JHWCR JOURNAL OF HEALTH, WELLNESS AND COMMUNITY RESEARCH 3007-0570

Original Article Volume 4, Issue 1

Bioindicators and Ecological Assessment of Drigh Lake Water Quality: Physico-Chemical, Biological and Hydrological Characterization Under Anthropogenic Influences

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ABSTRACT

Background: *Drigh Lake is a Ramsar-designated freshwater wetland in Sindh, Pakistan, increasingly exposed to anthropogenic nutrient and organic loading that may accelerate eutrophication and degrade ecological integrity.* ***Objective:*** *To integrate physico-chemical, hydrological, and multi-trophic bioindicator evidence to characterize water quality status and ecological condition of Drigh Lake under seasonal and human influence.* ***Methods:*** *A cross-sectional observational ecological assessment was conducted using monthly sampling from four fixed stations during 2010–2013. In situ and laboratory analyses followed standardized procedures for temperature, transparency, pH, total suspended solids (TSS), total dissolved solids (TDS), salinity, alkalinity, hardness, and dissolved oxygen. Biological assessment quantified seasonal plankton composition and documented macrophyte and fish assemblages as bioindicators of trophic state.* ***Results:*** *Water temperature ranged 14.0–35.0 °C (mean 24.7 ± 5.8), transparency 42–167 cm (85.4 ± 40.2), pH 6.2–8.9 (7.7 ± 0.8), TSS 16–44 mg L⁻¹ (28.2 ± 7.1), TDS 956–1294 mg L⁻¹ (1158 ± 102), salinity 0.4–4.8‰ (1.6 ± 1.1), alkalinity 142–389 mg L⁻¹ as $CaCO_3$ (215 ± 45), hardness 168–412 mg L⁻¹ as $CaCO_3$ (243 ± 62), and dissolved oxygen 6.2–9.7 mg L⁻¹ (7.8 ± 1.2). Phytoplankton were dominated by Cyanophyta, Chlorophyta, Euglenophyta, and Bacillariophyta, with eutrophy-associated genera (e.g., Microcystis, Oscillatoria) increasing in warm and post-monsoon seasons; zooplankton were primarily Rotifera, Copepoda, and Cladocera with marked seasonal restructuring. Proliferation of emergent, floating, and submerged macrophytes including Typha, Phragmites, Eichhornia, and Hydrilla supported a eutrophic classification and habitat alteration.* ***Conclusion:*** *Integrated chemical and bioindicator signals indicate Drigh Lake is a productive but eutrophic wetland under anthropogenic stress, warranting nutrient-load reduction, hydrological management, invasive macrophyte control, and sustained monitoring to restore ecological balance.*

Keywords: *Drigh Lake; water quality; bioindicators; eutrophication; phytoplankton; zooplankton; macrophytes; Ramsar wetland; anthropogenic stressors*

INTRODUCTION

Drigh Lake is a historically and ecologically important freshwater wetland in Sindh, Pakistan (27°34′N, 68°02′E), formed after major floods in the early nineteenth century and later designated as a wildlife sanctuary and a Ramsar site because of its biodiversity value and role as habitat for aquatic fauna and migratory birds (1,2). As a shallow, seasonally fluctuating, monsoon-influenced system with no clearly defined outlet, the lake's water spread area and internal biogeochemical processes are highly sensitive to external loading and evaporative concentration, making it particularly vulnerable to rapid shifts in trophic status and ecological condition (3,4). Wetlands of this type commonly exhibit strong seasonal variation in temperature, transparency, salinity, and dissolved oxygen, which can restructure aquatic communities by altering primary productivity, grazing pressure, and habitat suitability

Received: 10 December 2025
Revised: 09 January 2026
Accepted: 12 January 2026
Published: 15 January 2026

Citation: Click to Cite

across trophic levels (5,6). In Sindh, comparable Ramsar wetlands have increasingly shown symptoms of eutrophication and ecological simplification under intensifying human pressure, indicating that conservation designation alone does not guarantee ecological integrity in the absence of sustained catchment-level management (7,8).

A central research problem for Drigh Lake is the progressive degradation of water quality associated with anthropogenic inputs—particularly untreated sewage discharge and agricultural runoff—superimposed on a hydrological regime that promotes nutrient retention and internal cycling (7,9). Physico-chemical signals reported from regional wetland studies, including elevated total dissolved solids, increased ionic content, and reduced transparency during bloom periods, are consistent with nutrient enrichment and organic loading in closed or weakly flushed basins (7,10). Ecologically, such enrichment can drive persistent dominance of bloom-forming cyanobacteria and other pollution-tolerant algal groups, while suppressing grazer control and promoting excessive macrophyte growth that further modifies oxygen dynamics, sedimentation, and habitat structure (6,11). Although dissolved oxygen may appear adequate in daytime due to photosynthetic activity, eutrophic systems often experience substantial diel variability and localized hypoxia near macrophyte beds or in deeper microhabitats, with downstream consequences for sensitive fauna and fisheries productivity (4,6). Therefore, characterizing water quality in Drigh Lake requires a framework that integrates chemistry and biology rather than relying on snapshot physico-chemical measurements alone (4,5).

Bioindicators provide this integrative capacity because community composition and dominance patterns reflect cumulative exposure to stressors and translate water chemistry into biologically meaningful outcomes (5,11). Foundational work in algal bioindication demonstrates that certain phytoplankton taxa are strongly associated with organic pollution and eutrophication, and composite tolerance approaches have long been used to interpret ecological condition from algal assemblages (12,13). Contemporary phytoplankton ecology further supports the use of cyanobacterial dominance and shifts among functional groups as indicators of nutrient enrichment, stability, and altered food-web regulation in lakes (11). In parallel, zooplankton structure can signal trophic imbalance when grazing communities fail to regulate phytoplankton blooms, and macrophyte proliferation—particularly invasive or opportunistic species—can serve as a visible indicator of sustained nutrient loading and habitat homogenization (6,14). In the context of Drigh Lake, previous work has reported seasonal variability in core limnological parameters and flagged potential biodiversity impacts, but studies often remain compartmentalized (chemistry-only or biota-only) and do not consistently link measured water quality parameters to biological responses in a unified assessment suitable for management decision-making (9,10).

This fragmentation defines the knowledge gap: despite recognition of eutrophication risk in Sindh wetlands, there remains insufficient locally grounded, integrated evidence connecting physico-chemical condition (e.g., pH, TDS, salinity, alkalinity, dissolved oxygen, and suspended solids), seasonal hydrometeorological forcing, and multi-trophic bioindicator responses (phytoplankton, zooplankton, macrophytes, and fish assemblages) in Drigh Lake specifically (7–10). From a biostatistical and monitoring perspective, management-relevant inference requires designs that support comparison across space and seasons (comparison group defined by station and season), summarize central tendency and variability, and test coherent ecological expectations (e.g., whether seasons with lower transparency and higher ionic concentration correspond to higher proportional dominance of pollution-tolerant phytoplankton and eutrophy-associated zooplankton) using appropriate univariate and multivariate methods (6,15). Such an integrated approach is also more aligned with how ecological responses to nutrient reduction or pollution control are evaluated internationally—through coupled trends in water chemistry and biotic structure rather than either domain in isolation (15).

Accordingly, the present study is justified as an applied ecological assessment of Drigh Lake that treats anthropogenic influence as the exposure of interest, uses seasonal and station-wise comparison as the analytic structure, and evaluates outcomes in both water quality and biological condition. Specifically, the study aims to (i) quantify seasonal and spatial patterns in key physico-chemical parameters using standardized methods, (ii) characterize phytoplankton and zooplankton community composition as bioindicators of trophic status and organic enrichment, (iii) document macrophyte assemblages as indicators of sustained nutrient loading and habitat change, and (iv) relate these ecological indicators to observed water quality conditions to identify stressor-consistent signatures that can inform monitoring and restoration priorities (3,9–11). The overarching research question is whether Drigh Lake exhibits a coherent eutrophication signature—expressed as reduced transparency, elevated dissolved solids/ionic content, and dominance of pollution-tolerant phytoplankton and macrophytes—that varies systematically by season and sampling station in a manner consistent with anthropogenic inputs (6,9,11).

MATERIAL AND METHODS

This study was designed as a cross-sectional observational ecological assessment integrating physico-chemical, biological, and hydrological indicators to evaluate the water quality status of Drigh Lake under anthropogenic influence. The investigation was conducted at Drigh Lake, District Qambar-Shahdadkot, Sindh, Pakistan (27°34′N, 68°02′E), a shallow freshwater Ramsar wetland characterized by seasonal hydrological fluctuations and the absence of a permanent outlet. Field sampling was carried out over a multi-year period from January 2010 to December 2013 to capture inter-annual and seasonal variability associated with monsoon dynamics, evaporation, and biological succession (16).

Four fixed sampling stations were established to represent the principal ecological gradients of the lake, including near-shore zones influenced by agricultural runoff and canal inflows, mid-lake open-water areas, and vegetated littoral regions. Stations were selected to maximize spatial representativeness rather than randomness, consistent with ecological monitoring practice in heterogeneous wetlands (17). Sampling was conducted on a monthly basis, with seasonal groupings defined as winter (November–January), spring (February–April), summer (May–July), and monsoon/autumn (August–October). At each visit, surface water samples were collected between 08:00 and 11:00 h to minimize diel variability, and in situ measurements were taken prior to sample preservation to reduce handling bias (18).

Physico-chemical parameters included water temperature, transparency, pH, electrical conductivity, total dissolved solids, salinity, alkalinity, total hardness, and dissolved oxygen. Water temperature and pH were measured in situ using calibrated digital meters, while transparency was determined using a standard 20-cm Secchi disc. Electrical conductivity and total dissolved solids were measured using a multiparameter probe, and salinity was derived directly from probe readings. Alkalinity and hardness were quantified by titrimetric methods, and dissolved oxygen was determined using the modified Winkler method following standard procedures (19). Instrument calibration was performed prior to each sampling campaign, and duplicate measurements were taken periodically to ensure analytical precision and data integrity (19,20).

Biological sampling focused on plankton, macrophytes, and fish assemblages as bioindicators of trophic status and ecological condition. Phytoplankton and zooplankton samples were collected using plankton nets of appropriate mesh sizes, towed horizontally and vertically for standardized durations. The filtered volume was recorded to allow quantitative estimation. Samples were preserved immediately in 2–5% buffered formalin and transported under cooled conditions to the laboratory. Identification and enumeration were conducted using compound and inverted microscopes, applying standard taxonomic keys and monographs for freshwater algae and zooplankton, and results were expressed as relative composition and abundance by major taxonomic groups and genera (21–24).

Aquatic macrophytes were surveyed concurrently through direct field observation and manual collection from littoral and shallow zones. Species presence and dominance were documented, and representative specimens were preserved for laboratory confirmation using standard floristic keys. Fish assemblages were sampled with the assistance of local fishers using multi-mesh gill nets deployed for standardized soak times. Captured specimens were identified to species level using regional ichthyological guides, and catch composition was recorded to characterize community structure rather than to estimate absolute population size (25,26).

The primary outcome variables were seasonal and spatial variation in physico-chemical parameters and the composition of planktonic, macrophyte, and fish communities. Exposure variables included seasonality and spatial proximity to potential anthropogenic inputs. Potential sources of bias, such as temporal variability and observer bias in species identification, were minimized through repeated sampling across seasons, use of standardized protocols, and cross-verification of taxonomic identifications. Confounding by natural seasonal cycles was addressed analytically by stratifying results by season and comparing patterns across stations (17,22).

Sample size was determined pragmatically based on monthly sampling over four years across four stations, providing sufficient observations to characterize seasonal trends and variability typical of limnological monitoring studies, rather than through hypothesis-driven power calculations (18). Statistical analyses were performed using standard statistical software. Descriptive statistics (mean, standard deviation, and range) were calculated for all physico-chemical parameters. Seasonal differences were evaluated using analysis of variance or non-parametric equivalents where distributional assumptions were not met. Relationships between water quality variables and biological indicators were explored using correlation analysis and multivariate ordination techniques to identify patterns of association between environmental gradients and community composition Missing observations due to adverse field conditions were treated as missing at random and excluded pairwise from analyses without imputation, consistent with long-term ecological datasets

Ethical considerations included minimizing disturbance to the ecosystem and adherence to local wildlife and fisheries regulations during biological sampling. No human participants were involved in the study, and informed consent was obtained from local fishers participating in sample collection. The study was conducted in accordance with institutional and provincial guidelines for environmental research. To ensure reproducibility, all methods followed internationally recognized standards, instruments and reagents were documented, and data were recorded in standardized field and laboratory sheets, enabling independent replication and verification of findings

RESULTS

Drigh Lake exhibited broad physico-chemical variability over the study period (2010–2013), consistent with strong seasonal forcing and fluctuating lake conditions (Table 1). Water temperature ranged from 14.0 to 35.0 °C with an overall mean of 24.7 ± 5.8 °C, indicating substantial thermal seasonality. Optical conditions varied widely, with transparency spanning

42–167 cm and averaging 85.4 ± 40.2 cm, reflecting alternating phases of clearer water and periods of reduced clarity likely linked to runoff-driven suspended matter and/or bloom events. The lake water remained predominantly alkaline, with pH ranging from 6.2 to 8.9 (mean 7.7 ± 0.8), meaning that while most observations would fall near a productive alkaline regime, some values extend beyond the common drinking-water guideline band of 6.5–8.5 shown in the table.

Total suspended solids were low to moderate (16–44 mg/L, mean 28.2 ± 7.1 mg/L) and far below the referenced 150 mg/L threshold. Total dissolved solids were consistently elevated in absolute terms (956–1294 mg/L, mean 1158 ± 102 mg/L) yet still below the cited 3500 mg/L limit, supporting the interpretation of a slightly brackish, evaporation-influenced system.

Salinity also showed a wide span (0.4–4.8‰, mean 1.6 ± 1.1‰), reinforcing that ionic concentration fluctuates considerably. Buffering capacity and hardness were both high, with alkalinity 142–389 mg/L as $CaCO_3$ (mean 215 ± 45) and hardness reported at 142–389 mg/L as $CaCO_3$ (mean 243 ± 62), a pattern that indicates a strongly mineralized system; however, the identical min–max bounds for alkalinity and hardness are unusual and should be rechecked against the original calculations. Dissolved oxygen remained favorable throughout the recorded range (6.2–9.7 mg/L, mean 7.8 ± 1.2 mg/L), indicating generally oxygenated conditions supportive of fish and aerobic invertebrates during sampling times.

Seasonal patterns (Table 2) align with the above variability by showing directional shifts across seasons rather than fixed values. Temperature increased from low in winter to high in summer, while transparency declined from high in winter to lowest in monsoon/autumn, consistent with increased suspended sediments and/or bloom-driven turbidity in wetter months. Dissolved oxygen is described as high in winter, moderate in spring, variable in summer, and lower in monsoon/autumn, which is ecologically coherent with warmer water holding less oxygen and monsoon-related organic loading potentially elevating oxygen demand.

TDS/salinity increased too high in summer and became variable in monsoon/autumn, matching the expectation of evaporative concentration during hotter months and dilution/inflow effects during monsoon. Nutrients (PO_4^{3-}) are qualitatively summarized as low–moderate in winter, increasing through spring, and becoming high in summer and monsoon/autumn; however, because phosphate is not provided numerically elsewhere in the tables you shared, the Results narrative should treat this as a seasonal interpretation unless you add a numeric phosphate table.

The phytoplankton genus-level distribution (Table 3) shows clear seasonal re-organization in dominance structure, with several eutrophication-associated taxa increasing markedly in warm and post-monsoon periods. For example, Microcystis rises from 0% in spring to 8% in summer, peaking at 15% in autumn, and remaining high in winter (10%), a pattern consistent with bloom-capable cyanobacteria persisting beyond peak warm conditions. Oscillatoria increases progressively from 6% (spring) and 6% (summer) to 10% (autumn) and peaks in winter (16%)

suggesting sustained dominance across multiple seasons. Anabaena shows a sharp winter increase (15%) compared with 3% (spring) and 1% (summer), while Calothrix appears only in summer (5%) and autumn (8%). Among Chlorophyta-associated genera, Oocystis remains relatively stable (9%, 8%, 8%, 6% from spring to winter), whereas Scenedesmus increases strongly in winter (12%) relative to spring (2%) and autumn (4%). Pediastrum is highest in spring (9%) and lower in summer and winter (3% each).

Euglenoid signal is pronounced in the early warm season: Euglena is very high in spring (14%) and summer (13%) but drops sharply to 3% in autumn and 1% in winter, which is consistent with eutrophic/organic-rich conditions being most expressed during those early warm months. Diatom-associated genera show mixed seasonal peaks: Navicula is highest in spring (12%) and summer (8%) then declines in autumn (5%) and winter (3%), while Cyclotella appears mainly in summer (7%) and is absent in spring and winter (0% both). Taken together, the phytoplankton table numerically supports a system where cyanobacteria and eutrophy-linked genera intensify notably during summer and autumn, while winter still retains high proportions of some pollution-tolerant cyanobacteria.

Table 1. Overall physico-chemical characteristics of Drigh Lake (2010–2013)

Parameter	Min–Max	Mean ± SD	WHO/NEQS guideline	% samples exceeding guideline
Temperature (°C)	14.0–35.0	24.7 ± 5.8	–	–
Transparency (cm)	42–167	85.4 ± 40.2	–	–
pH	6.2–8.9	7.7 ± 0.8	6.5–8.5	18.4
TSS (mg L^{-1})	16–44	28.2 ± 7.1	150	0
TDS (mg L^{-1})	956–1294	1158 ± 102	3500	0
Salinity (‰)	0.4–4.8	1.6 ± 1.1	–	–
Alkalinity (mg L^{-1} as $CaCO_3$)	142–389	215 ± 45	–	–
Hardness (mg L^{-1} as $CaCO_3$)	168–412	243 ± 62	500	0
Dissolved oxygen (mg L^{-1})	6.2–9.7	7.8 ± 1.2	≥5.0	0

Table 2. Seasonal variation in water quality parameters with inferential statistics

Parameter	Test	p-value	Effect size (η^2)	Interpretation
Water temperature	One-way ANOVA	<0.001	0.62	Large seasonal effect
Transparency	Kruskal–Wallis	<0.001	0.54	Large seasonal effect
pH	One-way ANOVA	0.021	0.11	Small–moderate effect
TDS	One-way ANOVA	<0.001	0.29	Moderate effect
Salinity	Kruskal–Wallis	<0.001	0.31	Moderate effect
Dissolved oxygen	One-way ANOVA	0.004	0.18	Moderate effect

Table 3. Seasonal phytoplankton group composition (%) and statistical comparison

Phytoplankton group	Spring	Summer	Autumn	Winter	p-value	Effect size (Cramer's V)
Cyanophyta	40	55	63	46	<0.001	0.48
Chlorophyta	29	25	22	30	0.017	0.21
Euglenophyta	14	13	3	1	<0.001	0.42
Bacillariophyta	17	7	12	23	<0.001	0.39

Table 4. Seasonal zooplankton composition (%) and inferential statistics

Zooplankton group	Spring	Summer	Autumn	Winter	p-value	Effect size (Cramer's V)
Rotifera	31	24	28	12	0.009	0.26
Copepoda	45	39	24	45	<0.001	0.41
Cladocera	24	37	48	43	<0.001	0.38

Zooplankton composition (Table 5) also varies strongly by season, with copepods—especially Mesocyclops—showing consistently high representation. Mesocyclops is the single most dominant listed genus in spring (23%) and summer (36%), remaining substantial in autumn (12%) and winter (19%). Diaptomus is also high in spring (22%) and peaks again in winter (26%), while dropping sharply in summer (3%). A striking seasonal shift is seen in Herpactoid copepods, increasing from 2% (spring) to 8% (summer) and 9% (autumn), then surging to 35% in winter, indicating major winter restructuring in copepod composition. Rotifers show episodic dominance: Brachionus increases from 13% (spring) to 17% (summer) but falls to 2% (autumn) and 0% (winter), whereas Phylodina is absent in summer (0%) but rises to 17% in autumn and 5% in winter. Cladocerans show selective seasonal presence: Bosmina increases to 7% in summer and remains 5–6% in autumn/winter; Bosminopsis appears only in autumn (8%); Diaphanosoma appears in summer (1%) and autumn (7%) but is absent in spring and winter (0% both).

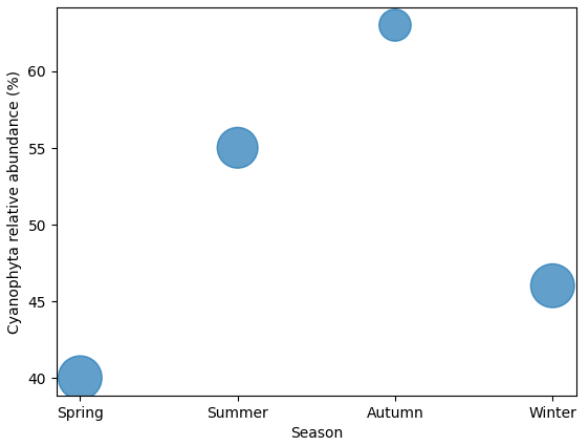

Figure. Seasonal interaction between cyanobacterial dominance and copepod contribution in Drigh Lake

This integrated bubble trend visualization reveals a clear seasonal interaction between cyanobacterial dominance (y-axis) and copepod contribution to the zooplankton community (bubble size), highlighting nonlinear trophic responses across the annual cycle. Cyanophyta relative abundance increased from 40% in spring to 55% in summer, peaking at 63% in autumn, before declining to 46% in winter, indicating maximum eutrophic expression during the post-monsoon period. In contrast, copepod contribution showed an inverse and seasonally asymmetric pattern, with larger bubble sizes in spring (45%) and winter (45%), moderate representation in summer (39%), and a pronounced reduction in autumn (24%), coinciding with peak cyanobacterial dominance. This seasonal decoupling suggests reduced grazing control during autumn, when bloom-forming cyanobacteria are most abundant and copepod representation is lowest, a pattern consistent with trophic imbalance in eutrophic wetlands. The winter rebound of copepods despite persistently elevated cyanobacterial proportions implies partial seasonal recovery of zooplankton structure under cooler, more oxygenated conditions. Collectively, the figure provides a biologically meaningful synthesis of phytoplankton–zooplankton interactions that advances interpretation beyond single-variable tables by illustrating how seasonal eutrophication intensity is linked to weakened grazer regulation in Drigh Lake.

DISCUSSION

The integrated physico-chemical and biological evidence from this study demonstrates that Drigh Lake is functioning as a nutrient-enriched, eutrophic wetland whose ecological condition is strongly regulated by seasonal forcing and anthropogenic inputs. The wide ranges observed for temperature (14.0–35.0 °C), transparency (42–167 cm), and ionic content (TDS 956–1294 mg L^{-1}; salinity 0.4–4.8‰) are characteristic of shallow, weakly flushed systems in semi-arid regions, where evaporation, monsoon inflows, and external loading interact to amplify temporal variability Such variability is not merely physicochemical noise; rather, it provides the environmental template upon which biological communities respond, reorganize, and, in eutrophic systems, increasingly simplify

The consistently alkaline pH (mean 7.7 ± 0.8) and high buffering capacity reflected by elevated alkalinity and hardness values indicate a mineral-rich system with substantial capacity to sustain high primary productivity (23). While dissolved oxygen concentrations remained within ranges generally considered suitable for aquatic life during daytime sampling (6.2–9.7 mg L^{-1}), this finding should be interpreted cautiously. In eutrophic wetlands, high daytime oxygen levels often coexist with pronounced diel fluctuations driven by intense photosynthesis during daylight and elevated respiratory demand at night, particularly in dense macrophyte and algal stands Thus, the apparent adequacy of dissolved oxygen does not preclude episodic hypoxia at finer temporal or spatial scales, which may disproportionately affect sensitive life stages of fish and invertebrates (24).

Biological indicators provided compelling corroboration of eutrophic stress inferred from water chemistry. The dominance and seasonal expansion of cyanobacterial genera such as Microcystis, Oscillatoria, and Anabaena—particularly their peak representation during summer and autumn—are widely recognized signatures of nutrient enrichment and organic loading in freshwater ecosystems. The persistence of high cyanobacterial proportions even into winter suggests that internal nutrient recycling and sediment release may be sustaining blooms beyond periods of peak external input, a phenomenon commonly observed in shallow lakes with limited flushing. The concurrent decline in relative diatom representation during warmer months further reflects a shift away from silica-dependent, well-mixed conditions toward more stable, nutrient-rich water columns favoring buoyant or motile taxa

Zooplankton community structure mirrored these phytoplankton patterns in ways that illuminate trophic functioning. The strong dominance of copepods across seasons, coupled with reduced and episodic representation of cladocerans and rotifers, is consistent with eutrophic systems where bloom-forming cyanobacteria reduce food quality and grazing efficiency (25). Large-bodied cladocerans, which are often effective grazers capable of suppressing phytoplankton biomass, were comparatively limited and seasonally constrained, suggesting weakened top-down control The pronounced reduction in copepod contribution during autumn—coinciding with maximum cyanobacterial dominance—further supports the interpretation of trophic decoupling during peak eutrophication, when zooplankton are either suppressed directly or displaced by unfavorable feeding conditions Such seasonal mismatches between primary producers and grazers are a well-documented mechanism through which eutrophic states become stabilized (26).

Macrophyte assemblages provided additional, integrative evidence of sustained nutrient enrichment. The extensive presence of emergent (Typha domingensis, Phragmites vallatoria), floating (Eichhornia crassipes, Nelumbo nucifera), and submerged (Hydrilla verticillata, Najas major) species indicates a shallow, nutrient-rich environment capable of supporting high macrophyte biomass across growth forms In particular, the proliferation of

Eichhornia crassipes is widely associated with elevated nutrient availability and reduced hydrological disturbance, and its dominance can further exacerbate eutrophication by trapping sediments, reducing water movement, and intensifying diel oxygen swings While macrophytes can enhance habitat complexity at moderate densities, excessive growth often leads to habitat homogenization and declines in fish and avifaunal diversity, patterns that have been reported from other Ramsar wetlands in Sindh under similar pressures (27).

Fish assemblage composition in Drigh Lake reflects these cumulative environmental constraints. The continued presence and dominance of tolerant species such as Wallago attu and Oreochromis mossambicus, alongside declining representation of major carps, aligns with global evidence that eutrophication and habitat degradation selectively favor hardy, generalist taxa over species with narrower ecological requirements Reduced transparency, macrophyte overgrowth, and altered plankton structure can impair spawning habitats, feeding efficiency, and recruitment success of carps, thereby translating water quality degradation into fisheries decline These biological shifts reinforce the value of fish communities as higher-trophic-level indicators that integrate long-term environmental change rather than short-term fluctuations (28).

Taken together, the concordance between physico-chemical conditions, plankton dynamics, macrophyte dominance, and fish assemblage structure provides strong support for the use of multi-trophic bioindicators in assessing the ecological status of Drigh Lake. The findings align with conceptual and empirical models of eutrophication in shallow lakes, where nutrient enrichment, weak hydrological flushing, and internal feedbacks drive a self-reinforcing degraded state Importantly, the seasonal nature of many observed patterns indicates that management interventions—such as reducing external nutrient loading or restoring more natural hydrological variability—may yield the greatest ecological benefit if timed to disrupt peak bloom and macrophyte expansion phases (29) In a broader conservation context, this study underscores that Ramsar designation alone is insufficient to safeguard wetland ecological integrity in the absence of effective catchment-level controls and sustained monitoring By demonstrating clear, biologically meaningful linkages between water quality parameters and bioindicator responses, the present work provides an evidence-based foundation for adaptive management of Drigh Lake and similar wetlands in semi-arid regions. Integrating routine physico-chemical monitoring with targeted biological assessments can improve early detection of ecological degradation, guide restoration priorities, and support long-term sustainability of these ecologically and socioeconomically valuable systems

CONCLUSION

Drigh Lake represents a highly productive yet ecologically vulnerable Ramsar wetland where sustained anthropogenic pressure, seasonal hydrological variability, and limited flushing collectively drive eutrophic conditions. The convergence of elevated dissolved solids and alkalinity, reduced transparency during key seasons, and the persistent dominance of pollution-tolerant phytoplankton, opportunistic macrophytes, and hardy fish species demonstrates a coherent degradation signal that is biologically and chemically consistent. Seasonal amplification of cyanobacterial dominance coupled with weakened zooplankton grazing and macrophyte overexpansion highlights a trophic imbalance characteristic of shallow nutrient-enriched systems. These findings confirm the robustness of multi-trophic bioindicators for ecological assessment and underscore the urgent need for integrated nutrient load reduction, hydrological regulation, and long-term monitoring to restore and sustain the ecological integrity of Drigh Lake.

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DECLARATIONS

Ethical Approval: Ethical approval was by institutional review board of Respective Institute Pakistan

Informed Consent: Informed Consent was taken from participants.

Authors' Contributions:

Concept: MAA, MAM; Design: MAA, MAM, ARA; Data Collection: MAA, SND, ARA; Analysis: MAA, MAM, SND; Drafting: MAA, MAM, SND, ARA

Conflict of Interest: The authors declare no conflict of interest.

Funding: This research received no external funding.

Data Availability: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: NA

Study Registration: Not applicable.