lower dissolved oxygen values in Banani (4.89 mg/L) and Gulshan (4.51 mg/L) lakes (Table 1), indicating inadequacy for maintaining a healthy aquatic ecosystem and ensuring the survival of aquatic species in these lakes (Uddin et al. 2023, ECR 1997).

The highest BOD levels occurred in the pre-monsoon period at all lakes, attributed to the discharge of organic-rich municipal sewage and industrial wastewater. Notably, Dhanmondi Lake displayed the lowest BOD concentration (7.62 mg/L) during the monsoon, while Gulshan Lake recorded the highest (20.03 mg/L) during the pre-monsoon (Table 1), surpassing the permissible limit of 6 mg/L by DOE (2001). Elevated BOD accelerates oxygen depletion in lake water, causing stress and suffocation for aquatic organisms, ultimately leading to their death (Uddin et al., 2023).

In the pre-monsoon season, Banani Lake had the highest turbidity value of 73.97 NTU, while Dhanmondi Lake recorded the lowest turbidity of 8.12 NTU during the monsoon (Table 1). Turbidity levels in all lakes were lowest during the monsoon, attributed to dilution and seasonal water flow, and highest in the pre-monsoon. Except for

Dhanmondi Lake in the monsoon, turbidity values in all three lakes lakes exceeded the acceptable limits set by EQS, 1997. Elevated turbidity poses an obstacle by impeding sunlight penetration, hindering plants and aquatic organisms' ability to undergo photosynthesis and leading to reduced dissolved oxygen levels in the water.

Trophic State Variables

During the study period, Dhanmondi Lake's TSI (SD) varied from a minimum of 63.6 in June '23 (Monsoon) to a maximum of 66.78 in May '24, demonstrating a steadily increasing trend every month until May '24 (Table 2).

Table 2 Temporal trends for the trophic state variables for Dhanmondi, Gulshan and Banani Lake

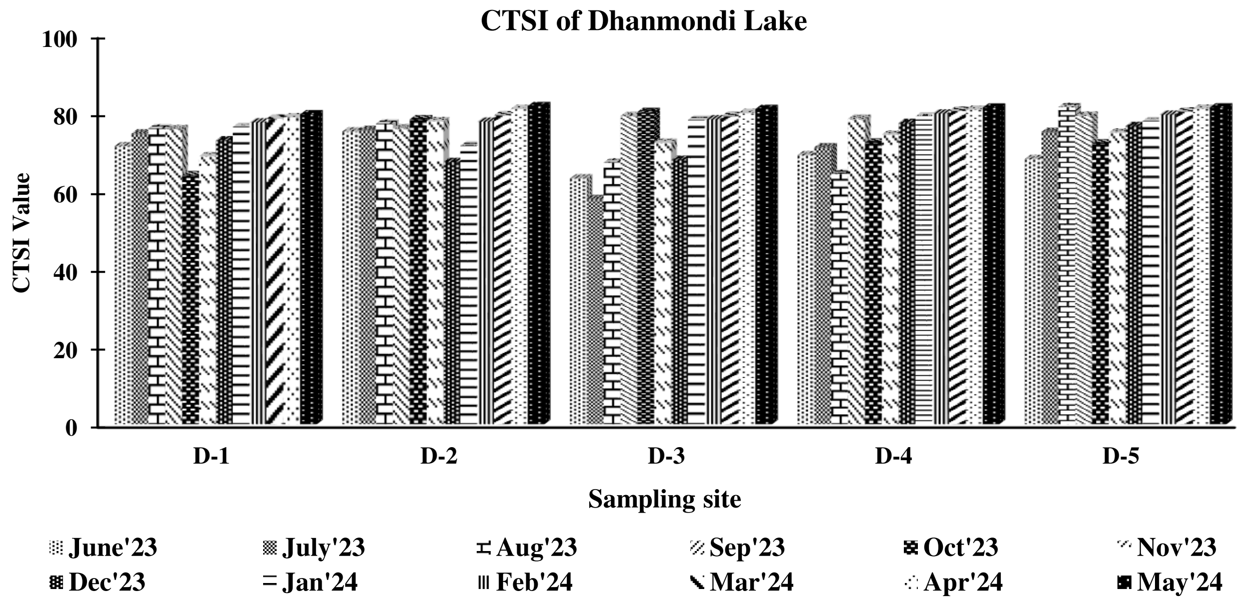
Lakes	Parameters	Monsoon				Post Monsoon				Pre-Monsoon			
		June'23	July'23	Aug'23	Sep'23	Oct'23	Nov'23	Dec'23	Jan'24	Feb'24	Mar'24	Apr'24	May'24
Dhanmondi	TSI (SD)	63.60	64.02	64.20	64.86	65.37	65.42	65.31	65.82	65.88	66.28	66.44	66.78
	TSI(TP)	56.43	59.24	65.06	74.14	60.62	62.91	56.97	68.08	72.60	74.10	75.48	76.16
	TSI(Chl-a)	88.04	89.23	90.29	94.07	94.05	92.49	94.88	95.78	97.08	98.19	98.95	99.92
	TLI(TN)	14.21	14.21	14.27	14.04	13.96	14.01	14.07	14.09	14.16	14.27	14.36	14.43
	TLI(TP)	4.82	5.06	5.57	6.37	5.18	5.39	4.86	5.84	6.24	6.37	6.49	6.55
	TLI(SD)	5.33	5.36	5.37	5.42	5.45	5.45	5.45	5.48	5.49	5.51	5.53	5.55
	TLI(Chl-a)	8.68	8.81	8.93	9.36	9.36	9.18	9.45	9.55	9.70	9.82	9.91	10.01
Gulshan	TSI (SD)	79.17	79.95	80.64	83.27	84.89	85.44	86.90	86.39	87.88	88.49	89.68	90.72
	TSI(TP)	89.39	90.92	114.06	104.46	93.47	96.24	87.10	92.50	96.43	97.69	99.16	100.91
	TSI(Chl-a)	83.82	84.89	86.31	96.77	97.31	98.02	98.28	96.39	96.23	97.03	98.72	100.49
	TLI(TN)	14.41	14.44	14.52	14.40	14.72	14.83	14.68	14.67	14.78	14.81	14.87	14.90
	TLI(TP)	7.71	7.85	9.88	9.04	8.07	8.32	7.51	7.99	8.33	8.44	8.57	8.73
	TLI(SD)	6.41	6.46	6.51	6.69	6.80	6.84	6.94	6.90	7.00	7.05	7.13	7.20
	TLI(Chl-a)	8.20	8.33	8.48	9.66	9.72	9.80	9.83	9.62	9.60	9.69	9.88	10.08
Banani	TSI (SD)	77.26	78.05	78.51	81.79	83.09	83.50	82.56	83.68	84.18	85.82	87.02	87.83
	TSI(TP)	40.67	44.44	86.63	78.44	98.55	90.19	93.00	94.99	98.04	100.22	101.86	104.18
	TSI(Chl-a)	83.60	84.72	87.30	99.37	99.13	100.12	98.45	96.45	99.28	98.50	99.72	101.35
	TLI(TN)	14.19	14.30	14.32	14.30	14.75	14.59	14.71	14.70	14.80	14.85	14.87	14.93
	TLI(TP)	3.43	3.76	7.47	6.75	8.52	7.78	8.03	8.21	8.47	8.67	8.81	9.02
	TLI(SD)	6.27	6.33	6.36	6.59	6.68	6.70	6.64	6.72	6.75	6.86	6.94	7.00
	TLI(Chl-a)	8.18	8.31	8.60	9.95	9.93	10.04	9.85	9.62	9.94	9.86	9.99	10.18

The TSI (Chl-a) of Dhanmondi Lake varied throughout the year, with a minimum of 88.04 during the Monsoon season and a maximum of 99.92 in the Pre-Monsoon season. The increasing trend of TLI (chl-a) observed in Dhanmondi Lake reflects the same pattern seen in TSI (Chl-a). The greater sunlight during the pre-monsoon season leads to notable growth in chlorophyll-a-containing organisms in aquatic plants and algae, resulting in higher TSI (Chl-a) and TLI (Chl-a) levels compared to other seasons. Gulshan and Banani Lakes showed temporal fluctuations in TSI (SD), TLI (SD), TSI (Chl-a), and TLI (Chl-a), resembling the increasing tendency observed in Dhanmondi Lake from June '23 to May '24 (Table 2). Throughout all seasons, the TSI (Chl-a) of all the lakes was found to be greater than the TSI (SD), presence of substantial suspended algal biomass, leading to turbidity and diminished light penetration. When TSI (Chl-a) surpasses TSI (SD), it indicates that the presence of algae in the water is the primary factor influencing light attenuation. (Carlson et al., 1977).

Overall the value of TSI (TP) and TLI (TN) of all the lakes were found to be higher than TSI (Chl-a), TLI (Chl-a) followed by TSI (SD) and TLI(SD), suggesting a rising surplus of phosphorous and nitrogen in the lake water. Anthropogenic disturbances, erosion, siltation, the disposal of household organic waste, and the use of direct detergent in household washing are all factors that have changed the water quality and may contribute to the excessive concentrations of phosphorus and nitrogen in the lake (Jennings et al.,2011; Abell et al.,2009). Natural environmental processes may be attributed to this phenomenon (Opiyo et al., 2019). Human-induced nutrient enrichment, especially phosphorus, significantly influences aquatic ecosystems. Alterations in phosphorus concentration in freshwater can lead to changes in its trophic status (Havens & Nürnberg, 2004).

Trophic State Index (TSI) & Trophic Level Index (TLI)

Figure 2 ,3 and 4 shows the graphical representations of the Carlson trophic state Index (CTSI) and Burn's Trophic Level Index (BTLI) for the studied lakes. According to CTSI, Dhanmondi Lake exhibited Eutrophic conditions from June 2023 to March 2024, after which it transitioned to the Hypereutrophic category (Fig. 2). As for TLI, each sampling site consistently fell under the Hypereutrophic category from June 2023 to May 2024, demonstrating a continuous increasing trend similar to the Trophic State Index (TSI) (Fig. 2).



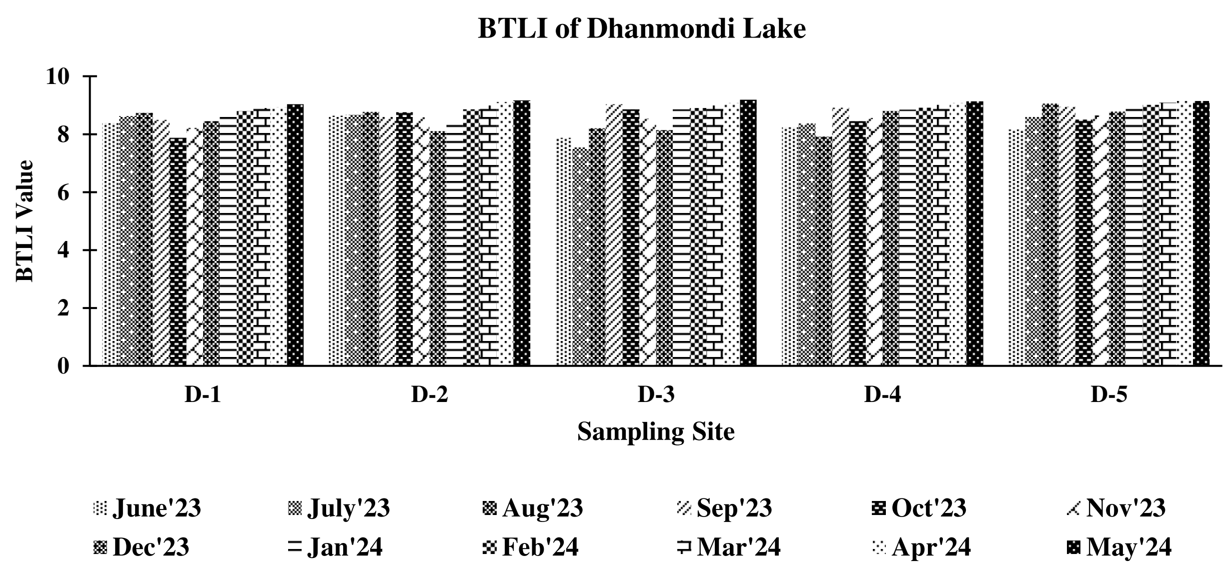


Fig. 2 Monthly variations of CTSI and BTLI of Dhanmondi Lakes during the year 2023-2024

For Gulshan Lake, all sampling sites assessed throughout the study exhibited hypereutrophic conditions, with values ranging from 84.12 to 97.37, except for G-5 in June 2023 (78.8) (Fig. 3). The Trophic Level Index (TLI) for Gulshan Lake categorized all sampling sites as hypereutrophic, with values ranging from 9.18 to 10.22, showing a consistent trend (Fig. 3). This could be due to a consistent influx of nutrients from the surrounding area, enhancing phytoplankton growth in the lakes (Havens & Nürnberg, 2004).

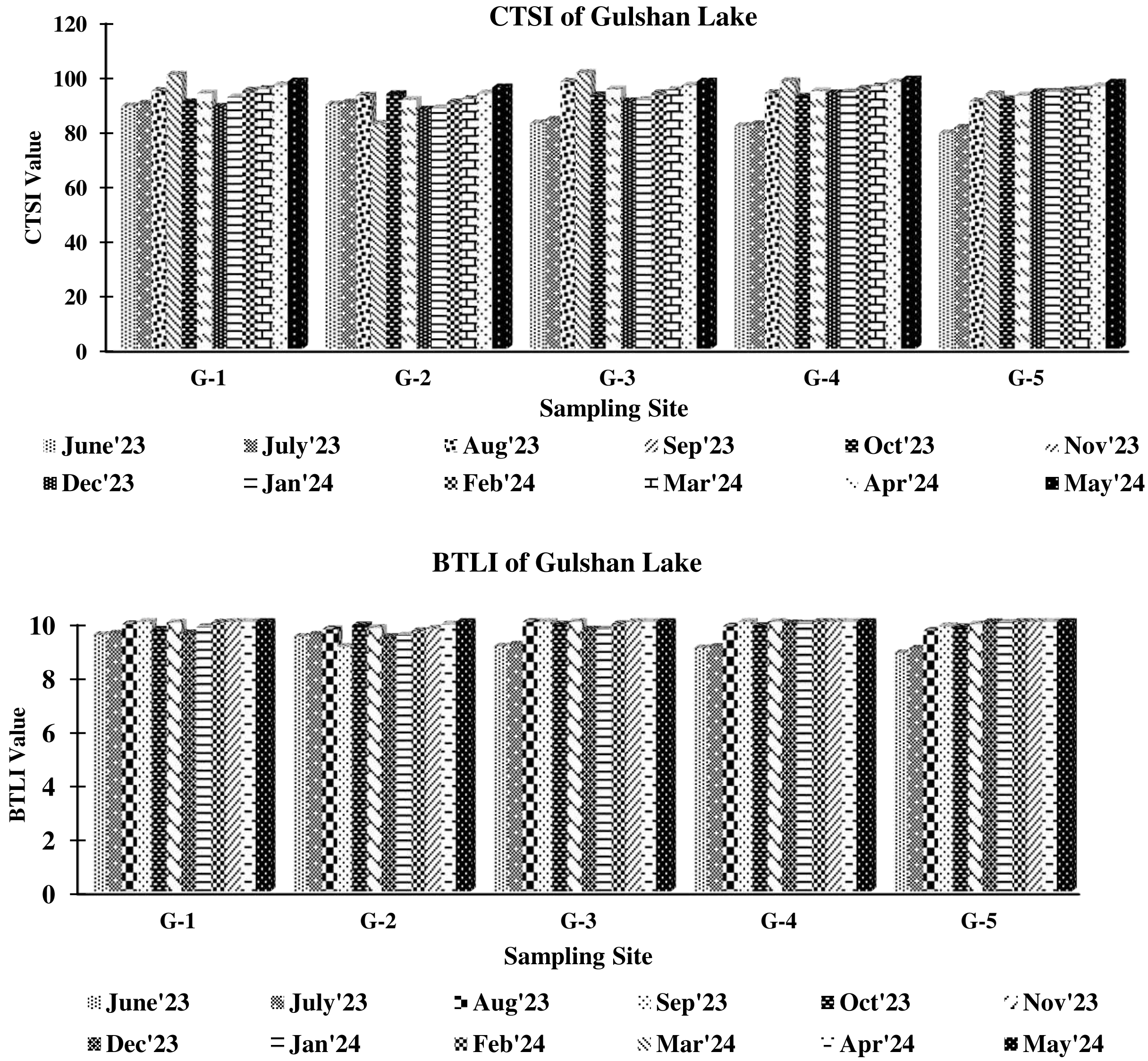
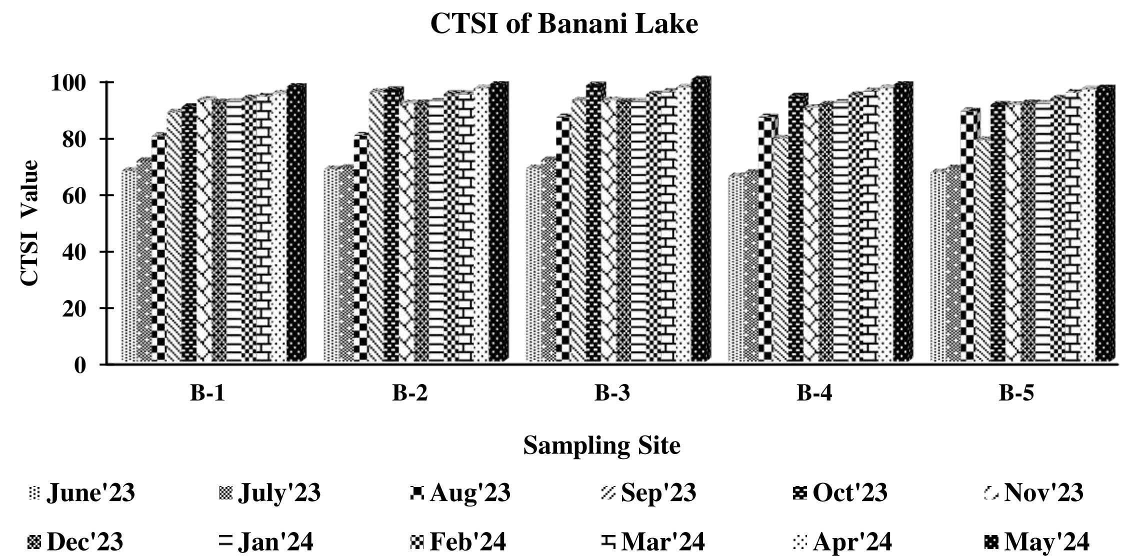


Fig. 3 Monthly variations of CTSI and BTLI of Gulshan Lake during the year 2023-2024

Banani Lake, in June and July 2023, was categorized as a eutrophic lake, with values ranging from 67.17 to 69.07, indicating a prevalence of blue-green algae (Fig. 4). However, from August 2023 to May 2024, Banani Lake exhibited Hypereutrophic conditions, with values gradually increasing from 87.14 to 97.78 each month, reflecting a substantial concentration of nutrients in the lake. The Trophic Level Index (TLI) for Banani Lake, similar to the other lakes, consistently fell within the Hypereutrophic category and ranging from 8.01 to 10.28, with an upward trend (Fig 4).



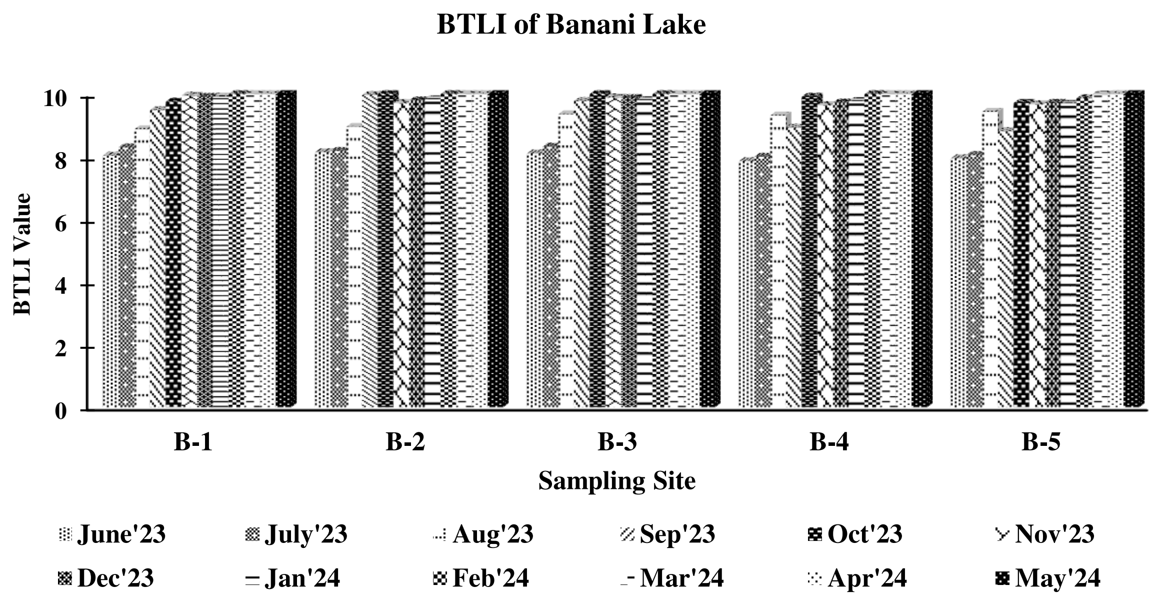


Fig. 4 Monthly variations of CTSI and BTLI of Banani Lake during the year 2023- 2024

In terms of season, the Trophic State Index (TSI) and Trophic Level Index (TLI) typically reach their highest levels during the pre-monsoon period, likely due to minimal rainfall and reduced water flow, allowing nutrients to accumulate in lakes (Zokm et al.,2018). Conversely, during the monsoon season, heavy rainfall increases water flow and dilutes nutrient concentrations in lakes (Table S2). This dilution effect can inhibit the growth of algae and other aquatic plants, as lower nutrient levels limit their ability to thrive (Yang et al.,2008).

The trophic status of Dhanmondi, Gulshan, and Banani Lakes, when compared to major lakes worldwide, highlights the critical need for implementing comprehensive management strategies to mitigate eutrophication and preserve the ecological balance of these urban lakes, as many of these lakes have become eutrophic or hyper-eutrophic (Table 3). This alarming trend is primarily driven by mismanaged anthropogenic activities, including unchecked nutrient runoff, waste discharge, and urban development, rather than natural processes (Saluja and Garg, 2017).

Table 3 Trophic state index (TSI) indicating trophic status of lakes world over

Lake	Country	TSI	Trophic status	Reference
Trichonis	Greece	36.4	Oligotrophic	Kehayias and Doulka, 2014
Naroch	Belarus	38.9	Oligotrophic	Adamovich et al.,2016
Chaohu	China	33.9–67.1	Mesotrophic to eutrophic	Yu et al. 2011
Deepor Beel	India	> 70	Eutrophic	Nibedita and Krishna, 2009
Three Gorges Reservoir	China	57	Eutrophic	Xu et al., 2010
Taihu Lake	China	77	Eutrophic	Liu et al., 2011
Krajwelek	Poland	60.5	Eutrophic	Jekatierynczuk-Rudczyk et al.,2014
Mansar	India	67	Eutrophic	Rai et al.,2001
Timsah	Egypt	60	Eutrophic	El-Serehy et al.,2018
Surinsar	India	61	Eutrophic	Singh et al.,2008
Mullankere	India	66.9	Eutrophic	Barki & Singa, 2014
Dr. Joao Penido	Brazil	53.5	Eutrophic	Bucci et al.,2015
Mansi Ganga	India	< 70	Eutrophic	Sharma et al., 2010
Akkamahadevi	India	53.4–56.1	Eutrophic	Barki and Singha, 2014
Bhindawas	India	64.6–73.9	Eutrophic to Hyper-eutrophic	Saluja and Garg, 2017
Lake Naivasha	Kenya	71-89.2	Eutrophic to hyper-eutrophic	Ndungu et al., 2013
Tso Kar	India	86	Hyper-eutrophic	Singh et al.,2008
Veli	India	76	Hyper-eutrophic	Sheela et al.,2011
Upper Lake	India	71.6	Hyper-eutrophic	Upadhyay et al.,2012
Renuka	India	79.16	Hyper-eutrophic	Kumar et al., 2019
Rewalsar	India	83.62	Hyper-eutrophic	Kumar et al., 2020
Dal	India	72	Hyper-eutrophic	Singh et al., 2008
Akkulam	India	80	Hyper-eutrophic	Sheela et al., 2011
Xiangxi Bay	China	>80	Hypereutrophic	Ye et al., 2006

Additionally, several other limiting factors, such as inadequate water circulation, sediment accumulation, and poor watershed management, exacerbate the situation, further elevating the Trophic State Index (TSI) values (Ndungu et al., 2013).

Spatial and Temporal trends of TSI & TLI

The spatial and temporal distribution maps revealed a distinct symmetry in both Trophic State Index (TSI) and Trophic Level Index (TLI) values at points D-1 and D-2 within Dhanmondi Lake, illustrated in Fig. 5(a). This symmetry was primarily influenced by seasonal variations, particularly the influx of organic matter and nutrients during the monsoon season from surrounding trees and gardens, exacerbating water quality issues.

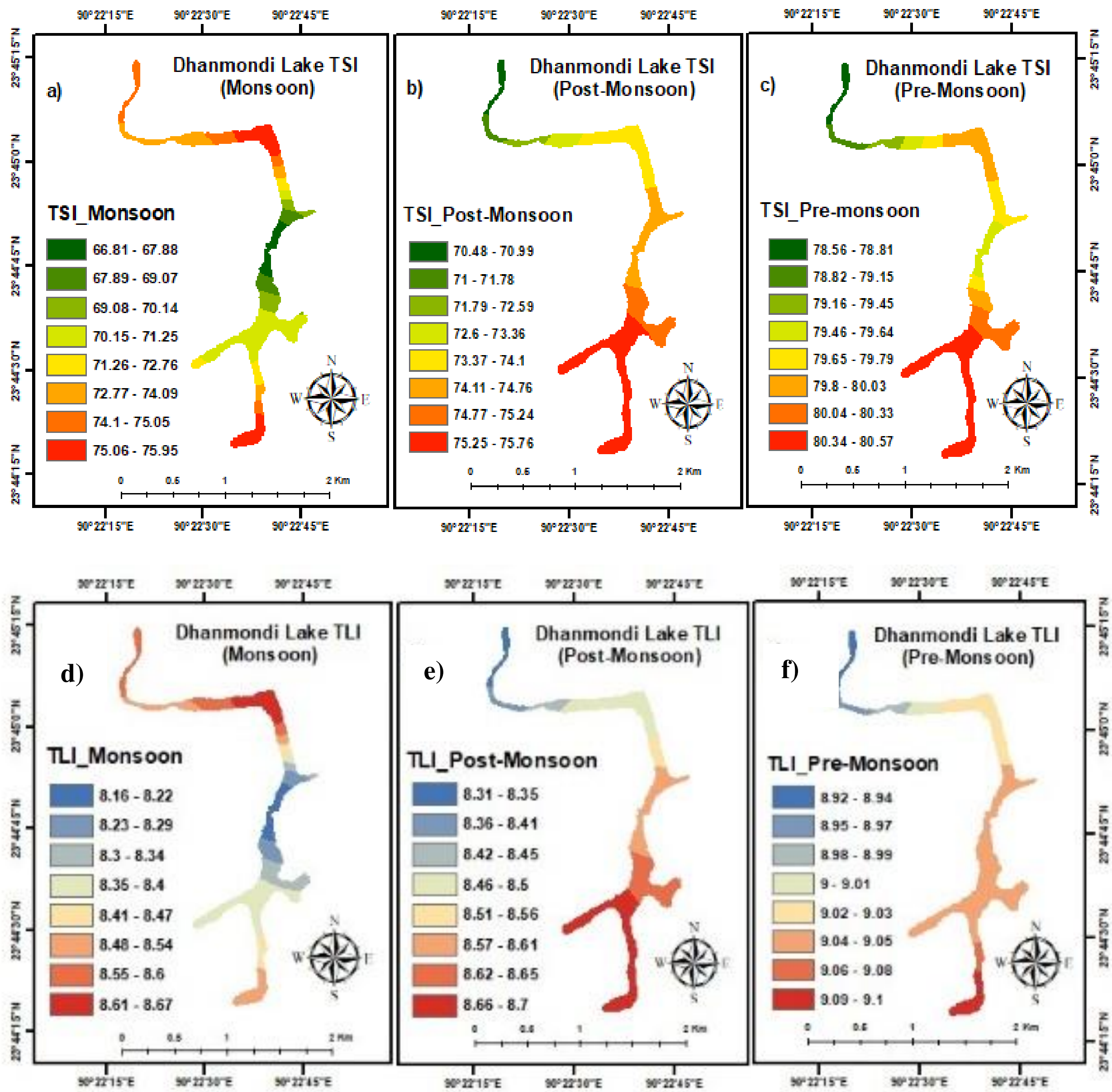


Fig. 5 Spatio-Temporal Variation of TSI and TLI of Dhanmondi Lake during the year 2023-2024

Points D-3 and D-4 experienced a contrasting pattern during the monsoon, undergoing a dilution effect from rainfall which temporarily improved water quality before transitioning into the red zone once the rain ceased, as depicted in Fig. 5(b and c). In contrast, point D-5 remained consistently within the red zone throughout the observation period, indicating persistent water quality challenges.

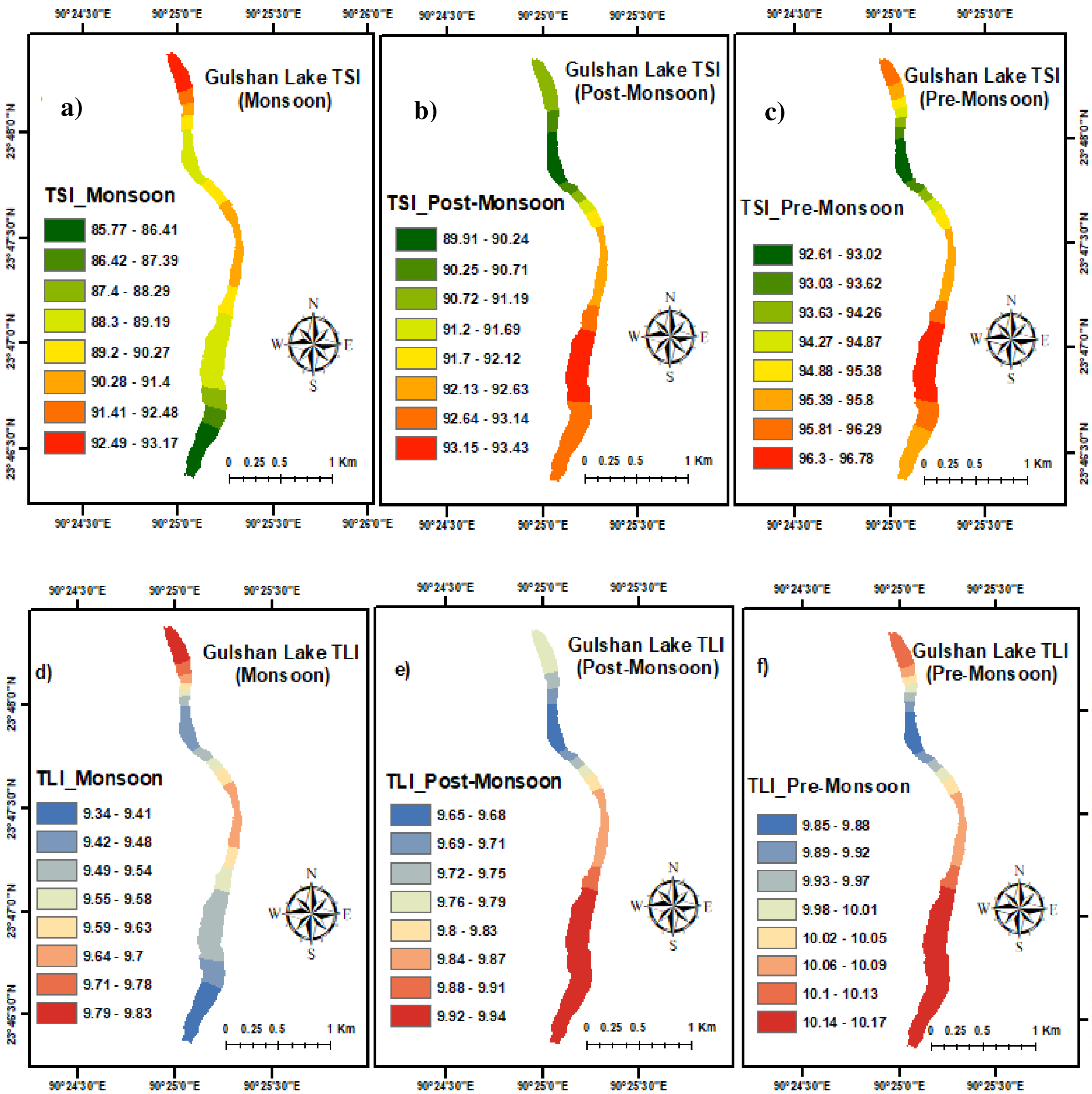


Fig. 6 Spatio-Temporal Variation of TSI and TLI of Gulshan Lake during the year 2023-2024

The G-1 site within Gulshan Lake exhibited significant improvements following a cleaning program initiated by the city corporation, particularly noticeable during the post-monsoon season, as illustrated in Fig. 6(b and e). However, subsequent seasons witnessed a decline in water quality, underscoring the necessity for ongoing monitoring and maintenance efforts in the lake area. At G-2, runoff during the monsoon season, depicted in Fig 6a and d, was balanced out in the following seasons. Conversely, G-3 consistently remained in the orange category, likely due to the presence of shading trees and soil absorption of rainwater. In contrast, G-4 experienced the dilution effect of rain, while G-5 exhibited the lowest water quality during the monsoon season, likely attributed to the vitiation effect of rainfall in an exposed area, as shown in Fig. 6 (c and f).

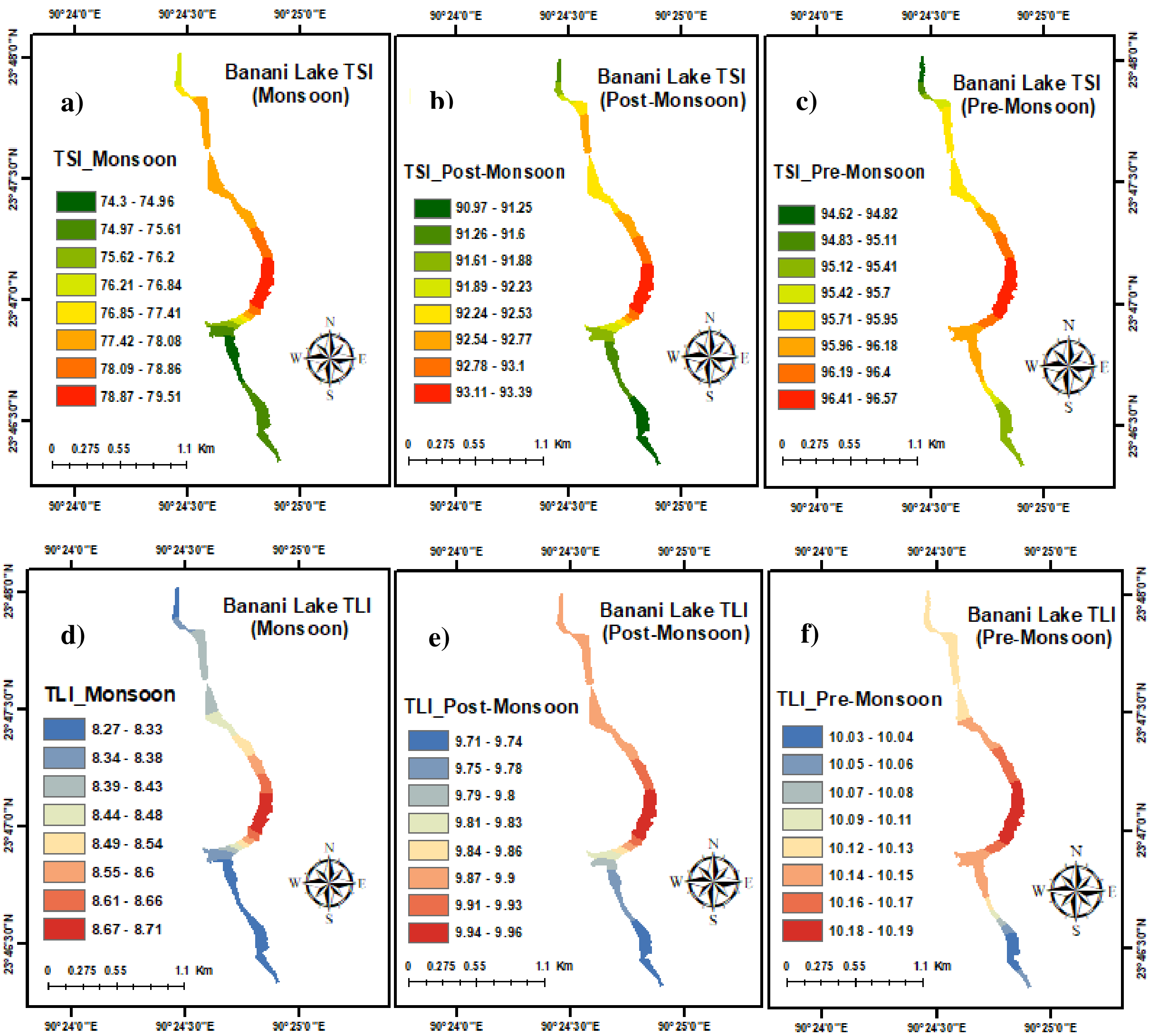


Fig. 7 Spatio-Temporal Variation of TSI and TLI of Banani Lake during the year 2023-2024

In Banani Lake, sites B-1, B-2, and B-3 exhibited elevated nutrient runoff during periods of precipitation, resulting in higher TSI and TLI values during the monsoon season, as depicted in Fig. 7(a and d). Conversely, site B-4 consistently demonstrated higher TSI and TLI values throughout the observation period, indicating a sustained nutrient load regardless of seasonal variations.

In contrast, site B-5 consistently displayed lower TSI and TLI values, except during the pre-monsoon period, as illustrated in Fig. 7(c and f). This lower value can be attributed to the abundance of sunlight in the area, which may suppress nutrient accumulation and algae growth. These findings underscore the complex interplay between environmental factors and water quality dynamics in Banani Lake, highlighting the need for targeted management strategies to address diverse water quality challenges across different lake sites.

Water Quality Index (WQI)

The temporal changes in the Water Quality Index (WQI) for Dhanmondi, Gulshan, and Banani lakes from July'23 to May'24 are shown in Fig. 8. At Dhanmondi Lake, the water quality was categorized as "Poor" in June 2023, but it deteriorated to "Very Poor" in the following two months (July'23 and Aug'23). From Sep’23 to May’24, the water quality in Dhanmondi Lake consistently deteriorated, reaching an “Unsuitable’’ level. The water quality in April'24 and May'24 was notably worse in comparison to the rest of the months (Fig 8).

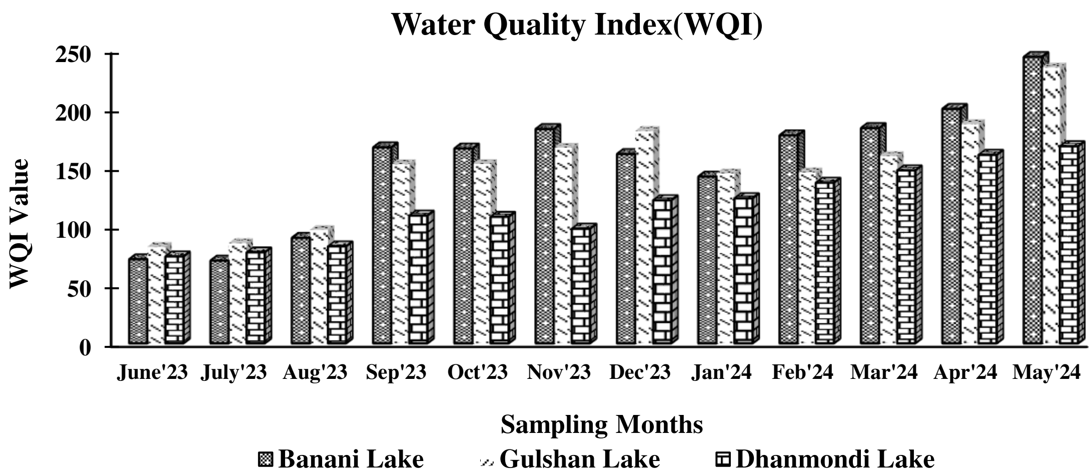
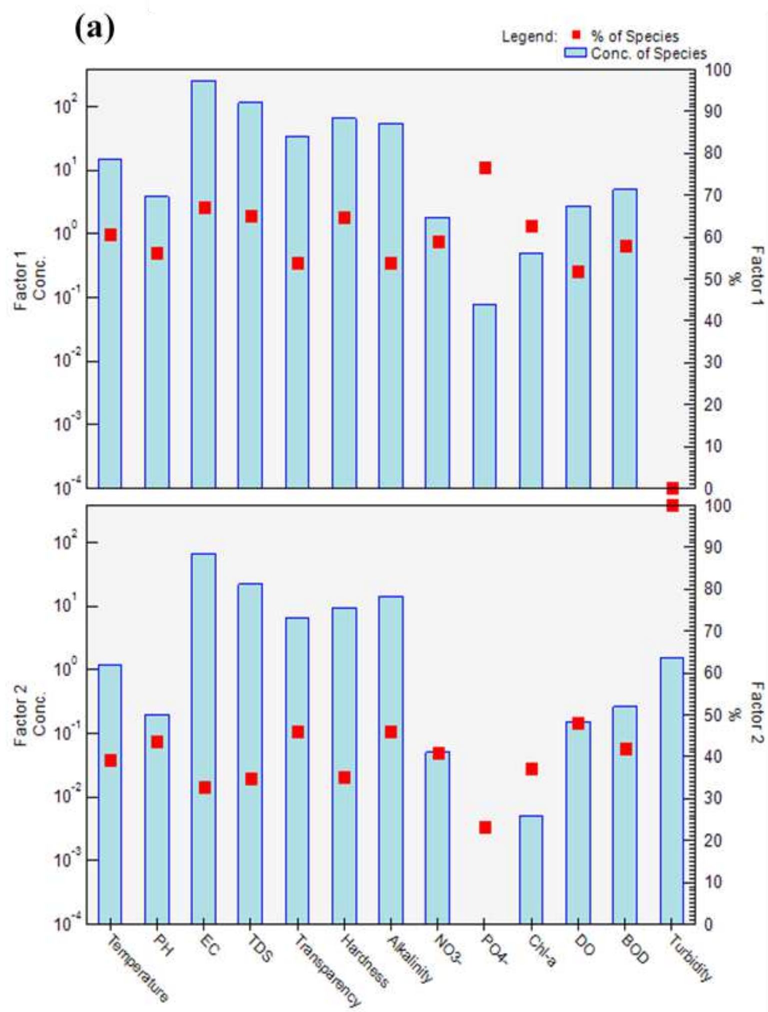


Fig. 8 Variation of monthly Water Quality Index (WQI) of Dhanmondi, Gulshan, Banani Lakes during the study period

Gulshan Lake experienced a "Very Poor" water quality in June’23, July ’23, and Aug’23. Subsequently, from Sep’23 to May’24, the water quality in Gulshan Lake consistently remained in the "Unsuitable" category, making it inadequate for both domestic use and aquaculture purposes. Banani Lake's water quality, assessed by the Water Quality Index (WQI), ranged from "Poor" to "Unsuitable" throughout the study period. In June’23 and July’23, it was classified as "Poor," deteriorating to "Very Poor" in Aug’23. Subsequently, from Sep’23 to May’24, Banani Lake's water quality consistently remained categorized as "Unsuitable," indicating a prolonged deterioration in water quality for the lake (Fig 8).

Identification of pollution sources

The PMF model utilized the physical and biological parameters of water and their associated analytical uncertainties to identify sources. The results of PCA, PMF, and Pearson correlation analysis can be found in Supplementary Tables S3 to S11 for comprehensive analysis. PCA of Dhanmondi Lake which is documented in Table S4 gave out 2 factors based on their eigenvalues (>1) that have a total variance of 78.69%. Therefore, these two factors were incorporated into the commonly utilized EPA PMF 5.0 model, as detailed in Table S3. Factor-1 contributes to 56% of the total 0 (64.8%), NO3-(59.17%) BOD (57.98%) and others which is supported by PC1 that covers 54.2% of the total variance. Similarly, according to Pearson correlation analysis filed at Table S5, BOD is strongly significant to Chl-a ($r = .999$, $p < 0.01$), EC ($r = .895$, $p < 0.01$) and Total Hardness ($r = .968$, $p < 0.01$). Chl-a is positively correlated with Total Hardness ($r = .976$, $p < 0.01$) and EC ($r = .909$, $p < 0.01$). The factor indicates nutrient intrusion from the surrounding area (Hashan & Moniruzzaman, 2022, Dodds, 2007, Liu et al., 2012, Nion et al., 2020). This includes waste discharge from restaurants that are built on the lakeshore, households, waste dumped by tourists, and organic residues from trees, animals, and humans. Factor-2, 44% of the total contribution, consists of Turbidity (99.99%) DO (48.1%), Transparency (46.24%), TA (46.15%), pH (43.82%), BOD (42.03%), NO_3- (40.83%), Temperature (39.13%) which is vouched by PC2 that covers 24.49% of the total variance. Turbidity is significant to TA ($r = .999$, $p < 0.01$), DO being strongly significant to Transparency ($r= .986$, $p < 0.01$), TDS to BOD ($r = .882$, $p < 0.01$), NO_3- to pH ($r = .969$, $p < 0.01$). Factor-2 expresses the erosion and runoff phenomenon resulting in the introduction of suspended particles which scatter the entering sunlight and affect temperature along with other water quality parameters (Hashan & Moniruzzaman, 2022; Islam et al., 2021; Çako et al., 2019;). Factor contributions and fingerprints are illustrated in Fig. 9a, b and Fig. S1, respectively.



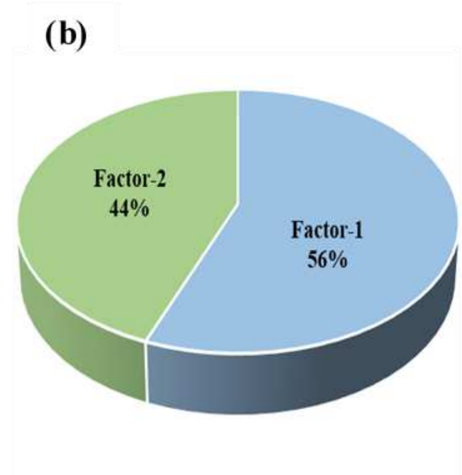


Fig. 9 Positive matrix factorization (PMF) model result; (a) Source apportioning contributions of factors to each parameters and (b) Total contributions of factors to the analyzed parameters in Dhanmondi Lake

PCA of Gulshan Lake, mentioned in Table S7, gave out 4 factors based on their eigenvalues (>1) that have a total variance of 91.97%. Consequently, these two factors were incorporated into the commonly used EPA PMF 5.0 model, as delineated in Table S5. Factor-1 (16% of the total contribution) is dominated by TDS (29.26%), EC (23.23%), NO_3- (22.14%), Temperature (17.7%), BOD (17.57%) which is supported by PC2 which is 21.69% of the total variance. According to Pearson Correlation Analysis mentioned in Table S8, BOD is strongly significant to EC (r= .989, $p < 0.01$), TDS (r= .962 $p < 0.01$), NO_3- (r= .952, $p < 0.01$). EC is strongly significant to BOD r= .820, $p < 0.01$). It indicates the discharge, dumped, and accumulation of wastes on lakeshores (Uddin et al., 2023; Islam et al., 2021; Zokm et al., 2018; Kazi et al., 2009; Hashan & Moniruzzaman, 2022; El-Serehy et al.,2018). Factor-2 (25% of the total contribution) is characterized by Total Alkalinity (34.83%), EC (34.75%), Transparency (30.08%), and pH (28.23%) which is supported by both PC1 (47.94% of the total variance) and PC2. It was seen that pH is significant to transparency (r= 910, $p < 0.01$). TDS is significant to EC (r= .992, $p < 0.01$). Factor -2 is the intrusion of salts from soil, waste water, and other human activities (Hashan & Moniruzzaman, 2022; Nion et al., 2020; Liu et al., 2012; Rahman et al., 2021).

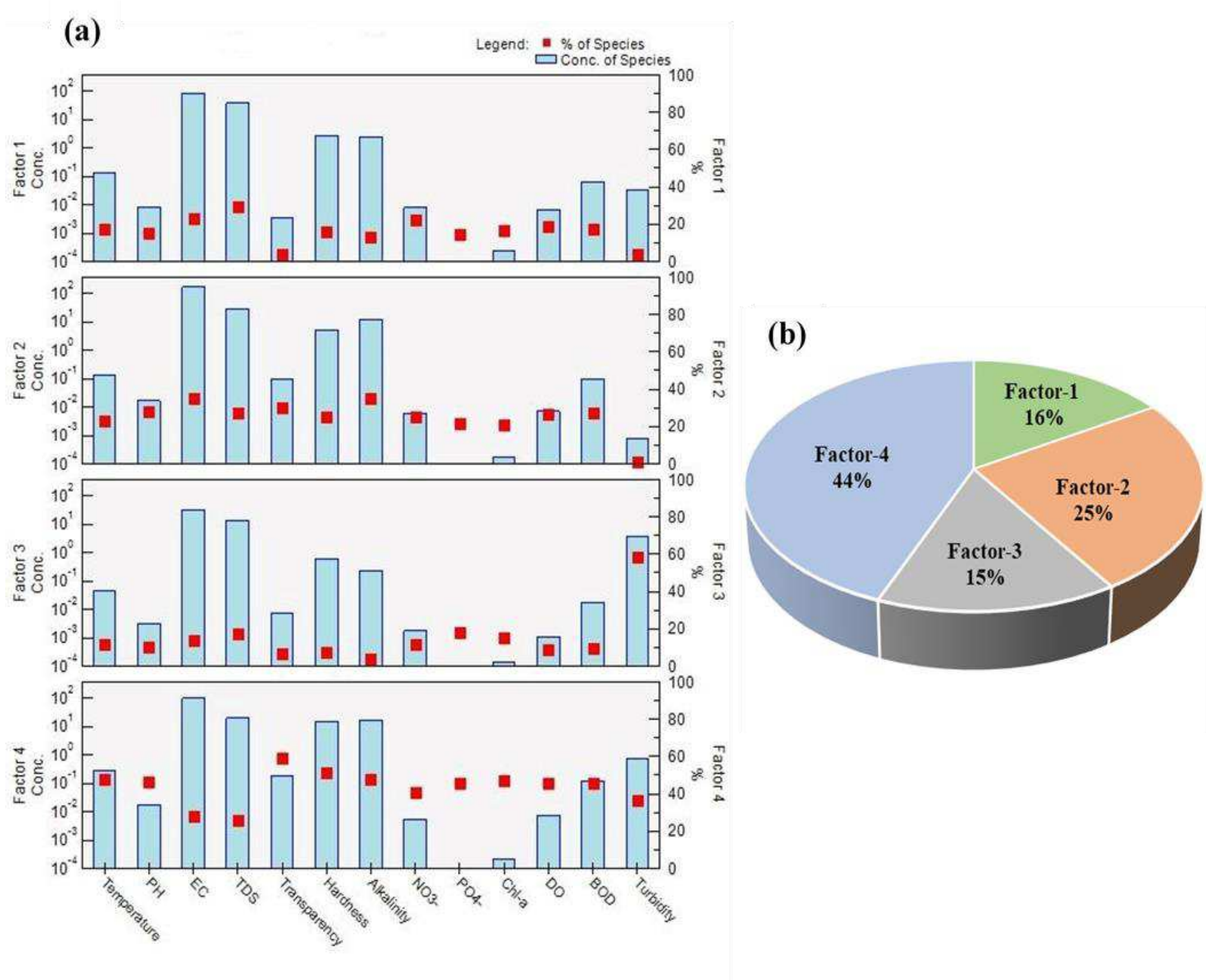


Fig. 10 Positive matrix factorization (PMF) model result; (a) Source apportioning contributions of factors to each parameters and (b) Total contributions of factors to the analyzed parameters in Gulshan Lake

Factor-3 (15% of the total contribution) consists of Turbidity (58.44%), PO_4- (17.93%), and TDS (17.61%) which is similar to PC3 (responsible for 14.37% of the total variance) where PO_4- is negatively significant to DO (r=.623, p <0.01). Factor 3 is the representative of erosion and runoff from the surrounding area (Hashan & Moniruzzaman, 2022; Dodds, 200; Liu et al., 2012). Factor-4 is characterized by Transparency (59.24%), Total Hardness (51.28%), Temperature (47.83%), TA (47.75%), Chl-a (47.48%), pH (46.62%), DO (45.86%) and PC4 (responsible for 7.96% of the total variance) and PC1 vouched for that. Chl-a is strongly significant to NO_3- (r= .974, p < 0.01), and Turbidity is significant to pH (r= .926, p < 0.01) and TDS (r= .892, p < 0.01). Factor -4 (44% of the total contribution) denotes the presence of large amounts of phytoplankton that was greatly witnessed in lake water which resulted in the colour formation to be green (Dodds, 2007; Nion et al., 2020; Rahman et al., 2021; Kazi et al., 2009). Visualization in Fingerprint is done in Fig S2 and Factor contributions are noted in Fig. 10 (a, b).

PCA of Banani Lake revealed three factors with eigenvalues >1, explaining a total variance of 92.08%, listed in Table S10. These factors were considered in the EPA PMF 5.0 model, outlined in Table S8. Factor-1 which is responsible for 24% of the total contribution of the sources, is dominated by Turbidity (85.72%), PO_4- (50.7%), TDS (29.12%), Temperature (25.72%), EC (25.47%) which is supported by PC1 (60.25% of the total variance).

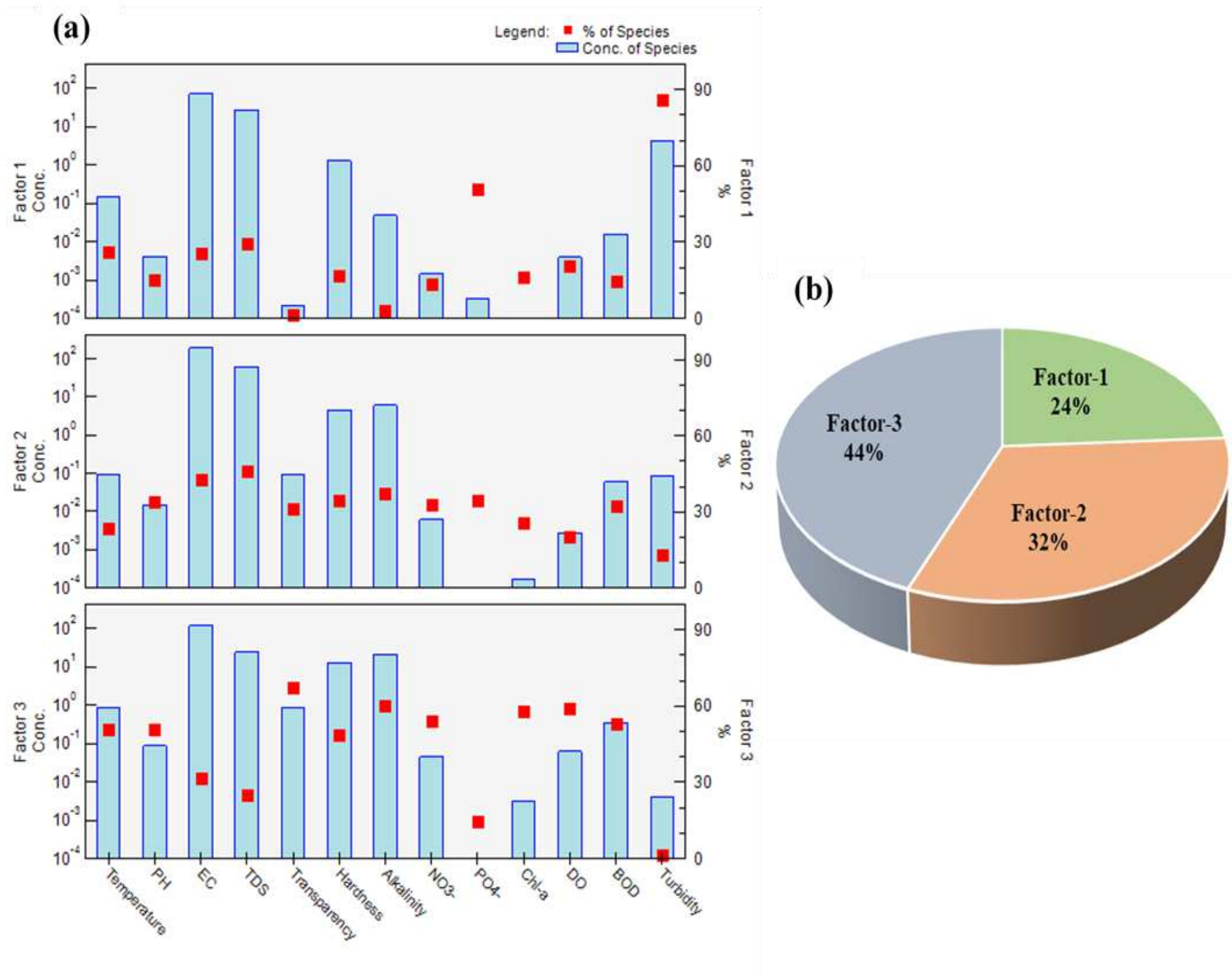


Fig. 11 Positive matrix factorization (PMF) model result; (a) Source apportioning contributions of factors to each parameters and (b) Total contributions of factors to the analyzed parameters in Banani Lake

According to Pearson Correlation Analysis exhibited in Table S11, TDS is strongly significant to EC (r= .997, $p < 0.01$). Factor -1 expresses the erosion and runoff phenomenon resulting in the introduction of suspended particles (Islam et al., 2021; Hashan & Moniruzzaman, 2022; El-Serehy et al.,2018). Factor-2, responsible for 32% of the total contribution, consists of TDS (46%), EC (42.65%), TA (37.09%), PO_4- (34.66%), TH (34.53%), pH (34.13%) which is supported by PC2 (19.03% of the total variance). PO_4- is strongly significant to NO_3- (r= .987, $p < 0.01$), Turbidity is strongly significant to TDS (r= .936, $p < 0.01$) and significant to EC (r= .905, $p < 0.01$). It indicates domestic discard of waste that was prominent in Banani Lake (Uddin et al., 2023; Islam et al., 2021; Zokm et al., 2018; El-Serehy et al.,2018). Factor-3 which has the 44% of the total contribution, houses Transparency (67.66%), TA (60.06%), Chl-a (58.1%), DO (59.22%), NO3- (53.97%), BOD (53.22%), Temperature (50.69%) supported by PC1 and PC3 (12.8% of the total variance). DO is strongly significant to Transparency (r= .996, $p < 0.01$), Chl-a is strongly significant to NO_3- (r= .994, $p < 0.01$), and BOD is strongly significant to Total Hardness (r= .997, $p < 0.01$). Factor-3 is responsible for 44% of the total contribution, expresses the intrusion of nutrients from waste, discharge of waste and wastewater, nursery and rickshaw garages that are built on the lakeshore, etc. (Dodds, 2007; Uddin et al., 2023; Liu et al., 2012; Nion et al., 2020). Fig S3 denotes the Fingerprint of Factors contributing to the pollution of Banani Lake while Factor contributions are in Fig. 11 (a, b).

Conclusion

In addressing growing pollution stresses in urban lakes, the TSI and TLI are valuable for assessing trophic conditions, offering crucial insights into nutrient levels, water quality, and overall urban lake health. Analysis of three lakes revealed severe pollution in Gulshan and Banani lakes compared to Dhanmondi lake. The study reveals a seasonal pattern where the pre-monsoon season prominently triggers rapid eutrophication across all lakes, driven by the influx of accumulated pollutants carried by runoff. Anthropogenic activities further exacerbate this phenomenon, particularly from urban sources, amplifying nutrient loads. In contrast, the monsoon and post-monsoon seasons witness a temporary alleviation of eutrophication, attributed to heavy rainfall diluting pollutants and enhancing water flow within lakes, thus exhibiting comparatively lower eutrophication levels than the pre-monsoon period. Despite variations in pollution levels, all three lakes consistently exhibited hypertrophic conditions based on TSI and TLI, indicating high nutrient concentrations. However, TLI being modified furthermore, the results of that are considered to be more accurate. The lakes experienced notable changes, including increased nitrate and phosphate levels with reduced transparency. Persistent inputs of nutrients and organic matter from diverse sources, combined with hydrological changes and rapid, unregulated urban development, contribute to ongoing water quality degradation and eutrophication in these lakes, emphasizing the urgency of targeted interventions for sustainable lake management. To address these challenges, reducing nutrient inputs is crucial and can be achieved by regulating agricultural runoff, limiting fertilizer use, and improving waste management to prevent untreated sewage and industrial discharge into the lakes. Establishing vegetative buffer zones around lakes can help filter pollutants before they reach the water. Additionally, promoting green infrastructure, such as rain gardens and permeable pavements, can more effectively manage stormwater runoff. Regular water quality monitoring allows for early detection of eutrophication and timely interventions, while public awareness campaigns are essential to educate communities on sustainable practices. These measures collectively support the sustainable management of urban lakes, preserving their ecological balance and ensuring their long-term health. So, the research contributes to the broader understanding of environmental challenges in rapidly growing urban areas and serves as a foundation for future studies and management interventions aimed at improving the trophic status of urban lakes in Dhaka City and similar settings worldwide.

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Data Availability

Data will be made available on reasonable request.

Declarations

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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