

Evaluation of Water Quality and Eutrophication Status of Lugo Lake in Northeastern Ethiopia, 2026

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Abstract

Background

Freshwater Lake eutrophication is one of the most widespread problems in the world. Freshwater lakes are threatened especially by anthropogenic activities. Nutrients from different sources enter lakes via untreated human wastes disposal and agricultural wastes containing usable forms of phosphorous and nitrogen which are critical for the growth of phytoplankton and other algae. This study undertook an integrated assessment of trophic status, nutrient enrichment, chlorophyll-a, and comprehensive pollution index. This study aimed to determine the water quality status and trophic state of Lugo Lake in northeastern Ethiopia.

Methods

A cross-sectional study was conducted to determine the status of nutrient enrichment, algal biomass and assess associated anthropogenic factors affecting Lugo Lake from February to May 2026. Physicochemical parameters and chlorophyll-a were analyzed using APHA standards. The trophic status of Lugo Lake was determined using Carlson's Trophic State Index (TSI). The comprehensive pollution index (CPI) was applied to assess the overall pollution status. Statistical analyses included descriptive statistics.

Results

The mean concentration of total phosphorus (0.41 mg/L), total nitrogen (0.30 mg/L) and chlorophyll a (30 µg/L) was indicated the presence of significant nutrient enrichment. The calculated TSI values were 85.02 (TSI-TP), 57.85 (TSI-SD), and 59.71 (TSI-Chl-a), with a composite TSI (CTSI) of 67.53, indicating the lake is eutrophic. Water temperature, dissolved oxygen, and pH levels were within ranges favorable for algal growth. Spatial variations among sampling sites showed higher pollution levels in areas affected by agriculture and recreational activities.

Conclusion

Lugo Lake was classified as eutrophic and affected by cultural eutrophication. The main factors causing eutrophication and algal blooms in Lugo Lake are phosphorus and nitrogen enrichment, which are caused by anthropogenic activities. Without appropriate management measures, the lake may shift toward a hypertrophic condition. Appropriate soil and water conservation measures, regulation of intensive agricultural activities, vegetation are recommended to reduce nutrient loading into the lake

1. Introduction

Freshwater lakes are one of the crucial natural resources essential ecosystem services to human and other organisms residing in as well as around them. Provisioning, supporting, regulating and cultural services are main themes for the numerous utilities of lake ecosystems that have ecological and economic significance [1]. Lake water provides multiple benefits, including food, water supply, irrigation, and other resources essential for communities living around the catchment area [2]. They harbor diverse biota, provide recreational services and have been used as ritual places for religious as well as cultural practices [3]. Despite their vast utilities, lakes have been threatened especially by activities of anthropogenic origin [4]. Pollutants enter into lakes via untreated human wastes disposal and agricultural wastes containing usable forms of phosphorous and nitrogen which are critical for the growth of phytoplankton, other algae and macrophytes of lakes' shoreline. These nutrients, phytoplankton and algae cause eutrophication of lakes [5, 6].

Pollution of lakes are occur as consequence of industrialization, rapid urbanization and use of chemical fertilizers. These pollutants lead to water quality degradation and loss of aquatic biodiversity. On the other hand, overexploitation of lake's water for the purpose of drinking, crop irrigation and industries caused not only decrease in water level of lakes but also massive accumulation of pollutants [7].

Eutrophication reduces water quality and decreases the ecological carrying capacity of lakes. These lead to a decline of its ecosystem services including drinking water supply, fish and other recreational activities. This also indicated that eutrophic conditions were responsible for decline in multiple uses of lentic systems. On the other hand, human activities often manipulate lakeshores where dynamic physical processes occur, and high diversity of species and productivity exist. These disturbances of littoral zone of lakes cause habitat loss and fragmentation for species inhabiting there in all or part of their life cycles such as invertebrates, fishes, birds and various plant species [8, 9].

Today, eutrophication of lakes became rampant throughout the globe mainly as a result of multitude of anthropogenic activities. Many lakes in the United States of America experienced eutrophic condition including Washington Lake and City Park Lake [10–12]. Due to anthropogenic activities lake eutrophication is also occur in many European lakes such as Pamvotis lake of Greece [13], Lugano lake found between Italy and Switzerland [14], Danish lakes [15] and Lake Balaton the largest lake in Central Europe [16]. The eutrophic condition of these lakes was mainly

attributed by population increase especially through immigration, domestic waste discharges from human settlements around the lakes and agricultural activities practiced within the catchment area of the lakes [17, 18]. In addition, many lakes in China were doomed by eutrophication and Lake Dianchi was among the most hypertrophic lakes of the world [19, 20] and Lake Taihu was a eutrophic status [21].

The various research findings indicated that a number of African lakes developed eutrophic condition [22]. The study indicated that Chivero Lake in Zimbabwe was hypertrophic attributed to discharge of sewage effluent [23, 24]. In a separate study conducted in Western Uganda, the condition of Crater Lakes varied from mesotrophic to hypertrophic states which were attributed to agricultural expansion and increased human settlement within the catchments, leading to nutrient loading to the lakes [25]. In east Africa, Lake Victoria experienced increased phosphorus levels, phytoplankton biomass, higher primary productivity and major changes in species composition [26, 27].

Similarly, many Ethiopian lakes were affected by cultural eutrophication which resulted decrease in biological diversity, oxygen depletion and disruption of the ecosystem [28–30]. The study indicated that Lake Chamo, Lake Abijata, and Lake Beseka were hypertrophic mainly due to high nutrient loading from surface runoff, animal waste from large populations, agricultural activities, fertilizer application, and urban sewage discharge [31–33]. Additionally, high amounts of total nitrogen (TN) and total phosphorous (TP) were recorded in Ethiopia which placed it in eutrophic like Lake Tana, Lake Ardibo, Lake Awasa and Lake Ziway [34–37].

Lugo Lake is one of the natural lakes of Ethiopia, where it lacks significant inflow from other water bodies and outflow from the lakes[30]. To the best of our knowledge, previous studies on Lugo Lake have mainly focused on zooplankton community structure and ecology, fish production, and macroinvertebrate pollution indicators; however, little is known about the lake's surface water quality and trophic state as determined by chlorophyll-a concentrations. This limited information may reduce awareness among responsible stakeholders regarding the need for lake protection and conservation. Additionally, this is the first integrated assessment of trophic status, nutrient enrichment, chlorophyll-a, and comprehensive pollution index of Lugo Lake. Therefore, this study aimed to determine the surface water quality status and trophic state of Lugo Lake that might be associated with anthropogenic factors that affect the lake.

2. Methods and Materials

2.1. Study Area

Lugo Lake is one of the highland freshwater lakes of Ethiopia with volcanic origin. It is located in the northeastern highlands of Ethiopia, around a distance of 430 km from Addis Ababa, in the South Wollo Zone of Amhara Region. Geographically, the study area is located between 11°03'–11°18' N latitude and 39°41'–40°08' E longitude, at an average elevation of 1,911 meters above sea level. The Lake has a closed drainage system and the total watershed area is about 77 km², of which 22.8 km² is occupied by Lugo Lake. The average depth of the Lake is 37 m and the maximum depth is 81 m. The area has average annual rainfall of 1141 mm and its temperature ranges from 18.6°C to 24.4°C [30, 38, 39].

2.2. Study Design and Period

A cross-sectional study was conducted to determine the surface water quality, trophic state, and associated anthropogenic activities affecting Lugo Lake from February to May 2026. The study included both field assessment and laboratory determination of water quality parameters (i.e. physicochemical and Chlorophyll-a) which were pertinent for this particular study.

2.3. Sampling Site Selection

A total of 10 sampling sites were selected based on the different anthropogenic activities practiced around the lake. These include Monastery (agriculture, recreation and religious rituals), human settlement coupled with agricultural practices, recreational lodges and a small town found within the lake catchment. From each selected sampling sites, water samples for physicochemical and biological analyses trophic state variables and Chlorophyll-a analysis were taken in the mid-point between littoral zone and the lake center. In addition, a single sampling site at the center of the lake was also considered. The geographical locations of sampling sites were recorded using GPS (Table 1).

Table 1

Geographical location, site description and anthropogenic activities and land use features of sampling sites in Lugo Lake, Ethiopia 2025.

Site	Description	Geographical Location			Land Use Features & Anthropogenic Activities
		Latitude	Longitude	Altitude (m)	
AS ₁	Agriculture	1251350 N	575060 E	1908	Crop production & livestock rearing; human settlement & buffer zone width < 25m; algae & macrophyte growth; recreational activity; water diversion for irrigation
AS ₂	Agriculture	1252297 N	575403 E	1896	Heavy grazing and presence of roads; crop production & livestock rearing; human settlement & buffer zone width > 100m; recreational activity
AS ₃	Agriculture	1251354 N	575068 E	1905	Crop production & livestock rearing; human settlement & buffer zone width < 25m; algae & macrophyte growth; water diversion for irrigation; recreational activity
AS ₄	Agriculture	1256905 N	575681 E	1896	Crop production & livestock rearing; heavy grazing; human settlement & buffer zone width < 25m; algae & macrophyte growth; water diversion for irrigation; instable Bank, recreational activity
AS ₅	Agriculture	1251750 N	575685 E	1897	Crop production & livestock rearing; human settlement & buffer zone width > 100m
RS ₁	Recreation	1252362 N	575064 E	1902	Commercial lodge and recreational activity; human settlement & buffer zone width < 25m; water diversion for gardening; bank instability; algae & macrophyte growth
RS ₂	Recreation	125178 0 N	575070 E	1897	Commercial lodge and recreational activity; human settlement & buffer zone width < 25m; water diversion for gardening; bank instability; algae & macrophyte growth
RS ₃	Recreation	1251954 N	575265 E	1896	Commercial lodge and recreational activity; human settlement & buffer zone width < 25m; water diversion for gardening; bank instability; algae & macrophyte growth
RS ₄	Recreation	1251853 N	575439 E	1897	Commercial lodge and recreational activity; human settlement & buffer zone width < 25m; water diversion for gardening; bank instability; algae & macrophyte growth
LC	Centre	1252095 N	575609 E	1898	

2.4. Sampling and Analysis Techniques

2.4.1. Water Sampling and Analysis

From each selected sampling site, composite water samples were taken at three different points of the lake for analysis of physicochemical water quality parameters and trophic state variables to get representative values. This was done by inserting clean and rinsed polyethylene sample bottles into approximately 30 cm below of the lake water surface. For the analysis of Total Nitrogen (TN), Total Phosphorous (TP), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) unfiltered water samples were collected using 300 ml polyethylene bottles. In addition, 100 ml filtered water sample was taken using polyethylene bottles to analyze Nitrate-Nitrogen (NO_3^- -N) and Soluble Reactive Phosphorous (SRP) from each sampling site. The samples were filtered using Whatman filter paper with pore size of 0.45 μm . The collected samples were transported under cold-chain conditions to the laboratory of the Department of Limnology Sciences and Technology at Addis Ababa University and analyzed immediately upon arrival. In-situ measurements are recommended for water quality parameters that highly alter their value during sample transit. Accordingly, measurements for Water Temperature (WT), Dissolved Oxygen (DO), Electrical Conductivity (EC) and Hydrogen ion concentration (pH) were conducted in-situ during field sampling using CX-401. The turbidity of the water was measured in-situ using portable turbid meter and the transparency of the lake water expressed as Secchi Depth (SD) was measured using secchi disk. In addition, SRP, TP, NO_3^- -N, TN, BOD and COD were analyzed following the standard methods for water and wastewater analysis recommended by APHA (2012). Eventually, the concentration of each physicochemical water quality parameter was measured using molecular spectra max plus spectrophotometer.

2.4.2. Sampling and Analysis of Chlorophyll-a (*Chl-a*)

The nutrient enrichment and the resulting increase in algal biomass/productivity were determined using Chlorophyll-a (Chl-a) concentration of the phytoplankton. The rapid response of phytoplankton to environmental changes makes chlorophyll-a a useful indicator of eutrophication [40].

To determine the concentration of *Chl-a*, 500 ml of composite water sample was taken from different points of each sampling site within photic zone of the lake using brown bottle. The collected samples were transported in a cold chain to the laboratory of Department of Limnology Addis

Ababa University, Ethiopia and the analysis was commenced immediately upon arrival. To determine the amount of Chl-a, 100 ml of subsample was filtered through GF/F filter from each original water sample. Then, 3 drops of saturated MgCO₃ solution was added. After filtration, the filter was carefully removed from filtration apparatus with forceps and folded in half with plankton side inward. Then the filter was placed inside aluminum foil and crease to make a light-tight packet. After this, the filter was placed in clean, dry, stopper test-tube containing approximately 2 ml of 90% acetone. Using the Teflon-tipped grinder, the sample was slowly grinded until filter is completely broken down. Then 90% acetone was added until total volume in tube is 10 ml and the tube was shaken. After this, the tubes were placed in refrigerator and allow extracting for 3 hours. Subsequently after 3 hours, the tubes were placed in centrifuge for 9 minutes at 2300 revolution per minute (RPM). The absorbance was read at wavelength of 665 and 750 nm against acetone blank. The concentration of *Chl-a* was calculated according to the following formula [41].

$$Chl - a = \frac{13.9 \, (E_{665} - E_{750}) * V_e}{V_s * Z}$$

Where *E*₆₆₅ is extinction at 665 nm, *E*₇₅₀ is extinction at 750nm, *V*_e is volume of extract (in ml), *V*_s is volume of sample filtered (in liters), *Z* path length of the cuvette spectrophotometric cell (in cm).

2.4.3. Evaluation of Comprehensive Pollution Status of Lugo Lake

The comprehensive surface water quality of lakes can be evaluated by Comprehensive Pollution Index (CPI) using selected water quality parameters as follows (Yan et al., 2015).

$$CPI = \frac{1}{n} \sum_{i=1}^n \frac{C_i}{S_i}$$

Where CPI is comprehensive pollution index, *C*_i is the measured concentration of the water quality parameter (mg/L), *S*_i represents the permissible limits of parameter of concern in surface water by Environmental Protection Authority in the particular country. The calculated CPI values were used to classify the pollution status of the lake (Table 2).

Table 2
Calculated CPI values

CPI	Water Quality Level
≤ 0.20	I Cleanness
0.20 to 0.40	II Sub-cleanness
0.41 to 1.00	III Slight Pollution
1.01 to 2.00	IV Moderate Pollution
≥ 2.01	V Severe Pollution

2.4.4. Determination of Trophic Status Indices (TSIs)

The trophic status of Lugo Lake was determined using the popular method introduced by Carlson (1977). Accordingly, the Comprehensive Trophic Status Index (CTSI) was estimated as the average TSI value of the three important trophic state variables i.e. TP (TSI-TP), SD (TSI-SD) and Chl-a (TSI-Chl-a) (Eq. 1 to 4).

TSI-TP = 14.42 ln (TP) + 4.15 Eq. 1

TSI-SD = 60-14.41 ln (SD) Eq. 2

TSI-Chla = 9.81 ln (*Chl-a*) + 30.6 Eq. 3

CTSI = (TSI-SD + TSI-TP + TSI-*Chl-a*)/3 Eq. 4

Where: ln=natural logarithm. From this equation, Carlson's TSI values ranged from Oligotrophic (TSI, < 40), Mesotrophic (TSI, 40–50), Eutrophic (TSI, 50–70) and Hypereutrophic (TSI, > 70) states. For TSI calculation, TP and chlorophyll-a concentrations were converted to µg/L prior to analysis, following Carlson (1977) (Table 3)

Table 3
TSI values and Trophic status

TSI Value	Trophic Status	Attributes
< 40	Oligotrophic	Clearwater, oxygen throughout the year in the hypolimnion, will anoxic during the summer
40–50	Mesotrophic	Water moderately clear but an increased probability of anoxic during the summer, decreased transparency, warm-water fisheries only
50–70	Eutrophic	Dominance of blue green algae, algal scum probable, extensive macrophyte problem
> 70	Hypereutrophic	Heavy algal blooms possible throughout the summer, summer fish kills, few macrophytes

2.5. Data Quality Assurance

All equipment used for measurement and analysis of the various parameters considered were pretested before the actual data collection commenced from the studied lake. Composite samples were taken from each selected sampling site in order to get representative samples. The collected samples were shipped to the lab using cold chain system. In-situ measurements were done for those parameters significantly changes during sample transit. Generally, all the necessary precautions were taken throughout sampling and analysis of data.

2.6. Statistical Analysis

Descriptive statistical analysis was performed to summarize the physicochemical water quality parameters, nutrient concentrations, chlorophyll-a levels, trophic state indices, and comprehensive pollution index values of Lugo Lake. The results were expressed using mean, standard deviation, and range values. Data organization, calculation, and analysis were conducted using STATISTICA version 8.0 and Microsoft Excel 2016. The trophic status of the lake was evaluated using Carlson's Trophic State Index (TSI) based on total phosphorus, chlorophyll-a, and Secchi depth measurements. In addition, the Comprehensive Pollution Index (CPI) was used to assess the overall pollution status of the lake based on selected physicochemical parameters.

3. Result and Discussion

3.1. Nutrients concentrations in Lugo Lake

3.1.1. Soluble Reactive Phosphorous (SRP)

The lowest concentration of soluble reactive phosphorous (SRP) was recorded in RS₁ and AS₂ (0.01 mg/L) while the highest value was registered in AS₂ and RS₄ sampling points (0.15 mg/L) (Table 4). The mean concentration of SRP in Lugo Lake was 0.06 mg/L, which was lower than the value recorded in Arenguade Lake (0.7–2.12 mg/L)[42], Zarivar Lake (0.15 mg/L)[43], Lake Tana (0.326 mg/L)[44] and Anchar Lake (0.41 mg/L)[45]. These might be due to higher anthropogenic activities that wield on these lakes (Table 1). However, the mean value of SRP in present study was higher than the values recorded in Tinishu Abaya [46], Hawasa[47], Ziqualla[48] and Navaishia [49]. The higher concentration of SRP in Lugo Lake might be attributed to various anthropogenic activities that have been practiced in and around its catchment including use fertilizers for crop production, livestock rearing, washing of clothes, recreational lodges, and presence of roads & railway construction which were observed during field assessment (Table 1). Generally, SRP value of 0.01mg/L could support algal growth in lentic systems[50].

3.1.2. Nitrate-nitrogen (NO₃-N)

The present study indicated that the concentration of NO₃-N throughout the sampling sites were almost similar with mean value of 0.143 mg/L (Table 4). This mean value was lower than the value observed in Angereb Reservoir (0.489 mg/L)[51], Anchar Lake (0.574 mg/L)[45] and Lake Tana (0.763 mg/L) [44]. The mean value of NO₃-N determined in Lugo Lake was higher than the values observed in Lake Chamo (0.033 mg/L) [47]and Lake Navaishia (0.012 mg/L) [49]. The increased level of NO₃-N in Lugo Lake might be attributed to extensive agricultural and recreational activities that encircle the catchment area of the lake (Table 1).

Table 4

Mean, standard deviation and range of physicochemical water quality parameters and chlorophyll-a concentration of samples taken from the surface water of Lugo lake, Ethiopia (measurement units are expressed in mg/L except for WT in °C, SD in m, pH no unit, EC in $\mu\text{S}/\text{cm}$, Turb in NTU and Chl-a in $\mu\text{g}/\text{L}$).

AS ₁	WT	SD	PH	DO	EC	Turb	BOD	COD	SRP	NO ₃ -N	TP	TN	Chl-a
	25.40	1.03	5.60	6.67	985	6.94	3.50	11.40	0.03	0.14	0.57	0.47	21
AS ₂	24.30	1.77	7.30	5.20	970	3.20	11.60	20.30	0.15	0.15	0.70	0.36	53
AS ₃	23.10	1.93	8.20	3.34	985	2.82	10.80	18.40	0.06	0.14	0.13	0.21	11
AS ₄	26.40	0.71	8.20	8.00	990	11.85	6.30	13.00	0.02	0.14	0.71	0.35	12
AS ₅	24.30	1.48	7.60	4.34	979	4.10	9.80	18.80	0.03	0.14	0.14	0.20	19
RS ₁	26.00	0.56	5.70	5.20	990	16.50	10.20	19.30	0.01	0.16	0.07	0.34	12
RS ₂	25.30	1.26	8.40	4.93	980	5.21	9.70	12.50	0.01	0.14	0.39	0.22	94
RS ₃	27.30	1.46	9.52	8.30	970	4.19	12.30	19.80	0.11	0.14	0.14	0.30	49
RS ₄	27.30	0.56	7.55	9.54	982	16.36	5.50	17.30	0.15	0.14	1.15	0.35	10
LC ₁	23.60	2.09	6.80	6.26	975	2.52	11.70	15.40	0.03	0.14	0.10	0.21	5.0
SD	1.46	0.56	1.21	1.95	7.27	5.49	2.98	3.30	0.05	0.006	0.36	0.08	28.28
Range	4.20	1.53	3.92	6.20	20	13.98	8.80	8.90	0.14	0.02	1.08	0.27	89.0
Mean	25.3	1.28	7.49	6.18	980.6	7.37	9.14	16.62	0.06	0.143	0.41	0.30	28.60

3.1.3. Total Phosphorous (TP)

Total phosphorous (TP) of water samples taken from the lake were varied between 0.07 and 1.15 mg/L with mean value of 0.41 mg/L. The maximum and minimum values of TP were observed at RS₄ and RS₁, respectively (Table 4). The mean concentration of TP was higher than those of Lake Chamo (0.182 mg/L)[47] and Lake Hawassa (0.034 mg/L) [47]. In addition, TP level of Lugo Lake was slightly higher than the TP level of Angerib Reservoir (0.11 mg/L)[52] and Lake Diahi (0.13 mg/L) in china[53]. The discrepancies might be attributed to variation in intensity of agricultural practices, recreational related activities observed around the watershed of the lakes and natural disturbances like internal phosphorous loading. The mean TP level of Lugo lake (0.41 mg/L) is slightly lower than the TP level in the study conducted in Lake Chamo (1.08–1.47 mg/L)[31] and the concentration recorded in Lake Tana (0.862 mg/L)[44]. The mean TP concentration of Lugo Lake was exactly the same with the maximum level of TP recorded in Lake Navaishia, Kenya that ranged from 0.027-0. 41 $\mu\text{g}/\text{L}$ [49].

Many literature indicated that higher concentration of TP potentially generate algal blooms. A study performed on Boye Pond (a pond found in the periphery of Jimma town, Ethiopia) showed that the concentration of TP was 0.2 mg/L may causes eutrophication of the pond [54]. Similarly in separate study, algae growth accelerated when the concentration of TP is between 0.1 and 0.75 mg/L [55]. According to Illinois water quality standard for TP in lakes should be 0.05 mg/L or lower[56]. However, concentration above 0.03 mg/L could be enough to stimulate algae growth. In addition, based on trophic state classification of Organization for Economic Development and Cooperation, the lower limit of characterizing as eutrophic is 0.035 mg/L[57]. Therefore, the mean concentration of TP recorded in the present study in Lugo Lake (0.41 mg/L) was in a range that could promote algal growth and subsequent algal bloom.

The slightly higher TSI-TP at the shore station was probably associated with the greater exposure of the station to wind blowing and sediment run from the watershed which is very close to shore station results increasing concentrations of TP in turn increase TSI value. Generally, high level of value of TP at both stations owing to due to the possible influx of phosphorous nutrient rich flood water into the lake water from the catchment and contaminated sewage through runoff via rivers, in turn, increasing TSI-TP[46] .

Any change in phosphorus concentration of freshwater ecosystem can also alter its trophic status. According to decline in the inflow of nutrients reduces phosphorus concentration in lakes which in turn reduces phytoplankton biomass[58]. Kleeberg's study finding suggests that phosphorous exerts a direct role in the eutrophication of water bodies. [59]. According to Bergmen, he observed a pronounced decrease in Secchi's depth transparency with the increase in phosphorus and chlorophyll-a concentrations. [60].

Phosphorus is one of the essential nutrients for plant growth. High phosphorus concentrations, however, can cause dense algal populations (blooms) and, therefore, can be a major cause of increased lake productivity, referred to as eutrophication. When phosphorus concentrations

exceed about 0.025 mg/L at the time of spring overturn in lakes and reservoirs, these water bodies may occasionally experience excess or nuisance growth of algae or other aquatic plants. Phosphorus is often the nutrient in shortest supply, therefore, limiting or controlling plant growth. In water, dissolved orthophosphate is that part of total phosphorus that is most readily available for use by algae [61].

3.1.4. Total Nitrogen (TN)

The present study conducted in Lugo Lake revealed that the concentration of total nitrogen (TN) value was ranged from 0.20 to 0.47 mg/L with mean value of 0.30 mg/L. The lowest and highest concentration of TN was measured at AS₅ (0.20 mg/L) and AS₁ (0.47 mg/L), respectively (Table 4). The mean value of TN observed in this study was lower than the values recorded in Daihai Lake (2.72 mg/l)[53], Bhindawas Lake (5.03 mg/L) [62], Lake Chamo (3.12–5.35 mg/L)[31] and Angereb reservoir (0.805 mg/L) [52]. However, the mean TN value of this study was higher than Asejire and Eleyele lakes of Nigeria[63] (Table 5). The main reason behind the discrepancies might be attributed to the variation in level of anthropogenic disturbance, geographical and environmental conditions prevailed in catchment area of the lakes. Generally, in many regions of the world nitrogen, can also lead to eutrophication. So the mean concentration of TN in the present study is sufficient to support growth and development of algae [55].

3.1.5. Chlorophyll-a (Chl-a)

The concentration of Chl-a in Lugo Lake ranged from 5 to 94 µg/L which were recorded at LC₁ and RS₂ (Table 4). The mean concentration of Chl-a in this study was 28.60 µg/L which was slightly lower than the concentration registered in Lake Chamo (31.2 µg/L)[47], Bishoftu Lake 60 mg/L [64] and Lake Tana in Ethiopia (38 µg/L) [44] (Table 4). According to the study conducted in Nigeria, Asejire and Eleyele Lakes had higher concentration of Chl-a as compared with the concentration found in Lugo Lake [63]. However, the mean concentration of Chl-a recorded in this study was almost similar with the concentration measured in Tinishu Abaya Lake[46] and Bhindawas Lake [62]. In the contrary, the mean Chl-a value of Lugo Lake was higher than the values registered in Dendi [48], Koka Lake [47] and Bera Lake[65](Table 5).

Table 5
Comparison of Chl-a concentration of Lugo Lake with other lakes.

Lake	Chl-a (µg/L)	Reference
Tinishu Abaya	28.75	Enawgaw & Lemma, 2018
Daihai	29.10	Hou et al., 2013
Angereb	4.20	Mengesha et al., 2013
Dendi	0.10	Degefu et al., 2014
Van	0.85	Ozguven & Yetis, 2020
Asejire	3.41	Ayoade et al., 2019
Eleyele	323.4	Ayoade et al., 2019
Bhindawas	28.07	Saluja & Garg, 2017
Bera	5.72	Sharip et al., 2019
Hawasa	10.43–25.21	Tilahun and Gunnel, 2010
Chamo	31.20	Tilahun and Gunnel, 2010
Tana	38.00	Tibebe et al., 2019
Navaishia	40–210	Ndungu et al., 2013
Bishoftu	60.00	Gebremariam & Taylor, 1997
Hora	29.00	Gebremariam & Taylor, 1997
Koka	16.00	Tilahun and Gunnel, 2010
Lugo	28.60	Present Study

3.1.6. Trophic state of Lugo Lake based on Carlson Trophic Index (Carlson, 1977)

According to Carlson (1977), the major parameters which are crucial for determining trophic state of lentic systems include TP,SD and Chl-a that enable to calculate Carlson Trophic Index (TSI). Based on TSI, the trophic state of lakes can be categorized in to oligotrophic, mesotrophic, eutrophic and hypertrophic (Carlson, 1977)[66]. In relation with TP, the TSI (TSI-TP) value of sites varied between 65.41 and 105.78 with mean value of 85.02 where the lowest and highest values were recorded in RS₁ and RS₄, respectively (Table 6). Accordingly, all sites were classified

under category of eutrophic state except RS_1 (Carlson, 1977) [66]. The mean value of TSI-TP found in the present study was higher than the value of Dendi, Wonchi and Ziqualla rift valley lakes of Ethiopia [48]. Similarly, TSI-TP of Lugo Lake was higher than Asejire and Eleyele lakes of Nigeria [63]. In the contrary, the mean TSI-TP value of this study was lower as compared with Lake Tana (88.405) of Ethiopia[44] and Simbi Lake (118.56) of Kenya [67].

With respect to SD, TSI (TSI-SD) value of sites ranged from 49.40 to 68.33 with mean value of 57.85 where the lowest and highest values were shown in LC_1 and RS_1 , respectively (Table 6). These values revealed that almost all sites considered in the present study fall under eutrophic condition (TSI-SD: 50–70)[66]. The mean TSI-SD value determined in this study was higher than the mean value recorded in Dendi, Wonchi and Ziqualla lakes of Ethiopia [48]. However, this mean value was lower than mean TSI-SD values of Asejire[63], Daihai [53]and Tinishu Abaya lakes [46] (Table 6).

Based on Chl-a concentration recorded in Lugo Lake, TSI (TSI- Chl-a) value varied from 46.39 to 75.17 with mean value of 59.71. The lowest and highest values were registered in LC_1 and RS_2 , respectively (Table 6). This mean value of TSI-Chl-a was lower as compared with Asejire (87.6) & Eleyele Lake (87.5)[63] and Simbi Lake (74.86) [67]. However, the mean TSI-Chl-a value of this study was higher than Daihai lake of China[53] and other rift valley lakes of Ethiopia[48](Table 6).

The overall Carlson Trophic State Index (CTSI) of Lugo Lake was 67.53 which put the lake under eutrophic category [66]. The CTSI value of this study was lower than the values estimated in Tinishu Abaya (74.02)[46], Asejire (80.90) [63]and Simbi (87.01) lakes [67] as reported which placed the lakes under hypertrophic state. However, the CTSI value of the present study was found to be much higher than rift valley lakes of Ethiopia as reported[48].

Human beings influence lake ecosystems increasing the concentration of plant nutrients, primarily phosphorus. The nutrients may enter into lakes as agricultural runoff, sewage or wastewater and also by cattle ranching. This causes over-enrichment of nutrients in the water bodies leading to the algal blooms. The decaying process of dead algal biomass may also result in the depletion of dissolved oxygen in the lakes causing anoxic environment [68].

Table 6
Trophic state of each sampling sites of Lugo Lake using Carlson Trophic Index (Carlson, 1977) and its comparison with other tropical lakes.

Lake		TSI-TP	TSI-SD	TSI-Chl-a	CTSI	Trophic State (Carlson, 1977)	References
Lugo	AS ₁	95.65	59.61	60.47	67.53	Eutrophic	Present Study
	AS ₂	98.62	51.81	69.55			
	AS ₃	74.34	50.54	54.12			
	AS ₄	98.82	64.99	54.98			
	AS ₅	75.41	54.30	59.48			
	RS ₁	65.41	68.33	54.98			
	RS ₂	90.18	56.72	75.17			
	RS ₃	75.41	54.52	68.78			
	RS ₄	105.78	68.24	53.19			
	LC ₁	70.56	49.40	46.39			
	Mean	85.02	57.85	59.71			
Zrivar		82.03	60.91	59.11	67.35	Eutrophic	Nezhad et al., 2014
Tana		88.405	58.23	62.66	69.77	Eutrophic	Tibebe et al., 2019
Tinishu Abaya		74.95	85.11	62.01	74.02	Hypereutrophic	Enawgaw & Lemma, 2018
Daihai		67.82	71.35	36.14	58.43	Eutrophic	Hou et al., 2013
Dendi		31.56	24.19	11.31	22.37	Oligotrophic	Degefu et al., 2014
Wonchi		34.75	36.81	41.95	37.84	Oligotrophic	Degefu et al., 2014
Ziqualla		48.46	50.01	38.20	45.56	Oligotrophic	Degefu et al., 2014
Simbi		118.56	67.60	74.86	87.01	Hypereutrophic	Opiyo et al., 2019
Asejire		76.2	76.21	87.6	80.9	Hypereutrophic	Ayoade et al., 2019
Eleyele		67.3	63	87.5	72.6	Hypereutrophic	Ayoade et al., 2019
Van		106.23	45.14	23.58	58.31	Eutrophic	Ozguven & Yetis, 2020

As indicated in Fig. 2, even though TSI values based on all trophic state variables showed as the lake was fall beyond borderline for eutrophic state, TSI-TP was significantly ($p < 0.05$) higher than mean TSI-SD and TSI-Chl-a values based Kruskal-Wallis (Tukey HSD) test. Despite CTSI value placed Lugo Lake under eutrophic category, it was fall under hypereutrophic based on mean TSI-TP value.

3.1.7. Evaluation of Lugo lake water quality using comprehensive pollution index (CPI)

Comprehensive pollution index (CPI) measures the cumulative pollution status of lakes using multiple water quality parameters [69]. CPI relates the amount of pollutants registered during investigation with their permissible standards in surface water. In the present study, six main water quality parameters considered to determine the CPI of Lugo Lake (Table 7). The pollution index of Lugo Lake based $\text{NO}_3\text{-N}$ ($P_{\text{NO}_3\text{-N}}$) ranged from 0.023 to 0.027 with the man value of 0.024. Based on SRP, the pollution index (P_{SRP}) of the lake varied from 0.03 to 0.50 with mean P_{SRP} value of 0.20. The pollution index of Lugo Lake based DO (P_{DO}) ranged from 0.56 to 1.59 with a mean value of 1.03. The lowest and highest value of P_{DO} was displayed at AS₃ and RS₄, respectively. Based on the concentration of BOD, pollution index (P_{BOD}) in this study ranged from 0.70 to 2.46 which were obtained at AS₁ and RS₃, respectively with mean P_{BOD} value of 1.83. Similarly, the mean pollution index based on turbidity ($T_{\text{turbidity}}$) and COD (P_{COD}) were 1.47 and 1.66, respectively (Table 7). Cumulatively, the CPI value of Lugo Lake based on the aforementioned six principal water quality parameters was 1.04 which indicates as the lake experienced moderate pollution as result of multiple anthropogenic activities that influence it.

Table 7. CPI values of Lugo Lake Ethiopia

Site	P _{NO3-N}	P _{SRP}	P _{DO}	P _{Turbidity}	P _{BOD}	P _{COD}	CPI
AS ₁	0.023	0.10	1.11	1.39	0.70	1.14	1.04
AS ₂	0.025	0.50	0.87	0.64	2.32	2.03	
AS ₃	0.023	0.20	0.56	0.56	2.16	1.84	
AS ₄	0.023	0.07	1.33	2.37	1.26	1.30	
AS ₅	0.023	0.10	0.72	0.82	1.96	1.88	
RS ₁	0.027	0.03	0.87	3.30	2.04	1.93	
RS ₂	0.023	0.03	0.82	1.04	1.94	1.25	
RS ₃	0.023	0.37	1.38	0.84	2.46	1.98	
RS ₄	0.023	0.50	1.59	3.27	1.10	1.73	
LC ₁	0.023	0.10	1.04	0.50	2.34	1.54	
Mean	0.024	0.20	1.03	1.47	1.83	1.66	

3.2. Assessment of Water Quality Parameters of Lugo Lake

3.2.1. Water Temperature (WT)

According to this study, the surface water temperature (WT) of sampling sites ranged from 23.10 to 27.30°C, where the highest and lowest values were recorded at the recreational sites (RS3 and RS4) and agricultural site (AS₃), respectively (Table 4).

The mean value of WT in Lugo Lake was 25.30, which is higher than Lake Tana [44], Lake Ziway [47], Lake Hawassa [47], in Ethiopia and Lake Navaishia (22.4) in Kenya[49]. On the other hand, the surface WT of Lugo Lake was lower than the surface water temperature recorded in Asejire (26.4°C) and Eleyele(27.1°C) lakes of Nigeria[63], Bera Lake (29.1°C) of Malaysia[65] (Table 8).The variation in WT among lakes may be associated with differences in atmospheric temperature, seasonal conditions, sampling time, and water characteristics.

3.2.2. pH

The hydrogen ion concentration (pH) value of the lake varied from 5.60 to 9.52, where the lowest and highest values were recorded at AS₁ and RS₃ respectively (Table 4). The mean value of pH of water samples was found to be 7.49, which was lower than the mean pH value of Hawassa Lake (8.66) [47], Lake Tana (7.90)[44], and Lake Navaishia (8.51)[49] ,Tinishu Abaya Lake (8.5) [46], Asejire Lake (8.5) [63] and Lake Daihai (8.45) [53]. Higher pH values may be associated with increased photosynthetic activity and CO₂ uptake by algae [70]. However, the mean pH value of Lugo Lake was higher than the value recorded in Bera Lake (5.4)[65]. The elevated pH values observed in some sampling sites may enhance phosphorus release from sediments, potentially promoting further phytoplankton growth [71].

3.2.3. Secchi Depth (SD)

Secchi depth (SD) measures light transparency of water and it is usually used to evaluate water clarity of lentic systems including lakes. In these systems, the transparency of water mainly depends on quantities of suspended particles and phytoplankton density in the water column [72]. In the present study, the highest transparency was registered at LC₁ (2.09 m) i.e. the center of the lake and lower transparency was recorded at RS₁ and RS₄ sampling sites (Table 4). The spatial differences of SD among sampling sites could be due to variations in depth as deeper stations might record high SD as compared with shallow ones [48], because shallow lakes may experience greater sediment disturbance. The mean SD value of this study (1.28 m) was higher than the mean value recorded in Tinishu Abaya Lake (0.18 m)[46], Asejire Lake (0.33 m) [63]and Lake Tana (0.865 m)[44](Table 8). The higher value of SD in Lugo Lake might be attributed to its lower phytoplankton biomass expressed as Chl-a, and suspended particles measured as turbidity than the aforementioned lakes (Table 4). However, this mean SD value of Lugo Lake was far lower than Dendi and Wonchi rift valley lakes of Ethiopia[48].

The temporal variations in SD could mainly be attributed to the seasonal variations in the amounts of precipitation received within that region whereby the rainy season is characterized by high run off from the surface and increased flooding brought by the high discharge. These inflows are characterized by enormous quantities of suspended particles when deposited in the water, decrease transparency [73].

3.2.4. Electrical Conductivity (EC)

The conductivity of water (EC) measures the capacity of water to conduct electric current and its amount depends on the concentration of ions and nutrients. In addition, it serves as a surrogate measure of total dissolved solids in water[74]. The measurement of EC in Lugo Lake ranged from 970 $\mu\text{S}/\text{cm}$ to 990 $\mu\text{S}/\text{cm}$ which were recorded at multiple sampling sites (Table 4). The mean value of EC in this study (980 $\mu\text{S}/\text{cm}$) was higher than Lake Tana[44], Tinishu Abaya[46], Anchar Lake[45] and other tropical lakes (Table 8). In the contrary, the mean value was far lower than the mean EC value recorded in Lake Chamo [47] and Daihai Lake [53] as the measurements indicated in (Table 8).

A mean of 980 $\mu\text{S}/\text{cm}$ registered in this study is favorable to aquatic organisms since an EC value of 250 $\mu\text{S}/\text{cm}$ is recognized as conducive for supporting life in freshwater ecosystems. However, higher value of EC decreases species diversity of aquatic life forms. On the other hand, the EC values recorded in all sampling sites were below WHO guideline recommended for drinking water (1500 $\mu\text{S}/\text{cm}$)[69].

3.2.5.. Dissolved Oxygen (DO)

The concentration of DO in Lugo Lake ranged from 3.34 to 9.54 mg/L that were recorded in AS₃ and RS₄, respectively (Table 4). The mean concentration of DO in this study was 6.18 mg/L, which was almost congruent with the concentration of DO recorded in Hawassa and Chamo Lakes [47], Lake Navaishia [49] and Lake Tana [44]. However, the concentration of DO recorded in this study was higher as compared with Daihai Lake (4.01 mg/L)[53], Bera Lake (4.7 mg/L) [65] and Anchar Lake (5.50 mg/L)[45]. In the contrary, the mean DO concentration measured in Zarivar (7.29 mg/L)[75], Eleyele (7.1 mg/L)[63] and Tinishu Abaya (8.49 mg/L) [46] lakes were higher than the concentration registered in the present study (6.18 mg/L) Table 8).

The mean concentration of DO in this study was within the standard range for DO value set by EU and WHO, between 5.0 and 9.0 mg/L[76]. Many literatures indicate a minimum of 5 mg/L DO is required for most aquatic lives [76]. Therefore DO level in the Lugo Lake is suitable for aquatic lives.

3.2.6. Turbidity

The turbidity of samples taken from surface water of Lugo Lake ranged from 2.52 to 16.50 NTU which was recorded at LC₁ and RS₁, respectively (Table 4). The mean value of turbidity in Lugo Lake (7.37 NTU) was higher than Zarivar Lake (1.62 NTU)[75]. However, the mean value of the lake was lower than Bera Lake[65]. Angereb reservoir [52] and Tinishu Abaya Lake [46]. This variation in turbidity between lakes might have resulted from the divergences in anthropogenic activities of catchment area, the presence/absence of buffer zone, the presence/absence of riparian vegetation in the lakes' buffer zone and differences in phytoplankton biomass in the lakes [77].

The World Health Organization (WHO) suggests that water used for drinking turbidity should be less than 5 NTU. Although lower values of turbidity were recorded in different sampling sites, the mean value of turbidity in Lugo Lake was higher than the permissible level recommended by WHO[78]. Thus the mean turbidity of Lugo Lake was 7.37 NTU which was indicated there was pollution of the lakes by scattered or suspended algae and other pollutants. This higher turbidity could be the result of rainfall which brought sediment-laden waters from the surface runoff via rivers Bobodo and Dacha, and because of surface run-off water with soil, domestic waste, cattle washing, and bathing activity.

3.2.7. Biochemical Oxygen Demand (BOD)

Biochemical oxygen demand (BOD) indicates the amount of oxygen needed to degrade the organic matter found in water[79]. In the present study, the concentration of BOD varied from 3.50 to 12.30 mg/L where the lowest and highest values were measured at AS₁ and RS₃, respectively (Table 4). The mean value of BOD measured in Lugo Lake was 9.14 mg/L. This value was higher than the values recorded Bhindawas (2.59 mg/L) [62], Zarivar (6 mg/L)[75] and Bera (6.41 mg/L) Lakes [65]. Higher BOD value might be associated with the presence of commercial lodges, recreational boats, human settlement and other agricultural activities observed in the study area (Table 1). This mean value of BOD obtained in Lugo Lake was higher than the recommended level/standard of BOD for surface water quality [79].

3.2.8. Chemical Oxygen Demand (COD)

The chemical oxygen demand (COD) value of samples taken from surface water of Lugo Lake ranged between 11.40–20.30 mg/L which were recorded at AS₁ and AS₂, respectively (Table 4). Although all values registered at different sampling points were greater than the recommended level for surface water, the mean COD value recorded in the present study (16.62 mg/L) was lower than the values obtained in Dahai Lake[53], Bera Lake[65] and Zarivar Lake [75].

Table 8

Comparison of physicochemical water quality measurements of Lugo Lake with other lakes (the units of measurement are similar with the units expressed in Table 4 above).

Lakes	SD	DO	WT	pH	Turb	EC	SRP	TP	NO ₃ -N	TN	BOD	COD	Reference
Tinishu Abaya	0.18	8.79	23.16	8.5	123.46	402.53	0.039	0.178	0.12				Enawgaw & Lemma, 2018
Daihai	0.72	4.01	23.1	8.45		9140		0.13	0.121	2.72		18.61	Hou et al., 2013
Angereb		6.654	22.57	8.4	18.55			0.11	0.489	0.805			Mengesha et al., 2013
Dendi	12.0		14.9–16.7	8.27		120	0.0029	0.0067	0.018				Degefu et al., 2014
Wonchi	5.0		14.9–16.7	8.1		201	0.0034	0.0084	0.001				Degefu et al., 2014
Ziqualla	1.0		8.8	7.91		78	0.0157	0.0216	0.015				Degefu et al., 2014
Anchar	0.5	5.5		7.9		374	0.402	0.708	0.574				Tahseen et al., 2018
Van	2.88	5.545	24.38	9.49		22.04		2.6		14.4	56	122.5	Ozguven & Yetis, 2020
Asejire	0.33	6.8	26.4	8.5				0.253		0.101			Ayoade et al., 2019
Eleyele	0.9	7.1	27.1	7.5				0.0717		0.04548			Ayoade et al., 2019
Bhindawas		4.19–8.55	13–34.6	6.82–9.65					0.65	5.03	2.59	8–144	Saluja & Garg, 2017
Bera	1.2	4.7	29.1	5.4	15.6	48.7		0.03			6.41	23	Sharip et al., 2019
Zarivar	1.263	7.293	19.29	7.94	1.623	357.7	0.15	0.47			6	37.4	Sharifinia et al., 2013
Hawasa		5 to 7	23.5	8.66		846	0.015	0.034	0.025				Tilahun and Gunnel, 2010
Chamo		5 to 9	26.3	8.84		1910	118	0.182	0.033				Tilahun and Gunnel, 2010
Tana	0.865	5.8	22	7.9		148.5	0.326	0.862	0.763				Tibebe et al., 2019
Navaishia		5.89	22.4	8.51		290	0.003	0.027 to 0.41	0.012				Ndungu et al., 2013
Lugo	1.28	6.18	25.3	7.49	7.37	980.6	0.06	0.41	0.143	0.3	9.14	16.62	Present Study

4. Limitation

This study has some limitations. First, sampling was conducted only between February and May 2026 and may not represent seasonal variations in water quality and trophic conditions throughout the year. Second, the cross-sectional nature of the study limits the ability to evaluate long-term temporal trends in eutrophication. Third, the study focused mainly on physicochemical and chlorophyll-a parameters and did not include detailed

biological assessments such as phytoplankton community composition. Therefore, future studies should incorporate multi-season monitoring and broader ecological assessments.

5. Conclusion and Recommendation

The findings of this study, Lugo Lake is eutrophic, although continued nutrient enrichment may increase the risk of hypertrophic conditions if mitigation measures are not implemented. The increasing concentrations of total phosphorus and chlorophyll-a suggest that nutrient enrichment is a major contributing factor to cultural eutrophication in the lake. The recorded water temperature, dissolved oxygen, and pH values were within ranges favorable for aquatic organisms and algal growth.

In this study, Carlson's trophic state index (TSI) was applied, and the results showed that the TSI values for Chl-a, TP, and SD indicated eutrophic conditions. The findings further suggest that the lake is under increasing pressure from cultural eutrophication and requires protection from anthropogenic disturbances to prevent further degradation. Agricultural runoff, shoreline disturbance, recreational activities, and increasing human population pressure may contribute to water quality deterioration.

To minimize further degradation, nutrient reduction efforts should focus on integrated watershed management and improved land-use practices. Managing agricultural runoff, regulating waste disposal, and establishing vegetated buffer zones around the lake may help reduce external nutrient loading and sediment input. In addition, the development of wastewater treatment systems for nearby settlements and recreational facilities could help improve water quality. Future studies should focus on advanced approaches, including sensor technologies, nutrient modeling, and restoration strategies, to improve understanding and management of eutrophication processes in the lake.

Overall, Lugo Lake is experiencing cultural eutrophication, which may potentially threaten its ecological integrity and ecosystem services if timely management interventions are not implemented.

Declarations

Funding Declaration

This research received no external funding from public, commercial, or not-for-profit organizations.

Ethical consideration

Ethical clearance was obtained from Wollo University College of Medicine and Health Sciences ethical Review Committee and reviewed and approved the study proposal. All methods were used in compliance with the appropriate guidelines and regulations. An official letter of cooperation was submitted to Tehuledere districts office before data collection.

Declaration of competing interest

We declare that there are no any competing financial interests or personal relationships that would have appeared to influence the work reported in this paper.

Author Contribution

A.M.E,A.G,A.B.A,T.S.J,M.M: Concepts, design, definition of intellectual content, literature search, data acquisition, data analysis, statistical analysis, manuscript preparation, manuscript editing and manuscript review; A.E.B,T.A,L.B.A,Y.M,K.A: Concepts, design, definition of intellectual content, literature search, data acquisition, data analysis and statistical analysis, manuscript editing and manuscript review. All authors approved the final version of the manuscript for publication.

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Data availability

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Figures

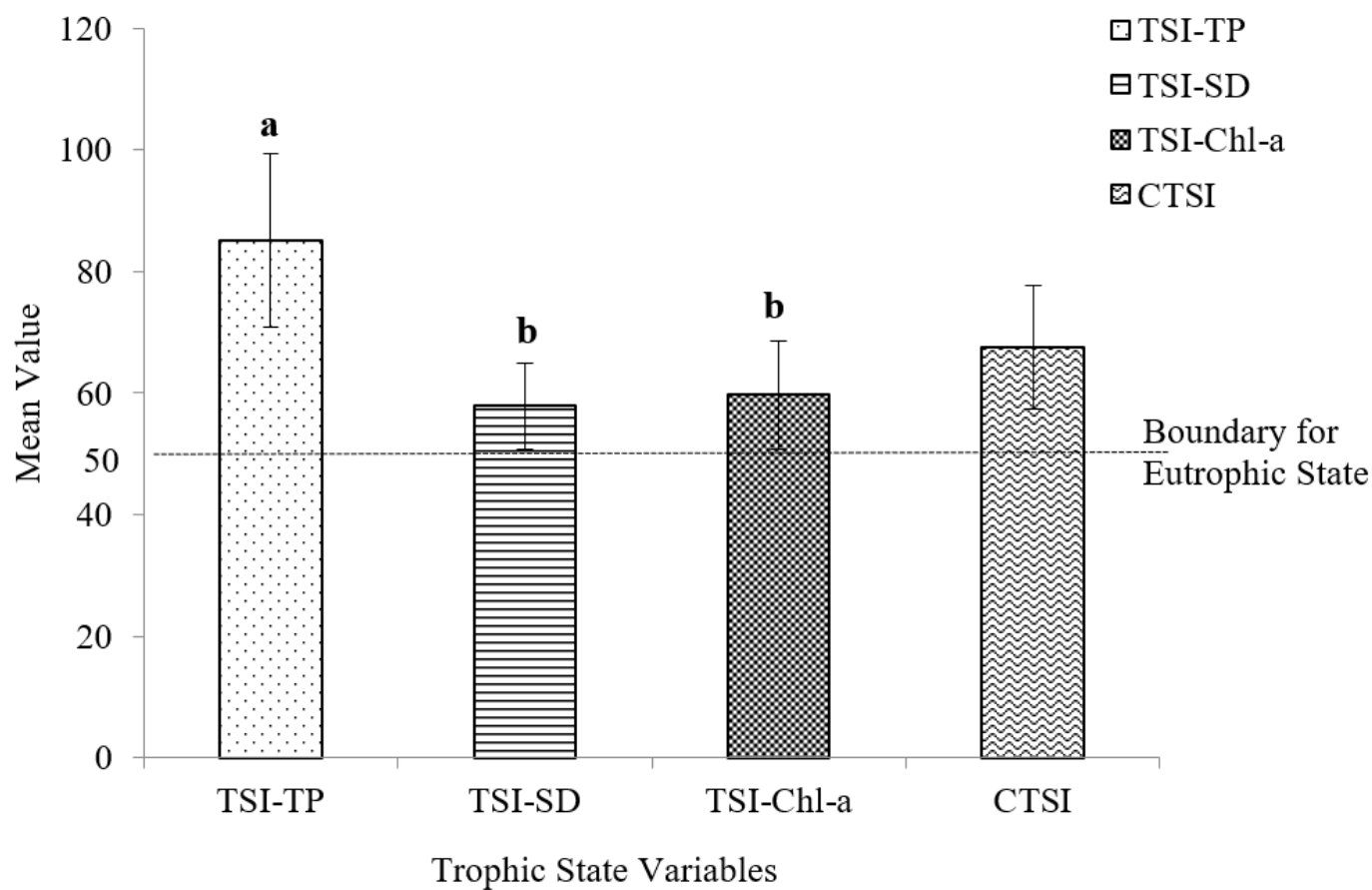


Figure 1

Comparison among mean TSI value of individual trophic state variables, cumulative trophic state of Lugo Lake and eutrophic state borderline based on Carlson (1977), Northeastern Ethiopia. (Different letters on the top of error bars indicate a significant difference ($p < 0.05$) based on Kruskal-Wallis (Tukey HSD) test.