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Integrated assessment of water quality and trophic status in High Altitude Andean lagoons: a multi-index and multivariate approach for sustainable fish farming management

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ABSTRACT

High-altitude Andean lagoons are ecologically sensitive systems whose water quality is under increasing pressure from the expansion of aquaculture and other human activities. An integrated assessment of water quality and trophic status was carried out in three lagoons located in the highlands of central Peru, using a multi-index and multivariate approach that combined physicochemical parameters, trophic indices (TRIX, TSI, molar N:P ratio), and heavy-metal indices, evaluated against Peruvian EQS, USEPA, and CCME water-quality standards. Principal component analysis explained 60.1% of the total variability, with the first axis (40.4%) structured by an organic-loading and nutrient gradient that consistently separated Tipicocha from the other lagoons. Total phosphorus in Tipicocha reached concentrations well above the Peruvian EQS threshold, and TRIX values classified all lagoons as eutrophic to hypertrophic (5.46–6.21). TSI (TP) classified Tipicocha and Tranca Grande as hypereutrophic, whereas TSI (Chl-*a*) remained within the eutrophic range (53–60), a pattern consistent with additional environmental constraints on phytoplankton biomass. Molar N:P ratios indicated strong nitrogen limitation in Tipicocha and Tranca Grande, whereas Pomacocha showed a seasonal shift from co-limitation during the dry season to potential nitrogen limitation during the rainy season. Metal contamination was low according to EQS and USEPA criteria, whereas CCME thresholds suggested moderate to high contamination (HPI up to 105.1), with systematic exceedances of Cd, Cu, and Zn at all sites. Taken together, the results point to strong trophic enrichment associated with fish-farming activity as the main pressure on water quality in these ecosystems and show that the choice of regulatory framework has a decisive influence on metal-risk classification.

1. Introduction

High-altitude Andean lagoons are fragile freshwater ecosystems that play a critical role in water regulation, biodiversity conservation, and local socio-economic activities. Characterized by low temperatures, marked hydrological seasonality, limited buffering capacity, and reduced water renewal, these systems are highly sensitive to external nutrient and organic matter inputs, even at low intensities (Patricia et al., 2015; Machate et al., 2023). Consequently, minor shifts in nutrient availability, dissolved oxygen, and algal productivity can rapidly alter their ecological integrity and compromise their suitability for human use (García-Sanz et al., 2021).

In the central Peruvian Andes, many of these lagoons face increasing production pressures, particularly cage-based rainbow trout farming (Chanamé-Zapata et al., 2020; Custodio and Peñaloza, 2025). This activity introduces significant loads of nutrients and organic matter through uneaten feed, feces, and metabolic excretions, altering nitrogen and phosphorus dynamics and accelerating eutrophication processes

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(Dalsgaard et al., 2023; Gao et al., 2025; Lin et al., 2026). Furthermore, while aquaculture is primarily linked to organic enrichment, monitoring potentially toxic metals (e.g., Fe, Cu, Cr, Cd, Pb, and Zn) is also critical, as these elements can influence water quality, pose risks to aquatic biota, and modify the environmental diagnosis depending on the regulatory framework applied (Song et al., 2023; Haque et al., 2024; Roldán Rodríguez et al., 2025).

To evaluate these impacts, tools like the Trophic Index (TRIX), Carlson's Trophic State Index (TSI), and molar N:P ratios are widely used to classify aquatic productivity and nutrient limitations (Carlson, 1996; Vollenweider et al., 1998; Giovanardi and Giovanardi, 2004; Pettine et al., 2007). Concurrently, indices such as the Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI) help summarize metal contamination relative to regulatory thresholds (Moldovan et al., 2022). Previous studies in Andean lagoons have successfully provided valuable, yet isolated insights into either trophic states or physicochemical parameters (Custodio et al., 2018a,b). However, a significant knowledge gap remains because most assessments still rely on conventional, single-dimensional descriptors that evaluate nutrient enrichment and metal contamination separately. Integrated frameworks are virtually non-existent for high-altitude aquaculture systems, particularly those that jointly assess both dimensions by accounting for seasonal hydrology and comparing the sensitivity of distinct national and international water quality standards, such as Peruvian EQS, USEPA, and CCME (MINAM, 2017; USEPA, 2025; CCME, 2003).

To address this gap, this study provides an integrated assessment of water quality and trophic status in three high-altitude Andean lagoons (Pomacocha, Tipicocha, and Tranca Grande) using a multi-index and multivariate approach. Within this framework, trophic status and metal pollution are treated as complementary dimensions of a unified diagnosis. This is achieved by jointly evaluating physicochemical parameters, trophic indicators, and metal contamination indices, while comparing dry and rainy seasons based on environmentally relevant metals (Fe, Cu, Cr, Cd, and Pb) alongside the TRIX index and multivariate tools. Additionally, this study offers scientific evidence aligned with Sustainable Development Goals 6 (Clean Water and Sanitation) and 2 (Zero Hunger) (United Nations, 2015) to support sustainable fish farming management in mountain regions.

2. Materials and methods

2.1. Study area

The study area is located in the upper Perené River basin in the central region of Peru. The lagoons Pomacocha (473139 E, 8697593 N), Tipicocha (475976 E, 8701280 N), and Tranca Grande (474549 E, 8703971 N) are high-altitude Andean lentic systems located between 4310 and 4330 m a.s.l. (Fig. 1). These water bodies differ in their main morphometric characteristics. Pomacocha has an approximate surface area of 120 ha and a depth of 9 m, Tranca Grande covers approximately 164 ha and reaches 25 m depth, whereas Tipicocha has an approximate surface area of 90 ha and a depth of 10 m (Chanamé-Zapata et al., 2020). These differences in area and depth may influence water renewal, dilution capacity, nutrient retention, and the local response to organic

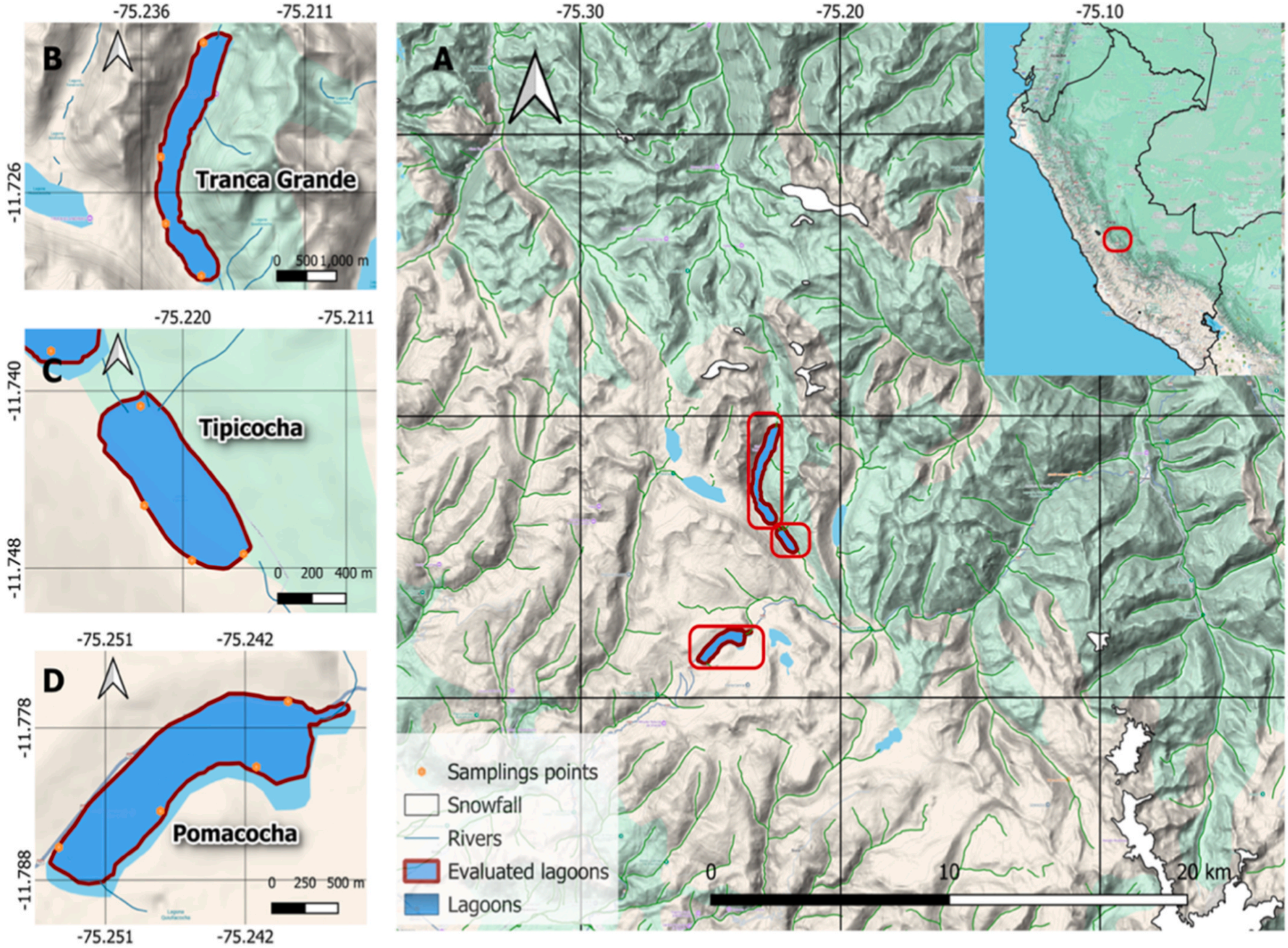

Fig. 1. Location map of the study area. (A) Regional map showing the location of the lagoons, (B) Tranca Grande (Tg), (C) Tipicocha (Tp), and (D) Pomacocha (Pc).

and nutrient inputs.

The local climate is characterized by two contrasting periods: a dry season from May to September and a rainy season from October to April. Annual precipitation ranges from 700 to 1100 mm, and air temperature varies between −2 and 16 °C. During the sampling campaigns, water temperature ranged from 9.3 to 16.6 °C, while turbidity varied from 7.3 to 10.18 NTU. Sediment composition is predominantly sandy in two of the water bodies and clayey in the third, suggesting differences in substrate conditions that may also affect nutrient retention and metal partitioning.

The shoreline and surrounding catchment areas are embedded in a high-Andean landscape subject to productive uses, particularly livestock grazing and rainbow trout farming. Since the 1990s, these ecosystems have been used for intensive rainbow trout (*Oncorhynchus mykiss*) farming using floating cages. The cages are located in the pelagic zone, with approximately 6 to 20 m between the lagoon bottom and the cage, depending on local depth conditions. This productive setting makes these lagoons suitable systems for evaluating how morphometry, hydrological seasonality, nutrient enrichment, and aquaculture activity interact in high-altitude Andean ecosystems.

2.2. Sampling design and in situ measurements

Two sampling campaigns were conducted in 2022: the dry season (period 1) and the rainy season (period 2), with four sampling sites per lagoon (n = 4). At each site, pH, electrical conductivity (EC), dissolved oxygen (DO), temperature, and total dissolved solids (TDS) were measured in situ using portable multiparameter meters from Hanna Instruments (models HI 991301, HI 9146, and HI 9835). To ensure data accuracy and traceability, sensors were calibrated at each sampling site. This procedure was performed strictly following the manufacturer's guidelines and using certified standard solutions. Subsurface samples were collected at a depth of 20 cm below the water surface to avoid surface microlayer interference, following standard water quality monitoring procedures. Samples were stored in polyethylene bottles and transported to the laboratory for further analysis.

The quantitative determination of chlorophyll-*a* was performed by fluorometry following a liquid-liquid extraction in a mixture of chloroform and methanol (2:1, v/v), in accordance with the to American Public Health Association (APHA) standardized protocol 10200 H (APHA, 2017). Fluorescence readings were obtained using a FluorPen FP 110 digital fluorometer (PSI, Czech Republic), configured with a dual excitation system (red/blue LED) with a maximum intensity of 3000 μmol m^{-2} s^{-1}. Prior to analysis, the instrument was calibrated with standards of known concentration, and the optical parameters were adjusted to ensure maximum sensitivity in the detection of the emission peaks specific to Chl *a*.

Biochemical oxygen demand (BOD_5) was quantified using the respirometric incubation method at 20 ± 1 °C for five days (SM 5210 B), employing an Oxitop IS 6 system (WTW, Germany) and a VELP F10400320 incubator. Total nitrogen (TN) was quantified using a Lovibond MD600 photometer, and total phosphorus (TP) was determined using the ascorbic acid method (SM 4500-P E).

Heavy metal determination was performed using a standard method validated by INACAL (National Institute of Quality of Peru), which involves digestion with HF, HNO_3, and $HClO_4$ (5:2:1, concentrated) followed by analysis on an ICP-MS (PerkinElmer NexION 1000). Quality control was ensured using reference standards, and the assessment of technical precision; all samples and blanks were analyzed in triplicate.

2.3. Environmental quality standards

Water quality assessment was conducted using the Environmental Quality Standards for Water established by Peru's Supreme Decree No. 004-2017-MINAM, specifically Category 4-E1 (conservation of the aquatic environment) (MINAM, 2017). Additionally, water quality criteria recommended by the USEPA were considered as a complementary international framework (USEPA, 2025), along with the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME, 2003). The corresponding maximum admissible values or reference thresholds for each standard were used as denominators for calculating the Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI), and as reference values for determining the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI). To enhance comparability and ecological relevance, both national EQS guidelines and international ones (CCME and USEPA) were applied.

2.4. Water quality index (WQI)

Water quality was assessed using the CCME-WQI, integrating the three components: scope (F_1), frequency (F_2), and amplitude (F_3) of guideline exceedances relative to the established threshold values for each parameter. The index was calculated using equations (1)–(5).

$$WQI = 100 - \left[\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right] \tag{1}$$

F_1 (Scope): The percentage of variables that exceed the permitted value

$$F_1 = \left[\frac{\textit{Number of failed variables}}{\textit{Total number of variables}}\right] x\,100 \tag{2}$$

F_2 (Frequency): The percentage of individual tests per variable that exceed the permitted value

$$F_2 = \left[\frac{\textit{Number of failed tests}}{\textit{Total number of tests}}\right] x\,100 \tag{3}$$

F_3 (Amplitude): The extent (excursion) by which the failed test exceeded the permitted value

$$F_3 = \left[\frac{nse}{0.01.nse + 0.01}\right] \tag{4}$$

$$\text{Where } nse = \left[\frac{\sum excursion}{\textit{Total number of test}}\right] \text{ and } excursion = \left[\frac{\textit{Failed test}}{\textit{Threshold value}}\right] - 1 \tag{5}$$

The WQI was calculated using individual replicates per lagoon and season, which enabled more precise estimation of the frequency (F_2) and amplitude (F_3) of exceedances. The indices were computed independently for each evaluated regulatory framework (Peruvian EQS Cat. 4-E1, CCME, and USEPA), considering only parameters with available guideline values in each standard. Water quality was classified according to CCME criteria: poor (0 – 44), marginal (45 – 64), fair (65 – 79), good (80 – 94), excellent (95 – 100).

2.5. Heavy metal pollution indices in water

To assess heavy metal contamination, the Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI) were determined using the maximum admissible concentrations (MACs) from three international regulatory frameworks as reference values: the Peruvian Environmental Quality Standards (EQS, Category 4-E1) (MINAM, 2017), the Canadian Council of Ministers of the Environment guidelines (CCME, 2003), and the Continuous Concentration Criteria (CCC) recommended by the United States Environmental Protection Agency (USEPA, 2025). This comparative approach enables contrasting the degree of impact under different levels of regulatory stringency aimed at protecting aquatic life.

To ensure methodological consistency, both indices were calculated independently for each standard, generating three sets of analytical results. This strategy allowed for evaluating the sensitivity of the indicators to various regulatory thresholds, providing a more robust and reliable interpretation of ecological risk in the studied high-altitude Andean aquatic systems.

2.6. Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) was calculated following the methodology proposed by Mohan et al. (1996), integrating the relative contribution of each metal through a weighting system inversely proportional to its guideline value (equations (6)–(8)).

$$W_i = \frac{1}{MAC_i} \tag{6}$$

$$Q_i = \frac{C_i}{MAC_i} \times 100 \tag{7}$$

$$HPI = \frac{\sum (W_i \cdot Q_i)}{\sum W_i} \tag{8}$$

Where C_i is the observed concentration of metal i, MAC_i is the maximum admissible concentration according to the corresponding standard, Q_i represents the sub-index of quality, and W_i is the weight assigned to each metal.

This weighted approach allows greater relevance to be given to metals with stricter regulatory limits, such as Cd and Cu, thereby increasing the index's sensitivity to highly toxic contaminants. HPI values < 100 indicate low contamination conditions or acceptable water quality, whereas HPI ≥ 100 reflect significant deterioration associated with heavy metal contamination. To ensure comparability across regulatory frameworks, the index was calculated independently for each standard (EQS Cat. 4-E1, CCME, and USEPA), using only the metals with available guideline values in each case.

2.7. Heavy Metal Evaluation Index (HEI)

The Heavy Metal Evaluation Index (HEI), proposed by Edet and Offiong (2002), was used as a complementary measure of the degree of contamination, expressing the total metal load in the water relative to its guideline values (equation (9)).

$$\text{HEI} = \sum \frac{C_i}{MAC_i} \tag{9}$$

Where C_i is the observed concentration and MAC_i is the maximum admissible value for each metal. Unlike the HPI, the HEI does not incorporate weighting, thus reflecting the cumulative total metal load in the aquatic ecosystem and being particularly useful for assessing the overall magnitude of contamination.

HEI values are interpreted according to the classification proposed in the literature: low (<10), moderate (10–20), and high (>20) level of contamination.

2.8. TRIX index

Trophic status was estimated using the TRIX index proposed by Vollenweider et al. (1998), which integrates chlorophyll-*a*, nutrients, and system oxygenation conditions (equation (10)).

$$TRIX = \frac{\log_{10}(Chl\text{-}a \times |D\%O| \times N \times P) + 1.5}{1.2} \tag{10}$$

Where Chl-*a* is the chlorophyll-a concentration expressed as mg m^{-3}, N is total nitrogen expressed as mg m^{-3}, P is total phosphorus expressed as mg m^{-3}, and $|D\%O|$ is the absolute deviation from oxygen saturation. Nutrient concentrations originally measured in mg L^{-1} were converted to mg m^{-3} before TRIX calculation, whereas chlorophyll-*a* values reported in μg L^{-1} were used as numerically equivalent to mg m^{-3}. Oxygen saturation was calculated using equations (11) and (12).

$$\%O_2 = \frac{DO}{DO_{sat}(T)} \times 100 \tag{11}$$

$$|D\%O| = |100 - \%O_2| \tag{12}$$

Where DO is the measured dissolved oxygen (mg/L) and $DO_{sat}(T)$ s the saturation concentration as a function of temperature (Benson and Krause, 1984), equation (13).

$$DO_{sat} = 14.62 - 0.3898T + 0.006969T^2 - 5.897 \times 10^{-5}T^3 \tag{13}$$

TRIX values were classified into four levels: <4 oligotrophic, 4–5 mesotrophic, 5–6 eutrophic, >6 hypertrophic.

2.9. Carlson Trophic State Index (TSI)

The Carlson Trophic State Index (Carlson, 1977) is one of the most widely used indicators for evaluating trophic status in lacustrine ecosystems, integrating variables related to nutrient availability and phytoplankton biomass. Two sub-indices were calculated: TSI (TP), based on total phosphorus as an indicator of potential nutrient availability, and TSI (Chl-*a*), based on chlorophyll-*a* as a direct measure of phytoplankton biomass (equation (14) and (15)).

$$TSI(TP) = 14.42\ ln\ \left(TP_{\mu g/L}\right) + 4.15 \tag{14}$$

$$TSI(Chl\text{-}a) = 9.81\ ln\ \left(Chl\text{-}a_{\mu g/L}\right) + 30.6 \tag{15}$$

Where *TP* and *Chl-a* are expressed in μg/L, and trophic-status classification was performed according to the ranges proposed by Carlson (1977) and update by Carlson (1996) which define the following categories: oligotrophic (<40), mesotrophic (40–50), eutrophic (50–70), and hypereutrophic (>70).

2.10. Molar N:P ratio and nutrient limitation

Nutrient stoichiometry was evaluated using the molar N:P ratio, calculated from the concentrations of total nitrogen (N) and total phosphorus (P) in equation (16).

$$N : P = \frac{N_{total}/14.007}{P_{total}/30.974} \tag{16}$$

The Redfield (1958) ratio, which describes the average stoichiometric relationship of nutrients in aquatic systems. The interpretation of the N:P ratio was based on thresholds widely reported in the literature: values < 16 indicate potential nitrogen limitation, values > 32 suggest phosphorus limitation, and intermediate values ($16 - 32$) reflect conditions of co-limitation (Smith et al., 1999).

This process was analyzed in conjunction with the TSI indices, allowing for a more comprehensive characterization of the trophic status and of the potential constraints on nutrient availability that control primary productivity in the system.

2.11. Data analysis

Descriptive statistics were computed and expressed as mean and standard deviation for each lagoon and season. Normality was assessed using the Shapiro–Wilk test, and homoscedasticity was evaluated with Levene's test. Comparisons among lagoon within each season were performed with Kruskal–Wallis ($\alpha = 0.05$), followed by pairwise multiple comparisons with Benjamini–Hochberg (FDR) correction. Seasonal differences within each lagoon were assessed using two-tailed Mann–Whitney (U) tests. Principal component analysis (PCA) was carried out on standardized physicochemical and metal variables.

Correlations among indices were evaluated using Spearman's rank correlation coefficient (ρ). All analyses were conducted in R v.4.3 (R Core Team, 2023) using the packages *FactoMineR* (Lê et al., 2008), *factoextra* (Kassambara and Mundt, 2020), *coin* (Hothorn et al., 2008), and *ggplot2* (Wickham, 2016).

3. Results

3.1. Between-lagoon and seasonal variability of physicochemical parameters, nutrients, and metals

Significant differences among lagoons were observed for several physicochemical parameters in both seasons (Table 1). Overall, Tipicocha (Tp) consistently showed the highest values of temperature, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), total phosphorus (P), and total nitrogen (N), indicating a higher organic-matter and nutrient load compared with the other lagoons. COD in Tp increased from 15.4 ± 0.1 mg L^{-1} during the dry season to 47.5 ± 2.6 mg L^{-1} during the rainy season ($p = 0.007$). In contrast, Pomacocha (Pc) generally showed the lowest nutrient and organic-load values, whereas Tranca Grande (Tg) presented intermediate conditions for most variables.

Dissolved oxygen (DO) showed an inverse pattern, with the lowest values recorded in Tp during both seasons and the highest values in Tg during the dry season. This pattern suggests an association between higher organic enrichment and lower oxygen availability. Total phosphorus (P)and total nitrogen (N) differed significantly among lagoons in both campaigns ($p = 0.007$), with Tp recording the highest phosphorus concentrations and Tg showing the highest nitrogen values. Pomacocha showed a marked seasonal reduction in both nutrients, particularly during the rainy season.

The distribution of physicochemical parameters and nutrients shown in Fig. 2 supports these among-lagoon differences. Tipicocha exhibited greater dispersion in variables related to organic loading, particularly BOD$_5$ and COD, whereas Pc showed lower values and narrower variability for most nutrient-related parameters. These patterns indicate that the main contrast among lagoons was associated with organic and nutrient enrichment rather than with a continuous intra-lagoon spatial gradient.

Regarding metals, Fe was the only element that showed significant differences among lagoons, particularly during the rainy season ($p = 0.022$), when Tg reached the highest concentration. In contrast, Cu, Cr, Cd, Pb, and Zn showed no significant differences among lagoons in either season ($p > 0.05$), indicating relatively homogeneous metal concentrations across the evaluated systems. The distributions shown in Fig. 3 also indicate that metals exhibited less pronounced among-lagoon variability than nutrients and physicochemical parameters. Overall, these results suggest that water-quality differences among the studied lagoons were mainly driven by organic loading and nutrient enrichment, whereas metals showed a weaker and more homogeneous pattern.

The distribution of metals (Fig. 3) showed differentiated patterns among the lagoons, although with less contrast compared to the physicochemical parameters. Iron (Fe) exhibited notably higher concentrations in Tranca Grande (Tg), while Pomacocha (Pc) and Tipicocha (Tp) showed lower and relatively similar values. In the case of Cu, greater variability was observed in Tp, with values tending to be higher than those in Pc and Tg.

The trace metals expressed in μg/L (Cr, Cd, and Pb) presented low concentrations across all lagoons, with only minor differences among sites. Nevertheless, a slight tendency toward higher Cd concentrations in Pc was observed, while Cr and Pb showed higher values in Tg. Zn showed moderate variation, with slightly higher values in Pc compared to the other lagoons.

Intra-lagoon variability was relatively low for most metals, suggesting a more homogeneous spatial distribution compared to nutrients and physicochemical parameters. These results indicate that, although spatial differences exist, metals exhibit less contrasting dynamics among the lagoons evaluated.

3.2. Correlation structure among water quality variables

Fig. 4 presents a Spearman correlation heatmap with FDR-BH correction, identifying statistically significant associations among the 15 water-quality variables evaluated across the lagoons. The dendrogram revealed two main clusters. The first comprised variables associated with organic loading and nutrients total phosphorus (P), total nitrogen (N), BOD$_5$, and COD which showed positive correlations among themselves. These variables exhibited negative correlations with DO, highlighting an inverse relationship between organic enrichment and oxygen availability.

The second cluster included variables related to the physicochemical conditions of the water and certain metals, such as EC, TDS, temperature, Fe, and Zn, which showed positive associations of moderate to high magnitude. Within this cluster, EC and TDS displayed a strong association, reflecting their common control by the ionic concentration of the water.

Some metals, including Cu and Cd, exhibited more heterogeneous

Table 1

Physicochemical parameters and heavy metal concentrations in three high Andean lagoons during dry and rainy seasons.

Variable	Units	Dry season (June)				Rainy season (November)			
		Pc mean ± sd	Tp mean ± sd	Tg mean ± sd	*p*-value	Pc mean ± sd	Tp mean ± sd	Tg mean ± sd	*p*-value
pH		6.8 ± 0.06a*	7.5 ± 0.62a*	7.7 ± 0.08a*	0.105	7.9 ± 0.06a*	8.7 ± 0.41b*	8.0 ± 0.11a*	0.024
EC	μS/cm	243.9 ± 6.4a*	264.4 ± 14.4a	234.6 ± 19.4b*	0.023	281.6 ± 2.7a*	290.1 ± 5.0a	274.8 ± 12.9a*	0.080
COD	mg/L	12.4 ± 0.4a	15.4 ± 0.1b*	13.3 ± 0.5a*	0.01	12.6 ± 0.4a	47.5 ± 2.6b*	30.7 ± 0.7a*	0.007
BOD$_5$	mg/L	6.3 ± 0.34a*	12.4 ± 0.5a	5.4 ± 0.58b*	0.015	5.1 ± 0.09a*	12.4 ± 0.5b	8.3 ± 0.20a*	0.007
DO	mg/L	6.4 ± 0.43a	5.8 ± 0.23a*	7.1 ± 0.08b	0.012	7.1 ± 0.11a	6.1 ± 0.07b*	7.1 ± 0.07a	0.024
T	°C	10.6 ± 0.2a*	16.6 ± 0.5b	12.3 ± 0.2a*	0.007	14.3 ± 0.8a*	17.3 ± 0.4a	11.4 ± 0.3b*	0.007
P	mg/L	0.035 ± 0.003a*	1.5 ± 0.01b*	0.760 ± 0.003a*	0.007	0.014 ± 0.001a*	1.1 ± 0.04b*	0.740 ± 0.009a*	0.007
N	mg/L	0.374 ± 0.020a*	0.812 ± 0.054a*	1.5 ± 0.01b*	0.007	0.093 ± 0.009a*	0.470 ± 0.034a*	1.6 ± 0.04b*	0.007
Fe	mg/L	0.183 ± 0.039a	0.182 ± 0.049a	0.190 ± 0.023a*	0.790	0.169 ± 0.018a	0.199 ± 0.058a	0.909 ± 0.152b*	0.022
Cu	mg/L	0.0062 ± 0.0002a	0.0044 ± 0.0014a	0.0080 ± 0.0028a	0.110	0.0052 ± 0.0012a	0.0043 ± 0.0012a	0.0053 ± 0.0008a	0.270
Cr	mg/L	0.0001 ± 0.0000a	0.0002 ± 0.0001a	0.0001 ± 0.0000a	0.150	0.0002 ± 0.0000a	0.0002 ± 0.0000a	0.0001 ± 0.0000a	0.200
Cd	mg/L	0.0005 ± 0.0003a	0.0001 ± 0.0000a	0.0002 ± 0.0000a	0.180	0.0002 ± 0.0001a	0.0002 ± 0.0000a	0.0002 ± 0.0000a	0.580
Pb	mg/L	0.0003 ± 0.0000a	0.0004 ± 0.0001a	0.0003 ± 0.0000a	0.260	0.0003 ± 0.0000a	0.0004 ± 0.0001a	0.0002 ± 0.0000a	0.330
Zn	mg/L	0.070 ± 0.003a*	0.068 ± 0.004a*	0.066 ± 0.006a	0.530	0.083 ± 0.002a*	0.081 ± 0.008a*	0.077 ± 0.005a	0.190

EC: electrical conductivity (μS/cm); COD: chemical oxygen demand (mg/L); BOD$_5$: 5-day biochemical oxygen demand (mg/L); DO: dissolved oxygen (mg/L); T: water temperature (°C); P: total phosphorus (mg/L); N: total nitrogen (mg/L); Fe, Cu, Cr, Cd, Pb, Zn in mg/L. Different lowercase letters (a, b) within each season indicate statistically significant differences among lagoons (Kruskal-Wallis + Benjamini-Hochberg post-hoc correction, $\alpha = 0.05$). Asterisk (*) denotes a significant seasonal difference within each lagoon (Mann-Whitney bilateral test, $\alpha = 0.05$). (Pomacocha – Pc, Tipicocha – Tp, Tranca Grande – Tg).

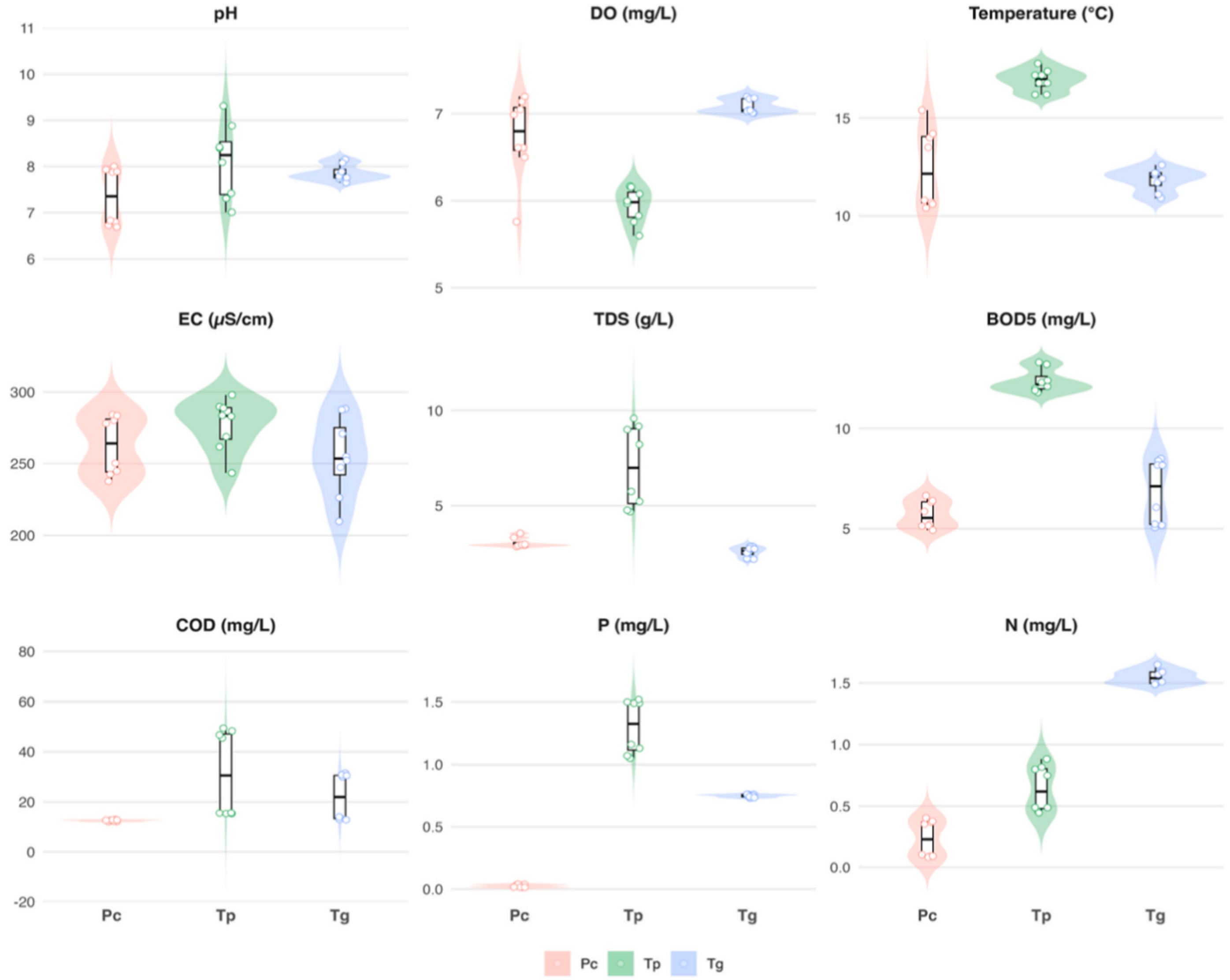

Fig. 2. Distribution of physicochemical parameters and nutrients in the lagoon Pomacocha (Pc), Tipicocha (Tp), and Tranca Grande (Tg). The violin plots represent the data distribution, the boxes indicate the interquartile range and median, and the points correspond to individual observations.

correlation patterns, indicating a more variable behavior possibly influenced by specific local conditions. The observed correlation structure suggests a clear differentiation between processes associated with nutrient and organic-matter dynamics and those related to physicochemical properties and metal presence, reflecting the coexistence of multiple gradients regulating water quality in the lagoons evaluated.

3.3. *Water quality assessment through principal component analysis*

Principal component analysis explained 60.1% of the total variability, with the first component (Dim1) accounting for 40.4% and the second component (Dim2) for 19.7% (Fig. 5). The ordination showed a clear differentiation among lagoon–season groups, indicating that water-quality variability was mainly structured by contrasts among lagoons and sampling periods.

Dim1 was mainly associated with variables related to organic, nutrient, and ionic enrichment. BOD_5, temperature, phosphorus, TDS, Cr, and Pb were projected toward positive Dim1 scores, whereas DO, total nitrogen, Fe, Cu, and Cd were oriented toward negative Dim1 scores. Samples from Tipicocha were mainly located on the positive side of Dim1, indicating their association with higher organic and nutrient enrichment.

Dim2 separated additional physicochemical and metal-related gradients. Pb, TDS, and Cd were associated with positive Dim2 scores, while pH, EC, COD, Zn, Fe, DO, and total nitrogen were oriented toward negative Dim2 scores. BOD_5 and COD showed related but not overlapping vectors, suggesting that both variables contributed differently to the multivariate structure. Similarly, pH and DO shared part of the negative Dim2 direction but were not closely collinear.

The PCA shows that organic and nutrient enrichment represented the dominant gradient differentiating lagoon–season groups, whereas metals showed a more secondary and heterogeneous contribution to water-quality variability.

3.4. *Comparison of water quality with national and international standards in high-altitude Andean lagoons used for fish farming*

The comparison shown in Table 2 reveals significant variability in compliance with national and international water-quality standards among lagoons and seasons. pH remained within the ranges established by all three regulatory frameworks in all cases. DO did not fall below the EQS ($\geq$5.0 mg/L) or USEPA ($\geq$5.5 mg/L) thresholds in any sample; however, Tipicocha did not meet the more stringent CCME guideline ($\geq$6.5 mg/L) in either season (dry: 5.80 mg/L; rainy: 6.12 mg/L). BOD_5

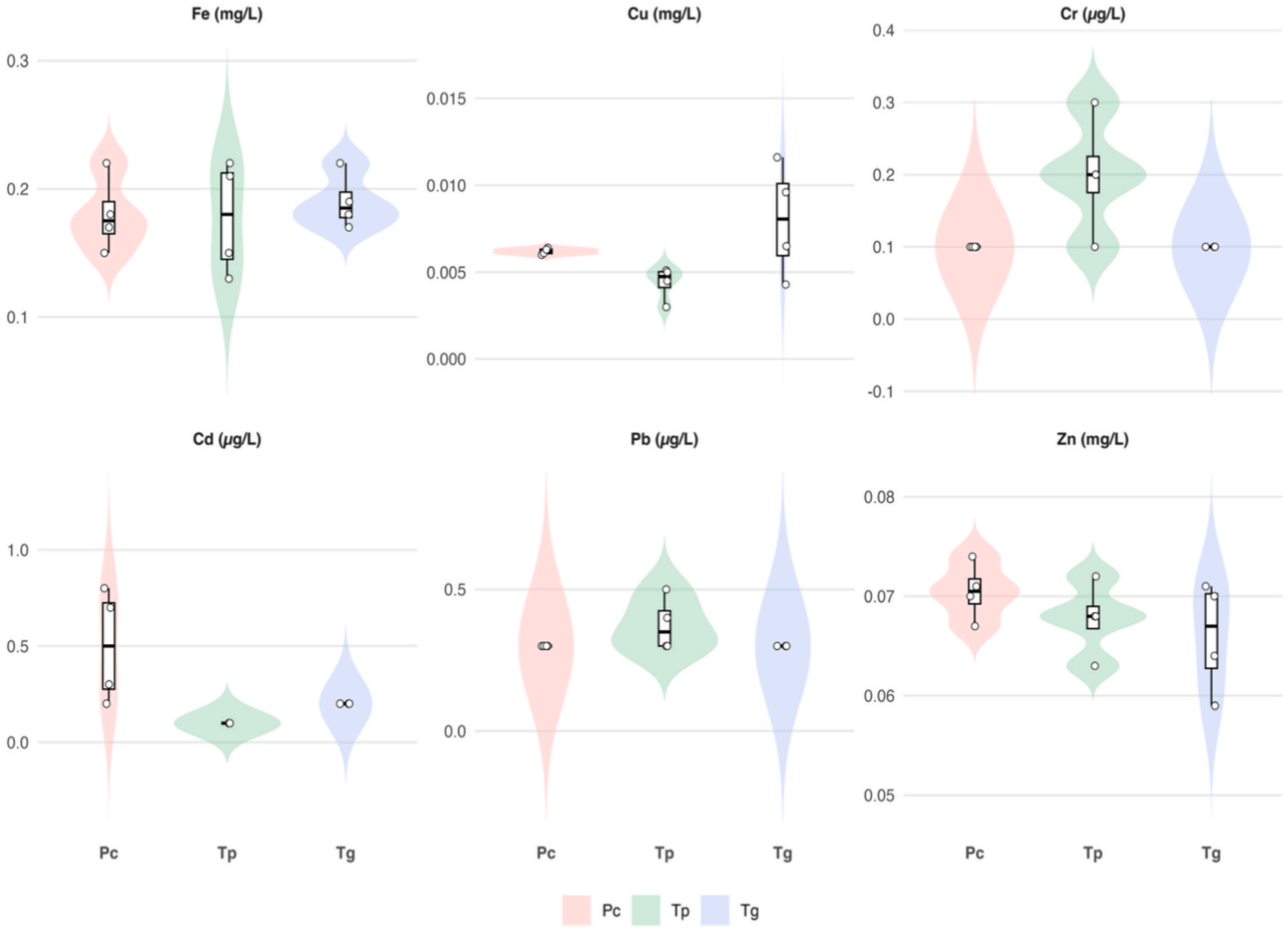

Fig. 3. Distribution of metals (Fe, Cu, Cr, Cd, Pb, and Zn) in the lagoon Pomacocha (Pc), Tipicocha (Tp), and Tranca Grande (Tg). Concentrations of Cr, Cd, and Pb are expressed in μg/L. The violin plots represent the data distribution, the boxes indicate the interquartile range and median, and the points correspond to individual observations.

exceeded the EQS standard (≤5.0 mg/L) in all lagoons and both seasons, with the highest values recorded in Tipicocha. EC remained below the EQS limit across all lagoons.

Total phosphorus (P) showed marked exceedances relative to all standards in Tipicocha and Tranca Grande in both seasons, whereas Pomacocha exhibited values at or below the EQS threshold. Total nitrogen (N) exceeded the EQS reference (≤0.315 mg/L) in all three lagoons during the dry season including Pomacocha (0.374 mg/L) and in Tipicocha and Tranca Grande during the rainy season, indicating a widespread nutrient load in these systems.

Regarding metals, Fe concentrations remained below all standard thresholds in most cases; the sole exception was Tranca Grande in the rainy season (0.909 mg/L), which exceeded the CCME limit (≤0.300 mg/L) while remaining below the USEPA criterion (≤1.000 mg/L). Cu remained below the EQS limit (≤0.100 mg/L) in all samples; however, all six observed values (0.0043–0.0080 mg/L) exceeded the CCME guideline (≤0.004 mg/L). Cr showed concentrations well below available reference thresholds in all samples.

Cd exceeded the EQS standard (≤0.00025 mg/L) in Pomacocha during the dry season (0.000350 mg/L). More notably, all samples from all lagoons and both seasons exceeded the substantially more stringent CCME guideline (≤0.000017 mg/L), indicating a systematic exceedance under this framework. Pb remained below the limits established by all three regulatory frameworks in all lagoons and seasons. Zn complied with both the EQS and USEPA thresholds (≤0.120 mg/L) across all samples; however, all six observations exceeded the CCME guideline (≤0.030 mg/L), with values ranging from 0.066 to 0.083 mg/L.

3.5. *Water quality index*

The WQI values shown in Table 3 exhibit marked variation among lagoons, seasons, and regulatory frameworks. Under the EQS Cat. 4-E1 standard, Pomacocha presented the best conditions, reaching the “good” category during the rainy season (WQI = 88.3) and “fair” during the dry season (WQI = 72.6). Tipicocha and Tranca Grande consistently fell in the “marginal” category, with WQI values ranging from 48.6 to 54.8, indicating a higher frequency and magnitude of guideline exceedances.

Under the CCME framework, the assessment was more restrictive, with a predominance of “marginal” to “poor” categories across all lagoons. Tipicocha recorded the lowest index values (WQI ≈ 29–30), classified as “poor” in both seasons. Tranca Grande was similarly classified as “poor” in both seasons, with its lowest value recorded in the rainy season (WQI = 30.1). Pomacocha showed a relative improvement during the rainy season (WQI = 66.8), reaching the “fair” category.

Under the USEPA CCC criteria, the evaluation was less restrictive. Pomacocha attained the “good” category in both seasons, with a value approaching “excellent” in the rainy season (WQI = 93.4). Tipicocha and Tranca Grande were classified as “marginal,” with WQI values ranging from 55.1 to 57.7.

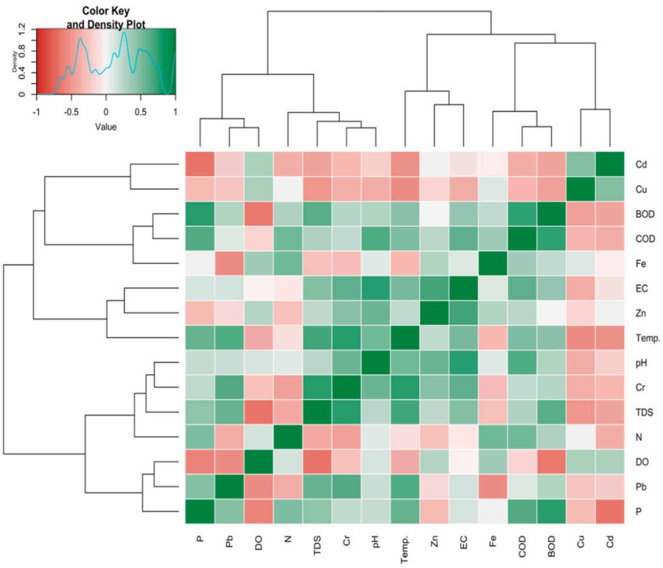

Fig. 4. Spearman correlation heatmap among physicochemical, nutrient, and metal variables in the studied lagoons. Colors represent the intensity and direction of the correlation (red: negative; green: positive). The dendrogram indicates hierarchical clustering of variables according to their similarity. Physicochemical variables: pH, electrical conductivity (EC), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), dissolved oxygen (DO), temperature (T), and total dissolved solids (TDS); nutrients: total phosphorus (P) and total nitrogen (N); heavy metals: iron (Fe), copper (Cu), chromium (Cr), cadmium (Cd), lead (Pb), and zinc (Zn).

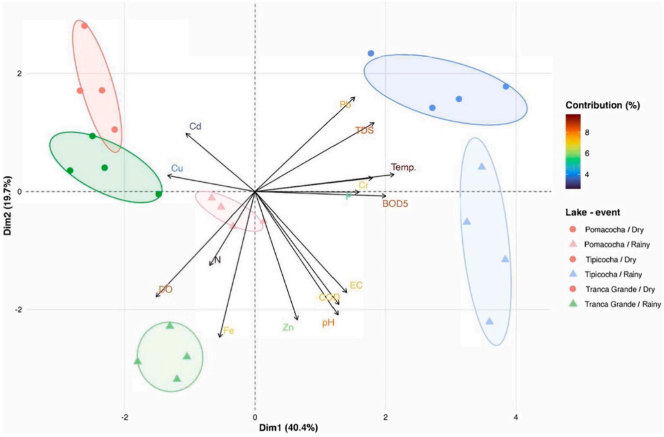

Fig. 5. Principal component analysis (PCA) of physicochemical parameters and dissolved metals in three high-altitude Andean lagoons (Pomacocha, Tipicocha, and Tranca Grande) during dry and rainy season sampling events. Points represent individual samples grouped by lagoon and season; ellipses indicate multivariate dispersion (68% confidence interval). Arrows represent the original variables, whose direction and magnitude reflect their contribution and correlation with the principal axes. The color scale indicates the relative contribution (%) of each variable to the model.

These results confirm that water-quality assessment varies substantially depending on the regulatory standard applied, with CCME criteria being the most stringent, followed by Peruvian EQS and USEPA. A consistent pattern of lower quality in Tipicocha and Tranca Grande relative to Pomacocha is evident across all frameworks. Seasonal improvement was most pronounced in Pomacocha, whereas Tranca Grande showed no consistent improvement during the rainy season.

3.6. Heavy metal pollution indices (HPI and HEI)

Table 4 shows a marked dependence of the pollution indices on the regulatory standard used for interpretation, rather than on substantial variation in the observed metal concentrations. Under the national regulatory framework (EQS Cat. 4-E1), HPI values (12.4–18.7) and HEI values (1.24–1.45) remained within the low contamination category in both seasons, suggesting limited influence of metals on water quality degradation in the evaluated systems. Similarly, under USEPA CCC criteria, the obtained values (HPI: 10.5–14.2; HEI: 0.88–1.06) were consistently classified as low contamination, reinforcing the interpretation of reduced metal-related pressure.

In contrast, application of the Canadian standard (CCME) revealed greater sensitivity of the HPI, particularly during the rainy season, where values increased from 78.3 to 105.1, shifting from low to high contamination classification. Under this same standard, the HEI indicated medium contamination in both seasons (2.65–3.82), which, although the total metal load remains moderate, reflects exceedances of individual elements against the more stringent thresholds defined by this framework.

3.7. Nutrients and TRIX (trophic status)

The TRIX index (Table 5) indicated predominantly eutrophic conditions across the three lagoons evaluated during both seasons. In the dry season, values ranged from 5.46 ± 0.10 in Pomacocha to 5.74 ± 0.08 in Tipicocha, with Tranca Grande showing an intermediate value of 5.68 ± 0.07; all three lagoons were classified as eutrophic.

During the rainy season, a general increase in the index was observed, particularly in Tipicocha (5.87 ± 0.38) and Tranca Grande (6.21 ± 0.14). Tranca Grande reached values above 6 in the rainy season, corresponding to a hypertrophic state. In contrast, Pomacocha exhibited lower seasonal variability, remaining within the eutrophic range (5.66 ± 0.06).

A consistent eutrophic pattern was observed across lagoons, with a tendency toward higher TRIX values during the rainy season. Tranca Grande reached the highest trophic state during the rainy season, attaining hypertrophic conditions, possibly associated with greater hydrological connectivity and nutrient inputs during higher water inflow periods.

3.8. Carlson TSI (TP), TSI (Chl-a), and N:P ratio indices

The trophic indices showed marked spatial heterogeneity among lagoons and a differentiated response between metrics based on nutrients and phytoplankton biomass (Table 6). TSI (TP) exhibited consistently elevated values in Tipicocha and Tranca Grande during both seasons, classifying them as hypereutrophic and reflecting high phosphorus availability in these systems. TSI (TP) values exceeding 100 in Tipicocha reflect extremely high total phosphorus concentrations relative to the Carlson calibration range, which is consistent with the observed values in Table 1. In contrast, Pomacocha showed lower TSI (TP) values, classified as eutrophic during the dry season and mesotrophic during the rainy season.

TSI (Chl-*a*) indicated eutrophic conditions in all three lagoons in both seasons, with lower variability among sites and seasons compared to TSI (TP). This relative homogeneity may indicate a more uniform phytoplankton biomass response across lagoons despite their differing nutrient loads.

The molar N:P ratio revealed contrasting nutrient limitation patterns among lagoons. Pomacocha showed values consistent with co-limitation during the dry season (N:P = 23.72) and potential nitrogen limitation during the rainy season (N:P = 14.97). Conversely, Tipicocha and Tranca Grande showed consistently low N:P ratios in both seasons (0.97–4.65), indicating strong nitrogen limitation. These findings reveal clear differences in trophic structure: Tipicocha and Tranca Grande are

Table 2
Comparison of physicochemical parameters and metals with water-quality standards (Peruvian EQS, CCME, and USEPA) in three high-altitude Andean lagoons during dry and rainy seasons.

Variable	Unit	EQS Cat.4-E1	CCME	USEPA CCC	Pc-Dry	Tp-Dry	Tg-Dry	Pc-Rainy	Tp-Rainy	Tg-Rainy
pH	—	6.5–9.0	6.5–9.0	6.5–9.0	6.762	7.531	7.745	7.933	8.740	7.973
BOD5	mg/L	≤5.0	—	—	**6.29**	**12.37**	**5.36**	**5.07**	**12.36**	**8.27**
DO	mg/L	≥5.0	≥6.5	≥5.5	6.43	5.80	7.11	7.12	6.12	7.09
EC	μS/cm	≤1000	—	—	245.00	264.00	235.00	282.00	290.00	275.00
P total	mg/L	≤0.035	≤0.050	≤0.100	**0.035**	**1.498**	**0.760**	0.014	**1.070**	**0.740**
N total	mg/L	≤0.315	—	—	**0.374**	**0.812**	**1.480**	0.093	**0.469**	**1.555**
Fe	mg/L	—	≤0.300	≤1.000	0.183	0.182	0.190	0.169	0.199	**0.909**
Cu	mg/L	≤0.100	≤0.004	≤0.009	**0.0062**	**0.0044**	**0.0080**	**0.0052**	**0.0043**	**0.0053**
Cr	mg/L	—	≤0.0089	—	0.000143	0.000245	0.000145	0.000165	0.000195	0.000140
Cd	mg/L	≤0.00025	≤0.000017	≤0.000250	**0.000350**	0.000140	0.000173	0.000185	0.000188	0.000163
Pb	mg/L	≤0.0025	≤0.001	≤0.0025	0.000270	0.000375	0.000270	0.000250	0.000355	0.000235
Zn	mg/L	≤0.120	≤0.030	≤0.120	**0.0695**	**0.0678**	**0.0660**	**0.0831**	**0.0808**	**0.0768**

Bold/red values indicate exceedances with respect to at least one standard. * exceeds CCME only; † exceeds CCME but not USEPA; ‡ exceeds CCME only (EQS and USEPA not exceeded). Pc = Pomacocha; Tp = Tipicocha; Tg = Tranca Grande. EQS = Environmental Quality Standards for Water of Peru, Category 4-E1, Supreme Decree 004-2017-MINAM; CCME = Canadian Water Quality Guidelines for the Protection of Aquatic Life; USEPA = National Recommended Water Quality Criteria (CCC, freshwater). Criteria for certain metals depend on water hardness and physicochemical conditions; values reported here are reference thresholds for comparative purposes only.

Table 3
CCME-WQI values under three water-quality standards in three high-altitude Andean lagoons during dry and rainy seasons.

Standard	Lagoon	Season	F1 (%)	F2 (%)	F3	WQI	Quality
EQS Cat.4-E1	Pomacocha (Pc)	Dry	36.4	27.3	13.6	72.6	Fair
	Pomacocha (Pc)	Rainy	18.2	9.1	0.4	88.3	Good
	Tipicocha (Tp)	Dry	27.3	27.3	80.3	48.6	Marginal
	Tipicocha (Tp)	Rainy	36.4	31.8	74.1	48.9	Marginal
	Tranca G. (Tg)	Dry	27.3	25.0	69.0	54.8	Marginal
	Tranca G. (Tg)	Rainy	36.4	31.8	69.2	51.3	Marginal
CCME Aquatic Life	Pomacocha (Pc)	Dry	54.5	54.5	46.2	48.1	Marginal
	Pomacocha (Pc)	Rainy	36.4	34.1	28.8	66.8	Fair
	Tipicocha (Tp)	Dry	63.6	56.8	87.9	29.3	Poor
	Tipicocha (Tp)	Rainy	63.6	59.1	84.2	30.2	Poor
	Tranca G. (Tg)	Dry	54.5	52.3	80.7	36.2	Poor
	Tranca G. (Tg)	Rainy	63.6	63.6	80.9	30.1	Poor
USEPA CCC	Pomacocha (Pc)	Dry	18.2	11.4	2.3	87.5	Good
	Pomacocha (Pc)	Rainy	9.1	6.8	0.2	93.4	Good
	Tipicocha (Tp)	Dry	18.2	18.2	73.5	55.1	Marginal
	Tipicocha (Tp)	Rainy	27.3	22.7	66.5	56.5	Marginal
	Tranca G. (Tg)	Dry	36.4	27.3	57.4	57.7	Marginal
	Tranca G. (Tg)	Rainy	36.4	31.8	57.7	56.5	Marginal

F_1 = Scope (% of variables exceeding threshold); F_2 = Frequency (% of tests exceeding threshold); F_3 = Amplitude (magnitude of exceedance); WQI = Water Quality Index. Evaluated variables: pH, EC, BOD_5, DO, P, N, Fe, Cu, Cr, Cd, Pb, Zn. Pc = Pomacocha; Tp = Tipicocha; Tg = Tranca Grande. EQS = Peruvian Environmental Quality Standards, Category 4-E1, Supreme Decree 004-2017-MINAM; CCME = Canadian Water Quality Guidelines for the Protection of Aquatic Life; USEPA CCC = National Recommended Water Quality Criteria, chronic freshwater criteria. Water quality classification: Excellent (95 – 100), Good (80 – 94), Fair (65 – 79), Marginal (45 – 64), Poor (0–44).

characterized by high phosphorus availability and strong potential nitrogen restriction, whereas Pomacocha presents relatively less enriched conditions and a more balanced nutrient dynamic.

4. Discussion

4.1. Organic loading and nutrient gradients

The results indicate that water quality in these high-altitude Andean lagoons used for fish farming is primarily structured by gradients of organic loading and nutrients, with Tipicocha consistently showing the highest concentrations of BOD_5, COD, total phosphorus, and total nitrogen, together with the lowest dissolved oxygen values. This pattern closely resembles that reported for other high-Andean lagoons in Junín, where Custodio and Peñaloza (2025) also found strong nutrient enrichment and oxygen depletion associated with fish farming and other local pressures. Similar responses have been observed in tropical and large lakes subject to cage aquaculture, where uneaten feed and excretions increase organic matter and dissolved nutrients, altering oxygen dynamics and water quality (Lubembe et al., 2024).

The PCA further supported this interpretation but also showed that BOD_5 and COD did not provide completely redundant information. Their partial separation suggests that both variables captured complementary components of organic enrichment: BOD_5 is more closely related to the biodegradable organic fraction and microbial oxygen demand, whereas COD represents a broader pool of chemically oxidizable compounds, including less biodegradable organic matter and other reducing substances. Similarly, the relative position of pH and dissolved oxygen should be interpreted with caution. Although both variables may respond partly to surface-water processes such as photosynthesis, respiration, and carbonate–CO_2 equilibrium, dissolved oxygen is also strongly influenced by organic matter degradation and mixing conditions. Therefore, their orientation in the PCA should be understood as part of the interacting physicochemical variability of these lagoons rather than as evidence of a direct causal relationship.

In the high-Andean context, the effects of organic and nutrient enrichment may be amplified by low buffering capacity, reduced water renewal, and low temperatures, which favor the accumulation of organic matter and slow its decomposition, as also highlighted for other mountain lakes by Machate et al. (2023). Hydrological seasonality acted mainly as a modulating factor, intensifying or attenuating pre-existing among-lagoon gradients rather than redefining them. This is consistent with observations from Andean wetlands and lagoons where between-lagoon differences linked to morphometry, hydrological setting, and intensity of use may outweigh purely seasonal effects (Custodio et al., 2018a,b; García-Sanz et al., 2021).

Table 4

Heavy metal pollution index (HPI) and heavy metal evaluation index (HEI) values under EQS, CCME, and USEPA frameworks by season.

Standard	Season	HPI	HPI quality	HEI	HEI quality
EQS Cat. 4-E1	Dry	12.4	Low contamination	1.24	Low contamination
EQS Cat. 4-E1	Rainy	18.7	Low contamination	1.45	Low contamination
CCME Aquatic Life	Dry	78.3	Low contamination	2.65	Medium contamination
CCME Aquatic Life	Rainy	105.1	High contamination	3.82	Medium contamination
USEPA CCC	Dry	10.5	Low contamination	0.88	Low contamination
USEPA CCC	Rainy	14.2	Low contamination	1.06	Low contamination

HPI = Heavy Metal Pollution Index; HEI = Heavy Metal Evaluation Index. Indices were calculated independently for each regulatory framework, considering only metals with available guideline values: EQS Cat. 4-E1 (Cu, Cd, Pb, Zn); CCME (Fe, Cu, Cr, Cd, Pb, Zn); USEPA CCC (Fe, Cu, Cd, Pb, Zn). Some metal thresholds under CCME and USEPA depend on water hardness and are used here for comparative purposes. HPI classification: low (less than 100), high (100 or above). HEI classification: low (less than 2), medium (2 – 4), high (greater than 4).

Table 5

TRIX index and trophic-status classification in the high-altitude Andean lagoon Pomacocha (Pc), Tipicocha (Tp), and Tranca Grande (Tg) during the dry and rainy seasons.

Lagoon	Season	TRIX	Trophic status
Pomacocha (Pc)	Dry	5.463 ± 0.099	Eutrophic
Tipicocha (Tp)	Dry	5.739 ± 0.081	Eutrophic
Tranca Grande (Tg)	Dry	5.678 ± 0.071	Eutrophic
Pomacocha (Pc)	Rainy	5.658 ± 0.064	Eutrophic
Tipicocha (Tp)	Rainy	5.873 ± 0.384	Eutrophic
Tranca Grande (Tg)	Rainy	6.206 ± 0.144	Hypertrophic

Values are presented as mean ± standard deviation from field replicates. Trophic-status classification was performed according to the ranges established by Vollenweider et al. (1998): oligotrophic (<4), mesotrophic (4 – 5), eutrophic (5 – 6), and hypertrophic (>6).

4.2. *Trophic status and nutrient limitation*

The joint assessment of TRIX and Carlson indices shows that eutrophication is the main alteration mechanism in the studied lagoons, but with marked between-lagoon differences. According to TSI (TP), Tipicocha and Tranca Grande reached hypereutrophic conditions, whereas Pomacocha ranged from mesotrophic to eutrophic. However, TRIX classified most lagoon–season combinations as eutrophic, with hypertrophic conditions only in Tranca Grande during the rainy season. The pronounced divergence between TSI (TP) and TSI (Chl-*a*), particularly in Tipicocha, where extremely high phosphorus concentrations coexisted with chlorophyll-*a* values characteristic of a eutrophic but not extreme state, suggests a partial decoupling between nutrient availability and phytoplankton biomass response. Similar discrepancies among trophic state indices have been described for temperate and Polish lakes, where TSI_{TP} tends to overestimate trophic status relative to chlorophyll in systems subject to additional physical or biological constraints (Karpowicz et al., 2025).

The molar N:P ratios suggested contrasting nutrient-constraint patterns that help explain these trophic configurations: Tipicocha and Tranca Grande exhibited consistently low N:P ratios, indicating strong potential nitrogen limitation, whereas Pomacocha shifted from co-limitation during the dry season to potential nitrogen limitation during the rainy season. Because TN:TP ratios are indirect indicators of nutrient limitation, these patterns should be interpreted as potential nutrient constraints rather than direct experimental evidence of limitation. This situation is comparable to that reported by Custodio and Peñaloza (2025) for other fish-farming lagoons in Junín, where high phosphorus availability and low N:P ratios favored nitrogen limitation and complex phytoplankton responses.

4.3. *Metal contamination and regulatory framework sensitivity*

Unlike nutrients, heavy metals showed more limited spatial and temporal variability, suggesting dynamics driven mainly by geogenic and diffuse processes rather than by strong point-source inputs. Similar behavior has been reported in other mountain aquatic systems, where local geology, weathering, and redox conditions exert primary control over metal mobilization and partitioning between dissolved and particulate phases (García-Sanz et al., 2021; Haque et al., 2024). Accordingly, HPI and HEI values indicated generally low contamination under the Peruvian EQS and USEPA criteria, in line with studies from low-industrialization basins where metals do not constitute the main driver of water quality degradation (Chettri et al., 2022).

However, the sensitivity of these indices changed markedly depending on the regulatory framework used, with CCME thresholds indicating medium contamination for HEI and, in the rainy season, high contamination for HPI (105.1). This result echoes the findings of Li (2014), who showed that index-based water quality classifications can vary substantially as a function of the numerical thresholds and

Table 6

Carlson Trophic State Index and molar N:P ratio for the three lagoons during the dry and rainy seasons.

Lagoon	Season	TSI (TP)	Trophic status (TP)	TSI (Chl-*a*)	Trophic status (Chl-*a*)	Molar N:P	N:P interpretation
Pomacocha (Pc)	Dry	55.45 ± 1.11	Eutrophic	53.12 ± 2.75	Eutrophic	23.72 ± 2.89	Co-limitation
Pomacocha (Pc)	Rainy	42.02 ± 0.81	Mesotrophic	54.28 ± 1.30	Eutrophic	14.97 ± 1.91	N limitation
Tipicocha (Tp)	Dry	109.59 ± 0.11	Hypereutrophic	59.73 ± 0.52	Eutrophic	1.20 ± 0.09	N limitation
Tipicocha (Tp)	Rainy	104.73 ± 0.48	Hypereutrophic	54.63 ± 1.89	Eutrophic	0.97 ± 0.04	N limitation
Tranca Grande (Tg)	Dry	99.81 ± 0.06	Hypereutrophic	58.81 ± 0.28	Eutrophic	4.31 ± 0.04	N limitation
Tranca Grande (Tg)	Rainy	99.42 ± 0.17	Hypereutrophic	57.96 ± 1.99	Eutrophic	4.65 ± 0.15	N limitation

Trophic state indices calculated for Pomacocha (Pc), Tipicocha (Tp), and Tranca Grande (Tg) during the dry and rainy seasons. TSI(TP) and TSI(*Chl-a*) were calculated using Carlson's trophic state equations for lacustrine systems, with total phosphorus (TP) and chlorophyll-a expressed in $\mu g\ L^{-1}$. The N:P ratio was estimated on a molar basis from total nitrogen and total phosphorus concentrations originally measured in $mg\ L^{-1}$. Values are presented as mean ± standard deviation from field replicates. Trophic classification followed the conventional Carlson TSI interpretation: oligotrophic (<40), mesotrophic (40–50), eutrophic (50–70), and hypereutrophic (>70). The molar N:P ratio was interpreted as an indicator of potential nutrient limitation: $N:P < 16$ suggests nitrogen limitation, 16–32 suggests co-limitation, and >32 suggests phosphorus limitation.

protection goals embedded in each guideline set. In our case, the differences observed among EQS, CCME, and USEPA standards demonstrate that water quality is not an absolute attribute, but rather a construct contingent on the reference values adopted, as also highlighted for other Andean and mining-influenced systems (García-Sanz et al., 2021; Haque et al., 2024).

The integration of multivariate analyses (PCA) with water-quality indices (WQI), trophic indices (TRIX, TSI), and metal indices (HPI, HEI) proved useful to capture the coexistence of multiple processes regulating water quality in the studied lagoons. Similar to recent approaches that combine multivariate statistics with index-based tools to synthesize complex datasets, this framework allowed us to identify dominant gradients, explore relationships among variables, and strengthen the ecological interpretation of the observed patterns (Muniz and Oliveira-Filho, 2023). Compared with studies relying on isolated indicators, our combined approach offers a more comprehensive basis to interpret how fish farming, natural geochemical background, and regulatory choices jointly shape the diagnosis of water quality and ecological risk in high-altitude Andean lagoons.

Although TRIX was originally developed for Mediterranean coastal systems, its application in high-altitude Andean lagoons can be understood as an exploratory and comparative use within a multi-index framework. In this sense, studies such as the present one represent an initial step toward evaluating the transferability of methodologies developed in European contexts to high-altitude Andean ecosystems, where altitude, low temperature, seasonal hydrology, and limited dilution capacity may modify the trophic response of the system. Therefore, TRIX-derived results should not be interpreted as a definitive validation of the index for these environments, but rather as a preliminary approximation that requires future local calibration, comparison with biological indicators, and longer-term monitoring.

4.4. Implications for fish farming management

Our results have clear implications for the management of cage-based fish farming in high-altitude Andean lagoons. The strong nutrient enrichment and hypereutrophic conditions indicated by TSI (TP) in Tipicocha and Tranca Grande, together with very low N:P ratios, suggest that nutrient inputs may be exceeding the apparent capacity of these systems to assimilate organic and phosphorus loads without trophic deterioration (Gao et al., 2025). In contrast, the meso-to eutrophic status and comparatively less severe nutrient imbalance observed in Pomacocha suggest that this lagoon may have a lower degree of trophic alteration than Tipicocha and Tranca Grande, although it remains vulnerable to further increases in nutrient loading, as described for other mountain lakes (Custodio and Peñaloza, 2025; Machate et al., 2023).

From a management perspective, these patterns support the implementation of site-specific production limits and feed management strategies, rather than uniform regulations across all lagoons. Measures such as optimizing feed conversion ratios, reducing feed losses, and adapting diet formulations to minimize phosphorus discharge have been shown to substantially reduce nutrient emissions from cage aquaculture (Dalsgaard et al., 2023). In addition, international experience demonstrates that monitoring frameworks that combine trophic indices, multivariate analyses, and metal-based indices can provide early warning signals of environmental degradation and guide adaptive management in intensively farmed lakes (Song et al., 2023). Our integrated multi-index approach is therefore directly applicable as a decision-support tool for defining lagoon-specific environmental thresholds and for designing more sustainable fish farming practices in high-altitude Andean ecosystems.

5. Conclusions

The study shows that organic and nutrient enrichment constitutes the dominant axis structuring the differences among lagoons and seasons, whereas metals play a secondary role and appear to respond mainly to geogenic controls and diffuse inputs. These findings indicate the need to expand research and environmental monitoring in these high-altitude lacustrine ecosystems in order to better identify potential sources of metals in the water.

The comparison of trophic indices indicates that all lagoons show signs of eutrophication; however, the phytoplankton response was not proportional to the degree of phosphorus enrichment. The decoupling between TSI (TP) and TSI (Chl-*a*), together with the contrasting N:P ratio patterns, reflects the influence of multiple environmental constraints characteristic of high-mountain systems and supports the use of approaches based on multiple nutrients and complementary indices.

Likewise, the differences in water-quality and metal-risk classification among the ECA, CCME, and USEPA criteria show that environmental diagnosis strongly depends on the regulatory framework applied. In this context, the integration of PCA, WQI, trophic indices, and metal indices constitutes a methodological framework transferable to other high-altitude Andean lagoons.

From a management perspective, this approach may support monitoring programs that integrate trophic, chemical, and regulatory indicators, prioritizing lagoons and seasons with higher nutrient loads and lower dilution capacity. It also provides technical criteria to guide production limits, cage location and density, feed management, and public policies aimed at reconciling aquaculture development with the conservation of increasingly pressured high-Andean water resources.

CRediT authorship contribution statement

María Custodio: Conceptualization, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Javier Huarcaya:** Conceptualization, Methodology, Project administration. **Dennis Ccopi:** Formal analysis, Methodology, Visualization. **Daniel Alvarez:** Data curation, Formal analysis, Methodology. **Samuel Pizarro:** Methodology, Validation, Visualization, Writing – review & editing. **Kevin Ortega:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maria Custodio reports equipment, drugs, or supplies was provided by National University of the Center of Peru. None If there are other authors, they 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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Data availability

Data will be made available on request.

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