Ecological Indicators 182 (2026) 114511

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Bioindicators in high-mountain lakes of the Alps: A viewpoint on current status and possible future directions

Paolo Pastorino[a,*], Antonia Concetta Elia[b], Elisabetta Pizzul[c], Marco Bertoli[c], Monia Renzi[c], Marino Prearo[a], Damià Barceló[d]

[a] Istituto Zooprofilattico Sperimentale del Piemonte, Liguria e Valle d'Aosta, via Bologna 148, 10154 Torino, Italy
[b] Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia, via Elce di Sotto 8, 06123 Perugia, Italy
[c] Dipartimento di Scienze della Vita, Università degli Studi di Trieste, via L. Giorgieri 10, 34127 Trieste, Italy
[d] Chemistry and Physics Department, University of Almeria, 04120 Almería, Spain

ARTICLE INFO

Keywords:
Alpine lakes
Amphibians
Diatoms
Fish
Macroinvertebrates
Phytoplankton, zooplankton

ABSTRACT

High-mountain lakes in the Alps are unique but highly sensitive ecosystems, characterized by nutrient scarcity, short ice-free periods, and simple food webs. Their remoteness and low local disturbance make them well-recognized sentinels of global environmental change, yet they are increasingly affected by climate warming, long-range atmospheric deposition, invasive species, and local anthropogenic pressures. Bioindicators represent key tools to assess these dynamics, but their application in Alpine lakes remains fragmented. To evaluate the current state of knowledge, we conducted a Scopus-based literature survey that retrieved 45 eligible studies published between 1997 and 2025. The analysis shows that research has primarily focused on macroinvertebrates, diatoms, and zooplankton, with fewer studies addressing fish, phytoplankton, and amphibians. Most investigations adopted single-taxon approaches, limiting the ability to capture ecosystem complexity and multi-stressor interactions. Moreover, geographic representation was uneven, with Italy and Austria dominating research efforts and other Alpine countries remaining underrepresented. A future shift toward multimetric indices integrating structural and functional indicators across trophic levels is required to achieve more comprehensive ecological assessments. These frameworks should be coupled with chemical monitoring, ecotoxicological bioassays, and emerging tools such as environmental DNA, paleoecological reconstructions, and remote sensing. Standardized protocols, shared databases, and collaborative networks will be essential to overcome current limitations. Advancing toward integrative and harmonized monitoring approaches will ensure that high-mountain lakes continue to function as critical benchmarks of ecological resilience and as early-warning systems under accelerating global change.

1. Introduction and scope of the perspective

High-mountain lakes in the Alps are unique but fragile ecosystems (Pastorino et al., 2024a). They are situated at high elevations, typically above the tree line (over 1500 m a.s.l.), often remote from roads and human settlements, and shaped by extreme environmental conditions (Catalan et al., 2006). These lakes are usually cold, low in nutrients, and covered by ice for much of the year (Battarbee et al., 2009). As a result, they have short growing seasons and support only a limited number of highly adapted species (Catalan et al., 2006). Their simple food webs and low levels of disturbance make them ideal places to study natural ecological processes and detect changes in the environment (Sánchez-Hernández et al., 2015).

In the Alpine region, there are several thousand high-mountain lakes, with Switzerland alone hosting nearly 1000 lakes at high elevations, most of them formed after the Little Ice Age (Mölg et al., 2021). The vast majority are very small, often less than 10 ha in surface area and only a few meters deep, while lakes exceeding 1 km^2 are extremely rare (Ma et al., 2021). This small size, combined with their reduced water volume, makes them particularly sensitive to changes in temperature, precipitation, and contaminant inputs (Pastorino et al., 2024a). Even minor alterations in climate or chemistry can rapidly influence their structure, nutrient dynamics, and resident biota (Rogora et al., 2003). Their limited buffering capacity also means that stress signals tend to

* Corresponding author.
E-mail address: paolo.pastorino@izsplv.it (P. Pastorino).

https://doi.org/10.1016/j.ecolind.2025.114511
Received 18 August 2025; Received in revised form 16 November 2025; Accepted 1 December 2025
Available online 11 December 2025
1470-160X/

manifest more quickly and with greater intensity than in larger, more complex lake systems (Schreder et al., 2023).

Compared to lowland lakes or other aquatic systems, Alpine high-mountain lakes are generally less directly impacted by local human activities such as agriculture, urbanization, or industrial discharges (Machate et al., 2023). This relative isolation allows them in many situations to have baseline condition closer to natural reference states, making them especially valuable for detecting subtle, long-term trends linked to global-scale drivers (Pastorino and Prearo, 2020). While lakes at lower elevations often experience rapid and visible degradation due to local pressures, the changes in high-mountain lakes can be slower but more tightly linked to large-scale atmospheric, climatic, and biogeochemical processes (Catalan et al., 2006).

Although they may seem untouched, these lakes are not protected from the effects of global change (Pastorino and Prearo, 2020). In recent years, alpine ecosystems have become increasingly affected by large-scale environmental pressures. Climate warming is altering temperature regimes, snow cover, and the timing of ice melt, thereby modifying the physical and chemical characteristics of high-mountain lakes (Smits et al., 2021). It is also driving a progressive contraction of alpine ecosystems, reducing the area available for cold-adapted biota (Frei et al., 2023). Upward treeline shifts and habitat loss are leading to range contractions, with cold specialists being replaced by thermophilous taxa (Rogora et al., 2018). Consequently, alpine lakes and ponds are experiencing increased disappearance linked to warming and glacier retreat (Lamouille-Hébert et al., 2024), disrupting biological communities and altering ecosystem functioning (Dainese et al., 2024).

In addition, many high-mountain lakes receive pollution from distant sources through the atmosphere (Machate et al., 2024). Pollutants such as nitrogen, sulfur, heavy metals, and persistent organic pollutants are carried by wind and rain and accumulate in lake water, sediments, and organisms (Camarero et al., 2009; Queral-Beltran et al., 2025). More recently, studies have found traces of personal care products, and microplastics even in these remote areas, showing that no place is completely free from human influence (Schmid et al., 2007; Pastorino et al., 2022a).

Another major concern is the introduction of non-native species, especially fish stocked for recreational fishing (Ventura et al., 2017). These species can disrupt native communities, reduce biodiversity, and impact sensitive groups such as amphibians (Tiberti and von Hardenberg, 2012). At the same time, tourism, land-use change, and shifting vegetation patterns due to warming all add new pressures to these already vulnerable systems (Schirpke et al., 2021).

Due to these combined stressors, Alpine high-mountain lakes are now widely recognized as early-warning systems or “sentinels” for environmental change (Birck et al., 2013; Moser et al., 2019; Medina-Sánchez et al., 2022; Lone and Balakrishna, 2023).

In this context, ecological indicators serve as essential tools for assessing ecosystem status and dynamics. Broadly defined, an ecological indicator can be considered a component, or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals (Heink and Kowarik, 2010). This includes both descriptive indicators (e.g., biological measures used to reflect environmental states) and normative indicators (used to evaluate the condition of ecosystems against desired targets or policy goals) (Heink and Kowarik, 2010). Indicators may derive from specific taxa, processes (e.g., decomposition), or environmental measures (e.g., temperature, pollutant concentrations), and they operate across various levels of ecological complexity (Dale and Beyeler, 2001). In a more restrictive sense, ecological indicators are sometimes considered solely in terms of biological components, such as individual species, populations, or communities, which can serve as sensitive measures of environmental change (Spellerberg, 2005). In this context, the concept of bioindicators is often employed, referring to organisms or biological responses that provide information on the quality of the environment and the intensity of anthropogenic pressures (Carignan and Villard, 2002; Markert et al., 2003). Bioindicators can range from microorganisms and plants to invertebrates and vertebrates, and are widely used in ecological monitoring because they integrate the effects of multiple stressors over space and time, often offering more ecologically relevant insights than purely physicochemical measurements (Parmar et al., 2016). In a broad sense, water physicochemical parameters such as temperature, dissolved oxygen, pH, conductivity, and nutrient concentrations can also be considered ecological indicators, as they provide critical information on habitat quality, ecological processes, and potential stressors, and are widely used alongside biological metrics in environmental assessment frameworks (US EPA, 2002; OECD, 2008). However, within the European Water Framework Directive (WFD), these variables are formally classified as supporting elements rather than biological quality elements, and are used to complement, rather than define, the assessment of ecological status (European Parliament and Council, 2000). It is important to note that the WFD ecological quality indicator framework itself is robust; challenges in capturing ecological status for certain waterbody types are often linked to how the framework is implemented at the national level, rather than to inadequacies in the Directive itself (Heiskanen et al., 2004). Member States may also integrate complementary indicators where needed to improve the ecological status classification (Hering et al., 2010).

The WFD largely excludes high-mountain lakes from its official monitoring network, as it prioritizes larger and more accessible lake systems; for example, monitoring efforts often focus on lakes with a surface area greater than 0.5 km^2, overlooking many smaller lakes (Boggero et al., 2023). Moreorver, despite the existence of the WFD as a common policy framework and the considerable intercalibration efforts carried out at the European level, a truly harmonized and comprehensive assessment framework specifically tailored for high-mountain lakes of the Alps is still lacking. In practice, the available literature remains fragmented: studies often focus on single taxa, are not standardized across regions, and rarely integrate multiple sources of ecological information. This fragmented approach makes it more challenging to obtain a holistic picture of environmental change in these sensitive habitats. This article does not aim to provide a systematic review; rather, it offers a literature-grounded perspective intended to stimulate reflection on how indicators could be better conceptualized and applied in high-mountain lake ecosystems in the Alps.

2. Methodology

To assess the state of the art about the use of ecological indicators in high-mountain lakes in the Alps, a literature search was conducted using the Scopus (https://www.scopus.com) database to identify studies focused on ecological assessment of high-mountain lakes in the Alpine region (Fig. 1). The search query included the following keywords: (high-mountain lakes OR high-altitude lakes) AND (ecological indicators OR environmental monitoring OR environmental indicators OR bioindicators OR biotic components) AND Alps. The search was carried out up to September 30, 2025. This strategy aimed to retrieve studies addressing ecological indicators, monitoring methodologies, and ecosystem assessments in Alpine lake environments. The initial search returned 579 records. To ensure scientific rigor and relevance, only original research articles written in English were considered; reviews, conference abstracts, and non-research formats (i.e., editorials) were excluded. Furthermore, studies were retained only if they were explicitly conducted in countries that encompass portions of the Alps. Only studies employing bioindicators were considered, while those based solely on physicochemical or hydro-morphological parameters were excluded. The final selection comprised 45 studies, which are presented in Table 1. Bar charts and the geographical map were created using the Python programming language within the Google Colab environment.

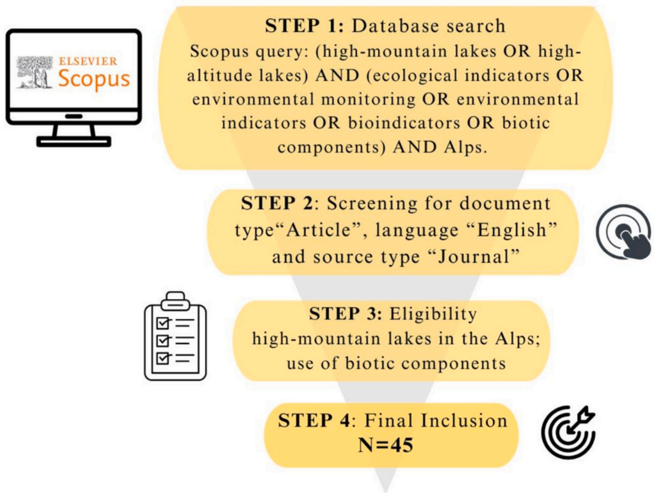

Fig. 1. Workflow for literature selection on ecological indicators in high-mountain lakes in the Alps. The process involved: (1) Scopus database search using a predefined query, (2) screening for relevant document type, language, and source, (3) applying eligibility criteria focused on high-mountain lakes in the Alps and studies using biotic components, and (4) final inclusion of articles.

3. Status of bioindicators in alpine high-mountain lakes

Historically, assessments of high-mountain lakes focused almost exclusively on water chemistry, with particular emphasis on water physicochemical parameters (e.g., temperature, pH, alkalinity, conductivity, major ions) (Psenner, 1989; Wögrath and Psenner, 1995; Kamenik et al., 2001; Rogora et al., 2003; Steingruber et al., 2021) and trace element concentrations in water (Tornimbeni and Rogora, 2012) and sediment samples (Camarero et al., 2009; Pastorino et al., 2020a). Such studies provided crucial baselines for detecting acidification trends, evaluating the influence of bedrock geology and weathering processes, and quantifying atmospheric pollutant inputs (Rogora, 2004). For instance, long-term monitoring across the Alps revealed clear links between changes in atmospheric sulphate and nitrate deposition and the recovery or persistence of acidification, while also documenting the role of lithology and climate warming in modulating solute export to lake waters (Rogora et al., 2013). However, these approaches were not considered in the present context because they do not account for biotic components, which are essential to understanding the ecological status and functioning of these ecosystems. This gap in integrating biotic information into monitoring frameworks guided the focus of the present perspective article toward studies that explicitly incorporate biotic components. Following the literature selection process, 45 studies published between 1997 and 2025 were identified (Table 1), each providing relevant insights into the application of bioindicators and environmental monitoring strategies in high-mountain lake ecosystems.

3.1. *Taxonomic overview of bioindicators*

The organisms most commonly investigated (i.e., phyto-zooplankton, diatoms, macroinvertebrates, fish and amphibians) are well-established bioindicators in freshwater because they respond sensitively to multiple stressors (e.g., nutrient enrichment, acidification, metal contamination, climate-driven hydrological shifts) and integrate environmental conditions over different temporal and spatial scales (De Carvalho et al., 2025). Other groups, such as microbial communities are increasingly acknowledged as complementary components for a more holistic assessment of lake ecosystem status (Stanić et al., 2025), but have not been assessed in high-mountain lakes located in the Alps.

Phytoplankton were considered in 17.8% of studies ($n = 8$) (Fig. 2a). As primary producers, phytoplankton are key drivers of high-mountain

Table 1
List of 45 selected studies employing bioindicators in Alpine and high-mountain lake research, organized chronologically, with corresponding biotic components and study locations.

Reference	Biotic component(s)	Country
Lotter et al., 1997	Diatoms, macroinverebrates, phytoplankton, zooplankton	Switzerland
Lotter et al., 1998	Diatoms, macroinverebrates, phytoplankton, zooplankton	Switzerland
Hofer et al., 2001	Fish	Austria, Italy
Winder and Spaak, 2001	Zooplankton	Switzerland
Tolotti, 2001	Phytoplankton, diatoms	Italy
Boggero et al., 2006	Macroinvertebrates	Italy, Austria, Switzerland, Slovenia
Füreder et al., 2006	Macroinvertebrates	Italy, Austria, Switzerland
Bigler et al., 2006	Diatoms, macroinverebrates, zooplankton	Switzerland
Denoël et al., 2007	Amphibian	France
Kernan et al., 2009	Diatoms, macroinverebrates, zooplankton	Switzerland
Marchetto et al., 2009	Phytoplankton, diatoms, macroinvertebrates zooplankton	Italy, Austria, Switzerland
Schabetsberger et al., 2009	Zooplankton	Austria
Filippi et al., 2011	Diatoms, macroinverebrates	Italy
Marusczak et al., 2011	Fish	France
Tiberti and von Hardenberg, 2012	Amphibian, Fish	Italy
Lods-Crozet et al., 2012	Macroinvertebrates	Switzerland
Trevisan et al., 2012	Phytoplankton	Italy
Khamis et al., 2014	Macroinvertebrates, zooplankton	Italy
Dumnicka et al., 2015	Macroinvertebrates	Italy
Ravnikar et al., 2016	Fish	Slovenia
Feret et al., 2017	Diatoms	France
Tiberti et al., 2019	Fish	Italy
Jacquemin et al., 2019	Phytoplankton	France
Rimet et al., 2019	Diatoms	France
Cantonati et al., 2019	Diatoms	Italy
Pastorino et al., 2020a	Fish, macroinvertebrates	Italy
Pastorino et al., 2020b	Macroinvertebrates	Italy
Tiberti et al., 2020	Phytoplankton, zooplankton, macroinvertebrates, fish, amphibian	Italy
Cantonati et al., 2021	Diatoms	Italy
Rott and Kofler, 2021	Diatoms	Austria
Bartels et al., 2021	Macroinvertebrates	Austria
Pastorino et al., 2022b	Amphibian	Italy
Tartarotti et al., 2022	Zooplankton	Austria
Sommer et al., 2022	Zooplankton	Austria
Salvi et al., 2022	Macroinvertebrates, testate amoeba	Italy
Pritsch et al., 2023	Phytoplankton, zooplankton	Austria, Italy
Bertoli et al., 2023	Macroinvertebrates	Italy
Boggero et al., 2023	Macroinvertebrates	Italy
Rimet et al., 2023	Diatoms	France
Pastorino et al., 2023a	Fish, macroinvertebrates, amphibian, zooplankton	Italy
Gabetti et al., 2024	Macroinvertebrates	Italy
Pastorino et al., 2025	Fish	Italy
Ciutti et al., 2025	Diatoms	Italy
Tartarotti et al., 2025	Zooplankton	Austria
Queral-Beltran et al., 2025	Fish	Italy

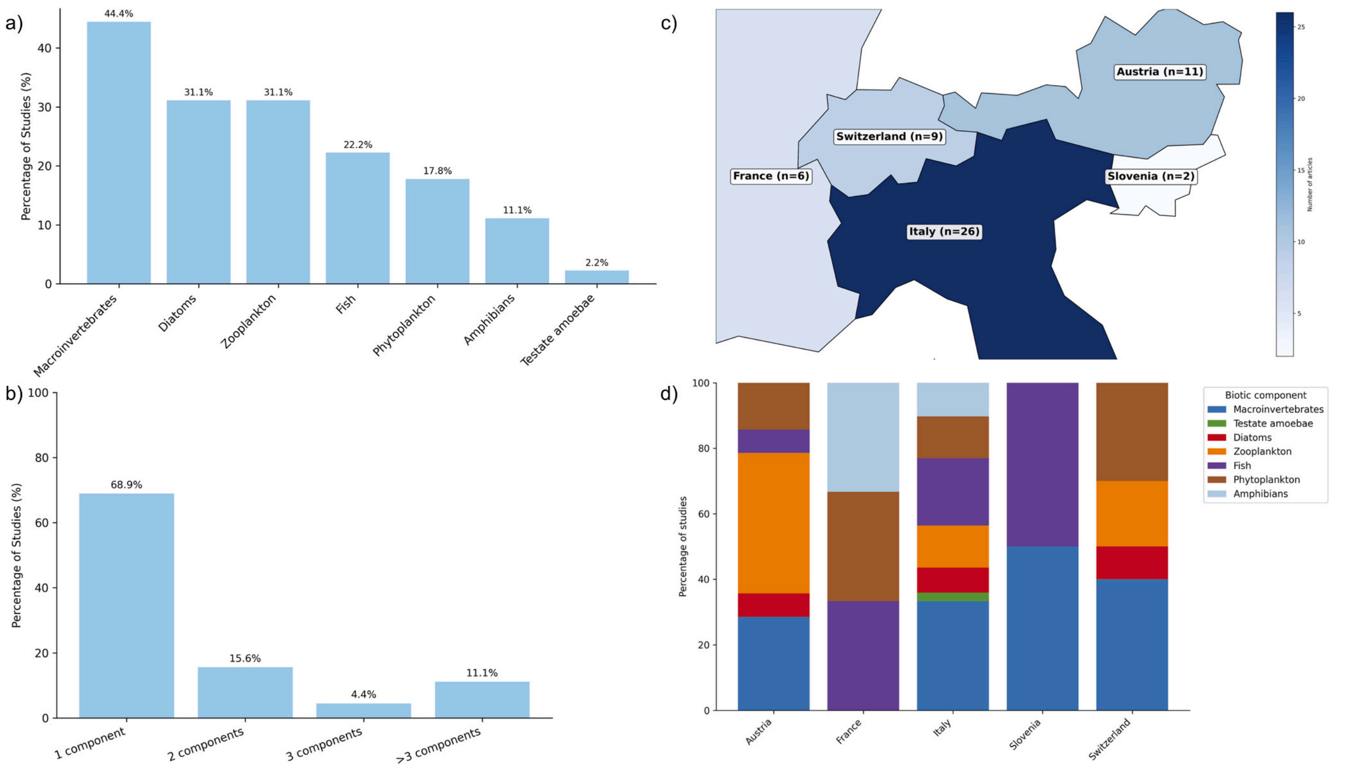

Fig. 2. Components used as bioindicators in studies on high-mountain lakes of the European Alps. Panel (a) shows the percentage of studies including each component, while (b) illustrates their geographic distribution across Alpine countries. Panel (c) summarizes the percentage of studies assessing one or multiple biological components, and (d) displays the relative contribution of each taxonomic group by country.

lake productivity, and their community composition responds rapidly to fluctuations in nutrient availability, light regime, and water temperature (Pugnetti and Bettinetti, 1999). Shifts toward mixotrophic flagellates or filamentous cyanobacteria may indicate warming or nutrient enrichment, and sedimentary pigments provide important information for reconstructing long-term changes in primary production (Zhang et al., 2019; Salmaso and Tolotti, 2021).

Diatoms occurred in 31.1% of the studies ($n = 14$) (Fig. 2a). Diatoms possess high species diversity, well-defined ecological tolerances, and rapid responses to variations in nutrient levels, water chemistry, temperature, and light, making them robust indicators in oligotrophic, climate-sensitive lakes (Kuefner et al., 2020; Ossyssek et al., 2022). Their siliceous frustules preserve well in sediments, enabling the reconstruction of past ecological trajectories, including responses to acidification and changes in water column stratification (Rott and Kofler, 2021; Cantonati et al., 2023).

Zooplankton were considered in 31.1% of the studies ($n = 14$) (Fig. 2a). Composed of rotifers and crustaceans (e.g., cladocerans, copepods), zooplankton have short generation times and high sensitivity to environmental variability, making them effective early-warning indicators of temperature changes, nutrient enrichment, and shifts in food-web structure (Cammarano and Manca, 1997; Brittain and Strecker, 2018). In alpine lakes, community composition is closely linked to ice-melt timing, stratification patterns, and primary productivity, while sedimentary remains such as resting eggs allow insights into past ecological states (Tiberti et al., 2025; Brancelj, 2021).

Macroinvertebrates were the most frequently employed bioindicators, appearing in 44.4% of studies ($n = 20$) (Fig. 2a). This group, which includes insect larvae (e.g., Chironomidae, Ephemeroptera, Plecoptera, Trichoptera), crustaceans, and mollusks, integrates multiple environmental signals, including hydrological regime, habitat structure, oxygen availability, and ice-cover duration, making them sensitive and reliable indicators of ecosystem status (Boggero, 2018; Bertoli et al., 2023). Their relatively long life cycles and low dispersal capacity allow them to capture changes over longer timescales, and chironomid head capsules preserved in sediments provide a powerful tool for paleolimnological reconstructions (Cantonati et al., 2021).

Fish were reported in 22.2% of studies ($n = 10$) (Fig. 2a). Because most high-mountain Alpine lakes were originally fishless, current populations largely result from historical stocking or recent introductions (Ventura et al., 2017). Their presence can serve both as an indicator of anthropogenic influence and as a reflection of environmental change (Pastorino et al., 2024a). Long-term records of fish abundance, age structure, and body condition can highlight climate-driven hydrological alterations and pollutant bioaccumulation, but introduced fish also exert strong top-down effects, altering food webs and nutrient cycling (Tiberti et al., 2014).

Amphibians were included in only 11.1% of studies ($n = 5$) (Fig. 2a). Species such as *Rana temporaria* are highly sensitive to physical and climatic drivers, including hydrological regime, ice-cover duration, and breeding season temperature (Corn, 2003; Bison et al., 2021). Their biphasic life cycle exposes them to both aquatic and terrestrial stressors, including habitat modification, chemical pollution, introduced fish predators, and emerging infectious diseases such as chytridiomycosis and ranaviruses (Pastorino et al., 2023b). Amphibians integrate information from both lake and catchment environments, functioning as effective sentinels of ecosystem integrity (Hopkins, 2007; Luedtke et al., 2023). Despite this potential, they remain underrepresented in biomonitoring programs, indicating an opportunity to expand future monitoring frameworks.

Testate amoebae were reported as bioindicators in only 2.2% ($n = 1$) of studies (Fig. 2a). Generally, they are considered highly sensitive bioindicators because their assemblages respond rapidly to variations in environmental conditions (Salvi et al., 2022). They show strong relationships with factors such as nutrient availability, pH, dissolved oxygen, salinity, and trace element contamination. In alpine lake sediments, shifts in their composition have been linked to both natural climate fluctuations (e.g., pluvial and drought phases, Little Ice Age events) and anthropogenic pressures like pollutant deposition (Wall et al., 2010). Their test morphology and species distribution reflect subtle ecological changes, making them valuable for detecting early signals of environmental stress in fragile high-mountain systems.

3.2. Geographic distribution of bioindicator research

Geographically, Italy was the most represented nation, accounting for 57.8% of the articles (n = 26), followed by Austria with 24.4% (n = 11) (Fig. 2b). Switzerland contributed 20% (n = 9), France 13.3% (n = 6), while Slovenia 4.4% (n = 2) (Fig. 2b). Italy's predominance in high-mountain lake research likely reflects not only its larger share of Alpine territory and greater number of high-mountain lakes, but also the presence of well-established national and regional research networks in limnology, ecotoxicology, and biodiversity monitoring. This tradition can be traced back to the pioneering work of Rina Monti (1871–1937), who is considered one of the founders of Italian limnology and whose early 20th-century investigations of Alpine lake ecology provided the conceptual basis for many subsequent studies (Cofano and De Ceglie, 2025). This geographic imbalance should be taken into account when interpreting trends across the Alpine region, as research hotspots may disproportionately shape our understanding of high-mountain lake ecology and may not fully represent conditions across the entire mountain range. Expanding coordinated monitoring and research initiatives in underrepresented areas such as France and Slovenia would provide a more comprehensive and balanced picture of Alpine lake biodiversity, ecosystem processes, and responses to multiple stressors.

3.3. Number and patterns of components in bioindicator use

Most studies (68.9%, n = 31) focused on a single biotic component, 15.6% (n = 7) investigated two components, 4.4% (n = 2) examined three components, and only 11.1% (n = 5) considered more than three (Fig. 2c).

The predominance of single-component approaches reflects not only the legacy of taxonomically focused monitoring traditions, but also several structural drivers that are particularly evident in Alpine high-mountain lakes. To date, many monitoring programs remain taxonomically narrow, despite increasing calls for multi-tiered, multi-component designs to better apprehend stressor interactions in these fragile ecosystems (Machate et al., 2023). Empirical multi-taxon studies (e.g., those including five taxonomic groups) have demonstrated that integrating multiple components can substantially improve explanatory power regarding hydrology and water quality drivers (Li et al., 2024). In line with this, multi-metric, multi-component frameworks are now widely promoted in the literature as more diagnostic and reliable (Biney et al., 2025). On the one hand, it could be argued that in Alpine high-mountain lakes, where food webs are less structured due to harsh environmental conditions, single or less complex indicators may be sufficient to describe ecosystem dynamics. However, the literature search from this study demonstrated that, in practice, multi-bioindicator approaches are increasingly applied even in these remote systems. However, the transition from single- to multi-component designs is not solely a conceptual challenge but also a structural one, shaped by the distribution of expertise within research communities. Many groups have historically specialized in one or two taxa, creating high-level expertise but also reinforcing narrow study designs. This pattern of specialization, while scientifically productive, has also limited incentives and capacities to adopt broader, multi-taxon approaches, thereby explaining the current predominance of single-component studies in Alpine high-mountain lake research. Indeed, clear differences emerge in the taxonomic focus of research.

Fig. 2d illustrates the relative contribution of each biotic component considered in studies conducted in high-mountain lakes across different Alpine countries. In Austria, most studies concentrated on zooplankton, followed by macroinvertebrates, phytoplankton, and, to a lesser extent, diatoms and fish. In France, studies were dominated by phytoplankton and amphibians, with fish accounting for the remaining share. Italy exhibited a more balanced approach, with macroinvertebrates and fish representing the largest proportions, followed by zooplankton and phytoplankton, and only a few studies on diatoms and testate amoebae. Slovenian studies showed a strong dominance of macroinvertebrates and fish, with other groups largely absent. In Switzerland, macroinvertebrates were again the most studied group, followed by phytoplankton and zooplankton, with fish and diatoms making up the remaining share. Funding priorities often reward continuity and maintenance of long-term datasets rather than support for integrative, high-risk designs. This creates a structural bias: novel multi-taxon proposals may be seen as riskier or less comparable to established baselines, thus less likely to receive funding. Meanwhile, regulatory traditions, especially those tied to implementation of the European WFD, typically prescribe a limited set of biological quality elements for ecological assessment, which can implicitly discourage the inclusion of additional taxa or novel sampling strategies (e.g. Poikane et al., 2020; Santos et al., 2021). Indeed, the WFD's "one-out, all-out" rule and the weighting of biological elements may penalize deviations from standard protocols, thereby constraining methodological innovation and cross-taxon monitoring (Cunningham, 2012; Weisner et al., 2022) In addition, Alpine high-mountain lakes pose severe logistical challenges that further reinforce narrow, repeatable monitoring protocols. Their remoteness and inaccessibility mean that transport of personnel and equipment is costly, risky or seasonal (e.g. only accessible by foot or helicopter) (Odetti et al., 2024). The ice-free season is extremely short, constraining field campaigns to narrow windows during summer, and unpredictable weather (storms, snow, wind) further limits sampling flexibility (Sommaruga, 2025). These constraints favor simpler protocols that can be deployed reliably under tight time budgets, rather than more complex, multi-taxon schemes that require extra time, different gear, or taxonomic specialists in the field, often accompanied by substantially higher financial costs for sampling, laboratory analysis, and expert identification.

3.4. Successes and limitations of existing bioindicators

The 45 studies considered here highlight that existing bioindicators have been reasonably successful at detecting major pressure gradients in Alpine high-mountain lakes, but their diagnostic power and transferability remain uneven. Benthic diatom assemblages from >60 high-mountain lakes in the French Alps and down-core records from 23 Bavarian-Tyrolean mountain lakes reveal coherent community shifts along depth, conductivity and geology gradients and over ~150–200 years of climate warming, confirming their value as long-term sentinels of both natural and anthropogenic change (Feret et al., 2017; Kuefner et al., 2020). Benthic macroinvertebrates likewise show promise: for example, in 28 lakes (2083–2727 m a.s.l.) in the Hohe Tauern National Park (Austria), habitat structure had strong effects, model deviance explained values (D^2) reached ~0.72 and ~ 0.54 for total abundance and family richness respectively (Bartels et al., 2021). In addition, a recovery-study in a mountain lake (~2087 m) found that macroinvertebrate community metrics improved substantially following fish eradication, underscoring their high sensitivity to trophic alteration (Tiberti and Brighenti, 2019).

In systems with fish introductions, bioindicators such as amphibians, macroinvertebrates and zooplankton show very strong effect sizes, with near-complete loss of large-bodied invertebrates and breeding amphibians where fish are present and partial recovery after fish removal, demonstrating high sensitivity to this specific stressor (Knapp et al., 2001).

However, quantitative performance is rarely evaluated across multiple stressors simultaneously, and even for well-developed groups the variance in community structure explained by measured environmental predictors is often modest (e.g., first canonical correspondence analysis axes in benthic diatom studies accounting for only ~10–20% of inertia), reflecting high natural heterogeneity and constraining predictive capacity for management (Feret et al., 2017). At the same time, several consistent shortcomings emerge when existing bioindicators are evaluated critically. First, many assessment tools were originally designed for lowland or sub-alpine lakes and then extrapolated upward; this risks misclassifying naturally ultra-oligotrophic, cold-adapted communities as "impaired" and hampers comparability among countries that use different typologies, reference criteria or metrics for similar high-mountain lake types (Solimini et al., 2014). For example, european intercalibration exercises show that macroinvertebrates methods for lakes are among the most difficult to standardise, with multiple national indices (including some used in Alpine regions) exhibiting weak or non-linear relationships to pressure gradients and high classification uncertainty near status boundaries (Poikane et al., 2016). Second, promising but emerging indicators, such as testate amoebae, have demonstrated high sensitivity to past climatic and pollution signals in individual Alpine or mountain lakes (Salvi et al., 2022), yet lack region-specific transfer functions and standardized indices, so their use remains largely exploratory rather than operational. Third, across all organism groups, most studies rely on compositional or richness metrics and rarely integrate functional traits, trophic interactions or ecosystem processes (e.g., metabolism, nutrient cycling); as a result, current bioindicator frameworks often detect that "something is changing" but still struggle to attribute causality, to distinguish among multiple stressors, or to provide quantitatively robust, comparable ecological status classes for Alpine high-mountain lakes. Finally, in many current studies, only one or a few biological components are examined, which limits the interpretation of results and risks overlooking changes that occur outside the sensitivity range of the selected bioindicators. Relying on only a few biological components as bioindicators can limit the interpretation of environmental assessments, as no single organism or parameter can detect the full range of potential stressors (Markert et al., 2003). Each bioindicator has a specific sensitivity range, meaning that changes occurring outside this range may remain undetected (Holt and Miller, 2010). Moreover, biological responses are often influenced by multiple factors, such as seasonality, habitat conditions, or natural population fluctuations, which can mask or mimic the effects of the stressor of interest (Holt and Miller, 2010; Gerhardt, 2002; Siddig et al., 2016). Consequently, assessments based on a narrow set of indicators risk overlooking important ecological changes, underscoring the need for a multi-indicator approach that integrates biological, chemical, and physical data for a more comprehensive evaluation of ecosystem health (Gerhardt, 2002; Markert et al., 2003).

4. Future perspectives and possible solutions

A comprehensive assessment of ecosystem condition in Alpine high-mountain lakes requires integrating multiple biological components (Fig. 3a) and functions through robust multimetric indices (MMIs) (Fig. 3b). These indices combine structural metrics, such as species composition, diversity, and functional guilds, with functional measures including reproductive success and trophic interactions, linking community organization to ecological performance (Karr and Chu, 1997; Culhane et al., 2014; Ndatimana et al., 2023). The development of MMIs in these systems should reflect their distinctive features: naturally low biodiversity, dominance of cold-adapted sepcies (e.g., Chironomidae, Oligochaeta), and high sensitivity to temperature shifts (Boggero et al., 2006). Structural metrics may include macroinvertebrate composition, diatoms and plankton diversity, and amphibian counts, while functional metrics could encompass primary production, decomposition rates, reproductive output of sentinel species (e.g., *Rana temporaria*), and trophic transfer efficiency. Among candidate bioindicators, a framework combining plankton, diatoms, macroinvertebrates, and amphibians offers broad diagnostic coverage: diatoms indicate nutrient and chemical conditions (Cantonati et al., 2021), macroinvertebrates reflect habitat

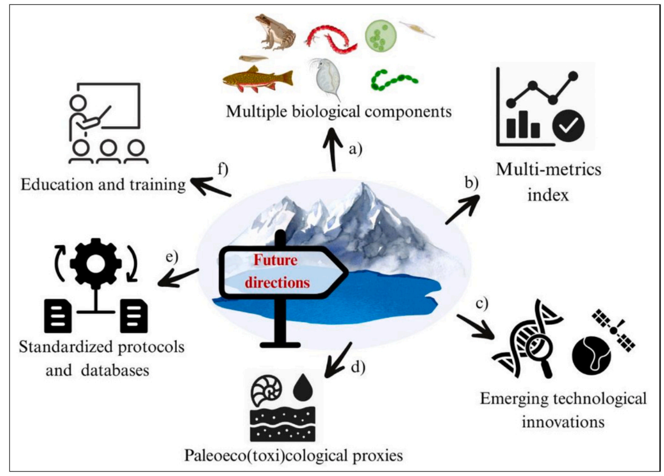

Fig. 3. Future direction in high-mountain lakes research. The diagram highlights key research and management priorities, including a) the integration of multiple biological components, b) the implementation of multi-metric indices, c) the adoption of emerging technological innovations, d) the use of paleoeco(toxi)logical proxies, e) the establishment of standardized protocols and databases, and f) the strengthening of education and training programs.

and fish introduction effects (Tiberti et al., 2019; Bartels et al., 2021), plankton respond rapidly to thermal and hydrological shifts (Pritsch et al., 2023), and amphibians integrate aquatic-terrestrial stressors (Pastorino et al., 2023b). Where present, fish, although non-native, should be considered not only as a monitored biological component (e.g., age structure, abundance, condition factor) but also as a potential source of pressure on native biodiversity, amphibian recruitment, and trophic dynamics. Alien species more broadly (e.g., invasive macrophytes, invertebrates) should be included both as structural indicators and as management-relevant stressors.

The bioindicators should be coupled with systematic monitoring of both traditional pollutants (trace elements and persistent organic contaminants) and emerging contaminants (e.g., pharmaceuticals, PFAS, micro-nanoplastics), as well as with ecotoxicological bioassays capable of revealing sublethal effects that may otherwise go undetected (Pastorino et al., 2022c). Indeed, integrating bioindicators with chemical measurements is a critical step. High-mountain lakes are particularly vulnerable to chemical contamination (Pastorino et al., 2024b), and linking biological observations with chemical data, while incorporating ecotoxicological endpoints such as oxidative stress biomarkers, allows early detection of sublethal effects before community-level changes become evident (Lemos, 2021; Lomartire et al., 2021).

Emerging technological innovations, including environmental DNA (eDNA), ancient DNA, and remote sensing, are poised to transform biodiversity monitoring and ecological assessment (Fig. 3c). These approaches were not represented in the 45 studies included in our review and should therefore be considered as forward-looking perspectives rather than current findings. eDNA methods, particularly when combined with metabarcoding, enable the detection of rare, elusive, or early-arriving species that are often missed by conventional surveys, while providing high taxonomic resolution and broad spatial coverage (Ruppert et al., 2019; Çevik and Çevik, 2025). Ancient DNA recovered from environmental samples, such as sediments, adds a valuable temporal dimension by reconstructing historical ecosystems and long-term biodiversity shifts (Oberreiter et al., 2024). Remote sensing technologies, ranging from satellites to drones, complement these molecular approaches by providing large-scale, fine-resolution data on environmental conditions and habitat dynamics (Pettorelli et al., 2018). Together, these emerging tools create spatially extensive and temporally rich datasets that can greatly enhance the resolution, accuracy, and efficiency of ecological assessments, representing a powerful complement to traditional field-based and taxonomic surveys (Dyson et al., 2024).

Understanding the dynamics of high-mountain lakes also requires extending the temporal perspective (Fig. 3d). Many studies rely on short-term or single-season surveys due to the logistical challenges of reaching remote sites. While these are valuable, they may miss seasonal or interannual patterns linked to climate variability, hydrological shifts, or episodic contaminant input. Establishing multi-year datasets, with synchronized collection of chemical and biological data, will help distinguish natural variability from long-term trends (Reuman et al., 2025). On this path, paleoecological indicators such as chironomids, diatoms, and testate amoebae preserved in lake sediment cores provide powerful tools for reconstructing past environmental conditions and documenting long-term ecological change. Chironomid head capsules can reveal historical patterns in temperature, oxygen levels, and productivity (Svitok et al., 2021), while diatom frustules offer insights into past pH values and nutrient status (Chen et al., 2025). Testate amoebae, often used to infer past hydrological and trophic conditions, add further resolution to environmental reconstructions (Salvi et al., 2022). Together, these proxies enable multi-century to millennial-scale assessments, helping distinguish natural variability from anthropogenic impacts in aquatic ecosystems (Hofmann et al., 2021). Paleoecotoxicology adds a further dimension, enabling the reconstruction of historical contaminant deposition and associated ecological responses (Korosi et al., 2017; Cheney et al., 2022).

Such progress will depend on the creation of open, standardized databases that store biological, chemical, and ecotoxicological data from high-mountain lakes (Fig. 3e). Shared repositories will facilitate collaboration between research institutions, enable meta-analyses across regions, and align monitoring programs with broader European biodiversity and contaminant surveillance frameworks. To ensure data comparability and reproducibility, it is essential to develop standardized protocols for the sampling of biotic components in high-mountain lakes, covering all relevant taxa. While detailed operational guidelines already exist, such as the United States Geological Survey's Techniques and Methods 2-A2 (USGS TM 2-A2) for alpine lakes, developed within USGS's national lake monitoring programs (Hoffman et al., 2005), and the Pond Life in Open and Closed Habitats method (PLOCH) for biodiversity assessment in small waterbodies (Oertli et al., 2005), created in the framework of European pond biodiversity studies, national protocols are available in certain countries as Italy. These include the standardized procedures for fish sampling (using electrofishing and multi-mesh gillnets according to ISO-CEN standards) developed by the Italian National Institute for Environmental Protection and Research (ISPRA) under the national implementation of the WFD (Volta et al., 2014), and for benthic macroinvertebrate assessment (ISPRA, 2014). At a broader national scale, although not specifically designed for alpine environments, the United States Environmental Protection Agency's National Lakes Assessment (NLA) provides an example of a scalable and multimetric monitoring framework that integrates biological, chemical, and physical indicators across a statistically representative network of lakes, offering methodological principles that could be adapted to high-mountain lake assessment programs (EPA, 2025). Regional frameworks are also available, such as the "Mountain lakes protocols" produced as part of the INTERREG PITEM Biodiv'ALP (Pastorino, 2021). Innovative tools, such as the portable Mountain Autonomous Robotic Monitoring Tool (MARMOT), developed by the Italian National Research Council (CNR) within the MARMOT research project (https://sites.google.com/view/marmotproject/home?authuser=0) for bathymetric mapping and environmental sampling in high-mountain lakes, also offer promising perspectives for harmonized monitoring. However, it is important to point out that significant logistical constraints must be acknowledged: the remote location of high-mountain lakes often implies long approaches on foot, limited transport capacity for heavy or power-demanding devices, short sampling windows due to snow cover and weather variability, and limited opportunities for repeated measurements within a season. These constraints highlight the need for robust, lightweight, and energy-efficient monitoring solutions that can function autonomously over extended periods with minimal maintenance. To address this gap, practical steps could include (i) developing WFD-compatible guidance specifically for high-mountain lakes, (ii) adopting size-threshold exemptions for very small or fishless lakes to avoid methodological bias, (iii) aligning national and regional protocols (e.g., ISPRA, PLOCH) under a common European umbrella, and (iv) integrating innovative tools such as remote sensing and autonomous samplers to improve spatial and temporal coverage. These steps should be accompanied by feasibility assessments, including pilot studies in representative alpine regions to evaluate scalability, interoperability between protocols, and cost-effectiveness under real-world field conditions. This staged approach would help identify technical and logistical bottlenecks early, allowing protocols and tools to reach higher readiness levels before large-scale implementation. Collaborative networks should be strengthened to harmonize methodologies, share expertise, and jointly address emerging challenges under global change scenarios.

Finally, the sustainable monitoring and protection of these ecosystems will require investment in education and training (Fig. 3f). Incorporating high-mountain lake research into university curricula, particularly in Bachelor of Science and Master of Science programs in environmental sciences, will prepare new generations of scientists to use both traditional and advanced techniques. Training in field sampling, molecular and biochemical analysis, remote sensing, and biostatistics will ensure the continuity of expertise needed for effective long-term monitoring.

The perspectives outlined above provide a forward-looking framework for strengthening ecological assessment and monitoring in Alpine high-mountain lakes; however, their implementation must realistically account for limited human and financial resources. For this reason, rather than attempting to apply all approaches simultaneously, monitoring strategies should be guided by a streamlined and cost-effective set of priorities. In particular, the adoption of a core multibiotic indicator set, the targeted analysis of high-relevance contaminant classes (trace elements, PFAS, pharmaceuticals, and micro- and nanoplastics) supported where feasible by ecotoxicological biomarkers, and the establishment of standardized long-term datasets at sentinel lakes represent a pragmatic balance between scientific relevance and operational feasibility.

At the same time, the broader innovation-oriented perspectives outlined above should not be interpreted as operational prescriptions but as a strategic research agenda to keep high-mountain lake biomonitoring moving forward. Even a single, well-designed sampling effort (e.g., a sediment core) can now yield multiple ecological, molecular, and chemical datasets, maximising information gain when field access is limited and analytical costs are declining. Accordingly, future progress will depend on balancing these pragmatic monitoring priorities with the gradual integration of emerging tools and approaches that enhance diagnostic power while respecting resource constraints.

5. Conclusions

The review of 45 studies conducted in Alpine high-mountain lakes reveals that current monitoring practices remain largely fragmented, with a predominant reliance on single-taxon approaches and limited integration of multiple biological components, physicochemical parameters, and functional indicators. Although important insights have been gained, particularly from macroinvertebrates, diatoms, and zooplankton, such approaches risk missing ecological changes that occur beyond the sensitivity range of any single bioindicator. Ensuring the long-term ecological integrity of these vulnerable ecosystems requires a transition toward multi-component, multi-trophic, and multi-scale assessment frameworks. The conservation of Alpine high-mountain lakes ultimately depends on our capacity to detect, interpret, and respond effectively to the signals they provide. Adopting comprehensive, standardized, and collaborative monitoring strategies will allow these ecosystems to continue functioning as critical sentinels of environmental change and as benchmarks for ecological resilience under accelerating global pressures.

CRediT authorship contribution statement

Paolo Pastorino: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Antonia Concetta Elia:** Writing – review & editing, Methodology, Conceptualization. **Elisabetta Pizzul:** Writing – review & editing, Conceptualization. **Marco Bertoli:** Writing – review & editing, Conceptualization. **Monia Renzi:** Writing – review & editing, Conceptualization. **Marino Prearo:** Writing – review & editing, Conceptualization. **Damià Barceló:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Bartels, A., Berninger, U.G., Hohenberger, F., Wickham, S., Petermann, J.S., 2021. Littoral macroinvertebrate communities of alpine lakes along an elevational gradient (Hohe Tauern National Park, Austria). PLoS One 16 (11), e0255619.
Battarbee, R.W., Kernan, M., Rose, N., 2009. Threatened and stressed mountain lakes of Europe: assessment and progress. Aquat. Ecosyst. Health Manag. 12 (2), 118–12.
Bertoli, M., Pizzul, E., Basile, S., Perilli, S., Tauler, R., Lacorte, S., Pastorino, P., 2023. Littoral macrobenthic invertebrates of two high-altitude lakes in the Alps: a small-scale analysis. Ecohydrol. Hydrobiol. 23 (2), 211–223.
Bigler, C., Heiri, O., Krskova, R., Lotter, A.F., Sturm, M., 2006. Distribution of diatoms, chironomids and cladocera in surface sediments of thirty mountain lakes in South-Eastern Switzerland. Aquat. Sci. 68 (2), 154–171.
Biney, E.E., Gyamfi, C., Karikari, A.Y., Darko, D., 2025. Reservoir ecological health assessment methods: a systematic review. Ecol. Indic. 171, 113130.
Birck, C., Epaillard, I., Leccia, F., Crassous, C., Morand, A., Miaud, C., Arnaud, F., 2013. Sentinel lakes: a network for the study and management of mountain lakes in the French Alps and in Corsica. J. Protect. Mountain Areas Res. 5 (1), 63–69.
Bison, M., Yoccoz, N.G., Carlson, B.Z., Klein, G., Laigle, I., Van Reeth, C., Delestrade, A., 2021. Earlier snowmelt advances breeding phenology of the common frog (*Rana temporaria*) but increases the risk of frost exposure and wetland drying. Front. Ecol. Evol. 9, 645585.
Boggero, A., 2018. Macroinvertebrates of Italian mountain lakes: a review. Redia: J. Zool./Giornale di Zoologia 101.
Boggero, A., Füreder, L., Lencioni, V., Simcic, T., Thaler, B., Ferrarese, U., Ettinger, R., 2006. Littoral chironomid communities of Alpine lakes in relation to environmental factors. Hydrobiologia 562 (1), 145–165.
Boggero, A., Zaupa, S., Cesarini, G., Ruocco, M., Ansaloni, I., Prevedelli, D., Fornaroli, R., 2023. Macroinvertebrate spatial diversity patterns of shore habitats in Italian high-altitude natural and permanent lakes and ponds. Water 15 (21), 3814.
Brancelj, A., 2021. Shifts in zooplankton communities in high-mountain lakes induced by singular events (fish stocking, earthquakes): evidence from a 20-year survey in Slovenia (Central Europe). Aquat. Ecol. 55 (4), 1253–1271.
Brittain, J.T., Strecker, A.L., 2018. The interactive effect of multiple stressors on crustacean zooplankton communities in montane lakes. Water Resour. Res. 54 (2), 939–954.
Camarero, L., Botev, I., Muri, G., Psenner, R., Rose, N., Stuchlík, E., 2009. Trace elements in alpine and arctic lake sediments as a record of diffuse atmospheric contamination across Europe. Freshw. Biol. 54 (12), 2518–2532.
Cammarano, P., Manca, M., 1997. Studies on zooplankton in two acidified high mountain lakes in the Alps. Hydrobiologia 356 (1), 97–109.
Cantonati, M., Angeli, N., Lange-Bertalot, H., 2019. Three new Fragilaria species (Bacillariophyta) from low-conductivity mountain freshwaters (Alps and Apennines). Phytotaxa 404 (6), 261.
Cantonati, M., Zorza, R., Bertoli, M., Pastorino, P., Salvi, G., Platania, G., Pizzul, E., 2021. Recent and subfossil diatom assemblages as indicators of environmental change (including fish introduction) in a high-mountain lake. Ecol. Indic. 125, 107603.
Cantonati, M., Cid-Rodríguez, M., Rossi, F., Leira, M., 2023. A simple and inexpensive method to gain diatom absolute abundances from permanent mounts in hydrobiological and paleoecological research. Appl. Sci. 13 (10), 6019.
Carignan, V., Villard, M.A., 2002. Selecting indicator species to monitor ecological integrity: a review. Environ. Monit. Assess. 78 (1), 45–61.
Catalan, J., Camarero, L., Felip, M., Pla, S., Ventura, M., Buchaca, T., Quijano, D.D.D., 2006. High mountain lakes: extreme habitats and witnesses of environmental changes. Limnetica 25 (1–2), 551–584.
Çevik, T., Çevik, N., 2025. Environmental DNA (eDNA): a review of ecosystem biodiversity detection and applications. Biodivers. Conserv. 1–37.
Chen, X., McGowan, S., Huang, X., Cao, Y., Bai, X., Li, J., Peng, J., 2025. Diatom-inferred water pH variability in response to climate change and acid deposition in subtropical peatlands. Water Res. 124153.
Cheney, C., Pothier, M., Thomas, P.J., Sarma, S.N., Poulain, A.J., Blais, J.M., 2022. Paleoecotoxicology: developing methods to assess the toxicity of lake sediment records influenced by legacy gold mining. Aquat. Toxicol. 250, 106248.
Ciutti, F., Blanco, S., Bertoli, M., Pizzul, E., Pastorino, P., Prearo, M., Cappelletti, C., 2025. Diatom diversity in a mountain lake in southern European Alps (Italy). Phytotaxa 710 (1), 1–21.
Cofano, A., De Ceglie, R., 2025. The "signora" of limnology. Rina Monti: geological experience, ecosystem protection and the impact of human activity. Rend. Online Soc. Geol. Ital. 66.
Corn, P.S., 2003. Amphibian breeding and climate change: importance of snow in the mountains. Conserv. Biol. 17 (2), 622–625.
Culhane, F.E., Briers, R.A., Tett, P., Fernandes, T.F., 2014. Structural and functional indices show similar performance in marine ecosystem quality assessment. Ecol. Indic. 43, 271–280.
Cunningham, R., 2012. Glass half full or half empty?. In Why 2009 Water Framework Directive Classification Results Are over-Optimistic about the State of Rivers despite the One-out, All-out rule. Royal Society for the Protection of Birds. https://www.wfduk.org/sites/default/files/Media/Wildlife%20and%20Countryside%20Link%20The%20One-Out%20All-Out%20pessimism%20myth%20Final.pdf.
Dainese, M., Crepaz, H., Bottarin, R., Fontana, V., Guariento, E., Hilpold, A., Niedrist, G., 2024. Global change experiments in mountain ecosystems: a systematic review. Ecol. Monogr. 94 (4), e1632.
Dale, V.H., Beyeler, S.C., 2001. Challenges in the development and use of ecological indicators. Ecol. Indic. 1 (1), 3–10.
De Carvalho, F.G., Loyau, A., Kelly-Irving, M., Schmeller, D.S., 2025. Aquatic ecosystem indices, linking ecosystem health to human health risks. Biodivers. Conserv. 34 (3), 723–767.
Denoël, M., Lena, J.P., Joly, P., 2007. Morph switching in a dimorphic population of Triturus alpestris (Amphibia, Caudata). Evol. Ecol. 21 (3), 325–335.
Dumnicka, E., Steingruber, S., Colombo, L., Zaupa, S., Boggero, A., 2015. Oligochaete assemblages of Swiss Alpine lakes. Ital. J. Zool. 82 (1), 112–123.
Dyson, K., Nicolau, A.P., Tenneson, K., Francesconi, W., Daniels, A., Andrich, G., Saah, D., 2024. Coupling remote sensing and eDNA to monitor environmental impact: a pilot to quantify the environmental benefits of sustainable agriculture in the Brazilian Amazon. PLoS One 19 (2), e0289437.
EPA, 2025. National Lakes Assessment. Available at: https://www.epa.gov/national-aquatic-resource-surveys/nla (Accessed: 15 November 2025).
European Parliament and Council, 2000. Directive 2000/60/EC establishing a framework for community action in the field of water policy. Offl. J. Eur. Comm. L 327/1. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060.
Feret, L., Bouchez, A., Rimet, F., 2017. Benthic diatom communities in high altitude lakes: A large scale study in the French Alps. In: Annales de Limnologie-International Journal of Limnology, vol. 53. EDP Sciences, pp. 411–423.
Filippi, M.L., Piliposian, G., Marziali, L., Angeli, N., Lencioni, V., Cantonati, M., 2011. Is it possible to study palaeoenvironmental changes in Alpine spring habitats? A few examples from the South-Eastern Alps (NE Italy). J. Limnol. 70, 155.
Frei, E.R., Barbeito, I., Erdle, L.M., Leibold, E., Bebi, P., 2023. Evidence for 40 years of treeline shift in a central alpine valley. Forests 14 (2), 412.
Füreder, L., Ettinger, R., Boggero, A., Thaler, B., Thies, H., 2006. Macroinvertebrate diversity in Alpine lakes: effects of altitude and catchment properties. Hydrobiologia 562 (1), 123–144.
Gabetti, A., Maganza, A., Mossotto, C., Rizzioli, B., Esposito, G., Bertoli, M., Pastorino, P., 2024. Macrobenthic assemblages and the influence of microhabitat in a High-Mountain Lake (Northwest Italy). Diversity 16 (6), 329.
Gerhardt, A., 2002. Bioindicator species and their use in biomonitoring. Environ. Monit. Assess. 78 (3), 229–242.
Heink, U., Kowarik, I., 2010. What are indicators? On the definition of indicators in ecology and environmental planning. Ecol. Indic. 10 (3), 584–593. https://doi.org/10.1016/j.ecolind.2009.09.009.
Heiskanen, A.S., Van de Bund, W., Cardoso, A.C., Nõges, P., 2004. Towards good ecological status of surface waters in Europe-interpretation and harmonisation of the concept. Water Sci. Technol. 49 (7), 169–177.
Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K., van de Bund, W., 2010. The European water framework directive at the age of 10: a critical review of the achievements with recommendations for the future. Sci. Total Environ. 408 (19), 4007–4019.
Hofer, R., Lackner, R., Kargl, J., Thaler, B., Tait, D., Bonetti, L., Flaim, G., 2001. Organochlorine and metal accumulation in fish (*Phoxinus phoxinus*) along a north-south transect in the Alps. Water Air Soil Pollut. 125 (1), 189–200.
Hoffman, R.L., Tyler, T.J., Larson, G.L., Adams, M.J., Wente, W., Galvan, S., 2005. Sampling Protocol for Monitoring Abiotic and Biotic Characteristics of Mountain Ponds and Lakes (No. 2-A2).
Hofmann, A.M., Kuefner, W., Mayr, C., Dubois, N., Geist, J., Raeder, U., 2021. Unravelling climate change impacts from other anthropogenic influences in a subalpine lake: a multi-proxy sediment study from Oberer Soiernsee (northern Alps, Germany). Hydrobiologia 848 (18).

Holt, E.A., Miller, S.W., 2010. Bioindicators: using organisms to measure environmental impacts. Nat. Educ. Knowl. 3 (10), 8.
Hopkins, W.A., 2007. Amphibians as models for studying environmental change. ILAR J. 48 (3), 270–277.
ISPRA, 2014. Metodi biologici per le acque superficiali interne. In: Manuali e Linee Guida, 111th edn. ISPRA, Roma, p. 234.
Jacquemin, C., Bertrand, C., Franquet, E., Mounier, S., Misson, B., Oursel, B., Cavalli, L., 2019. Effects of catchment area and nutrient deposition regime on phytoplankton functionality in alpine lakes. Sci. Total Environ. 674, 114–127.
Kamenik, C., Schmidt, R., Kum, G., Psenner, R., 2001. The influence of catchment characteristics on the water chemistry of mountain lakes. Arct. Antarct. Alp. Res. 33 (4), 404–409.
Karr, J.R., Chu, E.W., 1997. Biological Monitoring and Assessment: Using Multimetric Indexes Effectively. University of Washington, Seattle, WA (EPA 235-R97-001).
Kernan, M., Ventura, M., Bitušík, P., Brancelj, A., Clarke, G., Velle, G., Catalan, J., 2009. Regionalisation of remote European mountain lake ecosystems according to their biota: environmental versus geographical patterns. Freshw. Biol. 54 (12), 2470–2493.
Khamis, K., Hannah, D.M., Brown, L.E., Tiberti, R., Milner, A.M., 2014. The use of invertebrates as indicators of environmental change in alpine rivers and lakes. Sci. Total Environ. 493, 1242–1254.
Knapp, R.A., Matthews, K.R., Sarnelle, O., 2001. Resistance and resilience of alpine lake fauna to fish introductions. Ecol. Monogr. 71 (3), 401–421.
Korosi, J.B., Thienpont, J.R., Smol, J.P., Blais, J.M., 2017. Paleo-ecotoxicology: what can lake sediments tell us about ecosystem responses to environmental pollutants? Environ. Sci. Technol. 51 (17), 9446–9457.
Kuefner, W., Hofmann, A., Ossyssek, S., Dubois, N., Geist, J., Raeder, U., 2020. Composition of highly diverse diatom community shifts as response to climate change: a down-core study of 23 central European mountain lakes. Ecol. Indic. 117, 106590.
Lamouille-Hébert, M., Arthaud, F., Datry, T., 2024. Climate change and the biodiversity of alpine ponds: challenges and perspectives. Ecol. Evol. 14 (2), e10883.
Lemos, M.F., 2021. Biomarker studies in stress biology: from the gene to population, from the organism to the application. Biology 10 (12), 1340.
Li, Z., Xie, H., Peng, Z., Heino, J., Ma, Y., Xiong, F., Chen, Y., 2024. Hydrology and water quality drive multiple biological indicators in a dam-modified large river. Water Res. X 25, 100251.
Lods-Crozet, B., Oertli, B., Robinson, C.T., 2012. Long-term patterns of chironomid assemblages in a high elevation stream/lake network (Switzerland): implications to global change. Fauna norvegica 31, 71–85.
Lomartire, S., Marques, J.C., Gonçalves, A.M., 2021. Biomarkers based tools to assess environmental and chemical stressors in aquatic systems. Ecol. Indic. 122, 107207.
Lone, A.M., Balakrishna, K., 2023. Deep and frozen: High-Mountain lakes as sentinels of regional limnology and global environmental changes. Limnol. Oceanogr. Bull. 32 (3), 98–101.
Lotter, A.F., Birks, H.J.B., Hofmann, W., Marchetto, A., 1997. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. I. Climate. J. Paleolimnol. 18 (4), 395–420.
Lotter, A.F., Birks, H.J.B., Hofmann, W., Marchetto, A., 1998. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. J. Paleolimnol. 19 (4), 443–463.
Luedtke, J.A., Chanson, J., Neam, K., Hobin, L., Maciel, A.O., Catenazzi, A., Stuart, S.N., 2023. Ongoing declines for the world's amphibians in the face of emerging threats. Nature 622 (7982), 308–314.
Ma, J., Song, C., Wang, Y., 2021. Spatially and temporally resolved monitoring of glacial lake changes in Alps during the recent two decades. Front. Earth Sci. 9, 723386.
Machate, O., Schmeller, D.S., Schulze, T., Brack, W., 2023. Mountain lakes as freshwater resources at risk from chemical pollution. Environ. Sci. Eur. 35 (1), 3.
Marchetto, A., Rogora, M., Boggero, A., Musazzi, S., Lami, A., Lotter, A.F., Barbieri, A., 2009. Response of Alpine lakes to major environmental gradients, as detected through planktonic, benthic and sedimentary assemblages. Adv. Limnol. 62, 419–440.
Markert, B.A., Breure, A.M., Zechmeister, H.G., 2003. Bioindicators and Biomonitors: Principles, Concepts and Applications. Elsevier.
Marusczak, N., Larose, C., Dommergue, A., Paquet, S., Beaulne, J.S., Maury-Brachet, R., Ferrari, C.P., 2011. Mercury and methylmercury concentrations in high altitude lakes and fish (Arctic charr) from the French Alps related to watershed characteristics. Sci. Total Environ. 409 (10), 1909–1915.
Medina-Sánchez, J.M., Cabrerizo, M.J., González-Olalla, J.M., Villar-Argaiz, M., Carrillo, P., 2022. High mountain lakes as remote sensors of global change. In: The Landscape of the Sierra Nevada: A Unique Laboratory of Global Processes in Spain. Springer International Publishing, Cham, pp. 261–278.
Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Odermatt, D., 2021. Inventory and evolution of glacial lakes since the little ice age: lessons from the case of Switzerland. Earth Surf. Process. Landf. 46 (13), 2551–2564.
Moser, K.A., Baron, J.S., Brahney, J., Oleksy, I.A., Saros, J.E., Hundey, E.J., Smol, J.P., 2019. Mountain lakes: eyes on global environmental change. Glob. Planet. Chang. 178, 77–95.
Ndatimana, G., Nantege, D., Arimoro, F.O., 2023. A review of the application of the macroinvertebrate-based multimetric indices (MMIs) for water quality monitoring in lakes. Environ. Sci. Pollut. Res. 30 (29), 73098–73115.
Oberreiter, V., Gelabert, P., Brück, F., Franz, S., Zelger, E., Szedlacsek, S., Pinhasi, R., 2024. Maximizing efficiency in sedimentary ancient DNA analysis: a novel extract pooling approach. Sci. Rep. 14 (1), 19388.
Odetti, A., Bruzzone, G., Ferretti, R., Aracri, S., Carotenuto, F., Vagnoli, C., Scagnetto, I., 2024. Lake environmental data harvester (LED) for Alpine lake monitoring with autonomous surface vehicles (ASVs). Remote Sens. 16 (11), 1998.
OECD, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD Publishing, Paris. https://doi.org/10.1787/9789264043466-en.
Oertli, B., Auderset Joye, D., Castella, E., Juge, R., Lehmann, A., Lachavanne, J.B., 2005. PLOCH: a standardized method for sampling and assessing the biodiversity in ponds. Aquat. Conserv. Mar. Freshwat. Ecosyst. 15 (6), 665–679.
Ossyssek, S., Hofmann, A.M., Geist, J., Raeder, U., 2022. Diatom red list species reveal high conservation value and vulnerability of mountain lakes. Diversity 14 (5), 389.
Parmar, T.K., Rawtani, D., Agrawal, Y.K., 2016. Bioindicators: the natural indicator of environmental pollution. Front. Life Sci. 9 (2), 110–118.
Pastorino, 2021. Protocolli realizzati sui laghi Alpi Cozie. In: Osservatori transfrontalieri sui cambiamenti globali e sul loro impatto sulla biodiversità, pp. 8–13. https://www.regione.piemonte.it/web/sites/default/files/media/documenti/2021-03/Protocollo_LAGHI_it.pdf.
Pastorino, P., Prearo, M., 2020. High-mountain lakes, indicators of global change: ecological characterization and environmental pressures. Diversity 12 (6), 260.
Pastorino, P., Prearo, M., Bertoli, M., Abete, M.C., Dondo, A., Salvi, G., Pizzul, E., 2020a. Accumulation of as, cd, Pb, and Zn in sediment, chironomids and fish from a high-mountain lake: first insights from the carnic Alps. Sci. Total Environ. 729, 139007.
Pastorino, P., Pizzul, E., Bertoli, M., Perilli, S., Brizio, P., Salvi, G., Squadrone, S., 2020b. Macrobenthic invertebrates as bioindicators of trace elements in high-mountain lakes. Environ. Sci. Pollut. Res. 27 (6), 5958–5970.
Pastorino, P., Prearo, M., Pizzul, E., Renzi, M., Ginebreda, A., Barceló, D., 2022a. High-mountain lakes as indicators of microplastic pollution: current and future perspectives. Water Emerg. Contaminants Nanoplastics 13 (1).
Pastorino, P., Prearo, M., Di Blasio, A., Barcelò, D., Anselmi, S., Colussi, S., Renzi, M., 2022b. Microplastics occurrence in the European common frog (*Rana temporaria*) from Cottian Alps (Northwest Italy). Diversity 14 (2), 66.
Pastorino, P., Prearo, M., Anselmi, S., Bentivoglio, T., Esposito, G., Bertoli, M., Renzi, M., 2022c. Combined effect of temperature and a reference toxicant (KCl) on *Daphnia middendorffiana* (Crustacea, Daphniidae) in a high-mountain lake. Ecol. Indic. 145, 109588.
Pastorino, P., Anselmi, S., Esposito, G., Bertoli, M., Pizzul, E., Barceló, D., Renzi, M., 2023a. Microplastics in biotic and abiotic compartments of high-mountain lakes from Alps. Ecol. Indic. 150, 110215.
Pastorino, P., Colussi, S., Varello, K., Meletiadis, A., Alberti, S., Di Blasio, A., Prearo, M., 2023b. Interdisciplinary approach to solve unusual mortalities in the European common frog (*Rana temporaria*) in two high-mountain ponds affected by climate change. Environ. Res. 222, 115411.
Pastorino, P., Elia, A.C., Pizzul, E., Bertoli, M., Renzi, M., Prearo, M., 2024a. The old and the new on threats to high-mountain lakes in the Alps: a comprehensive examination with future research directions. Ecol. Indic. 160, 111812.
Pastorino, P., Barceló, D., Prearo, M., 2024b. Alps at risk: high-mountain lakes as reservoirs of persistent and emerging contaminants. J. Contam. Hydrol. 264, 104361.
Pastorino, P., Bertoli, M., Caldaroni, B., Giugliano, R., Ciccotelli, V., Vivaldi, B., Elia, A. C., 2025. Influence of water chemistry and contaminant occurrence on the oxidative stress ecology of *Cottus gobio* in a high-mountain lake (carnic Alps). Environ. Res. 264, 120343.
Pettorelli, N., Schulte to Bühne, H., Tulloch, A., Dubois, G., Macinnis-Ng, C., Queirós, A. M., Nicholson, E., 2018. Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward. Remote Sens. Ecol. Conserv. 4 (2), 71–93.
Poikane, S., Johnson, R.K., Sandin, L., Schartau, A.K., Solimini, A.G., Urbanič, G., Böhmer, J., 2016. Benthic macroinvertebrates in lake ecological assessment: a review of methods, intercalibration and practical recommendations. Sci. Total Environ. 543, 123–134.
Poikane, S., Herrero, F.S., Kelly, M.G., Borja, A., Birk, S., van de Bund, W., 2020. European aquatic ecological assessment methods: a critical review of their sensitivity to key pressures. Sci. Total Environ. 740, 140075.
Pritsch, H., Schirpke, U., Jersabek, C.D., Kurmayer, R., 2023. Plankton community composition in mountain lakes and consequences for ecosystem services. Ecol. Indic. 154, 110532.
Psenner, R., 1989. Chemistry of high mountain lakes in siliceous chatchments of the central eastern Alps. Aquat. Sci. 51 (2), 108–128.
Pugnetti, A., Bettinetti, R., 1999. Biomass and species structure of the phytoplankton of an high mountain Lake (lake Paione Superiore, Central Alps, Italy). J. Limnol. 58 (2), 127–130.
Queral-Beltran, A., Pastorino, P., Prearo, M., Tauler, R., Lacorte, S., 2025. Still there: persistent organic pollutants in fish from two Italian high-mountain lakes. Environ. Chem. Ecotoxicol. 7, 686–695.
Ravnikar, T., Bohanec, M., Muri, G., 2016. Monitoring and assessment of anthropogenic activities in mountain lakes: a case of the fifth Triglav Lake in the Julian Alps. Environ. Monit. Assess. 188 (4), 253.
Reuman, D.C., Walter, J.A., Sheppard, L.W., Karatayev, V.A., Kadiyala, E.S., Lohmann, A. C., Castorani, M.C., 2025. Insights into spatial synchrony enabled by long-term data. Ecol. Lett. 28 (4), e70112.
Rimet, F., Feret, L., Bouchez, A., Dorioz, J.M., Dambrine, E., 2019. Factors influencing the heterogeneity of benthic diatom communities along the shoreline of natural alpine lakes. Hydrobiologia 839 (1), 103–118.
Rimet, F., Pinseel, E., Bouchez, A., Japoshvili, B., Mumladze, L., 2023. Diatom endemism and taxonomic turnover: assessment in high-altitude alpine lakes covering a large geographical range. Sci. Total Environ. 871, 161970.

Rogora, M., 2004. Acidification and recovery at mountain lakes in Central Alps assessed by the MAGIC model. J. Limnol. 63 (1), 133–142.

Rogora, M., Mosello, R., Arisci, S., 2003. The effect of climate warming on the hydrochemistry of alpine lakes. Water Air Soil Pollut. 148 (1), 347–361.

Rogora, M., Colombo, L., Lepori, F., Marchetto, A., Steingruber, S., Tornimbeni, O., 2013. Thirty years of chemical changes in alpine acid-sensitive lakes in the Alps. Water Air Soil Pollut. 224 (10), 1746.

Rogora, M., Frate, L., Carranza, M.L., Freppaz, M., Stanisci, A., Bertani, I., Matteucci, G., 2018. Assessment of climate change effects on mountain ecosystems through a cross-site analysis in the Alps and Apennines. Sci. Total Environ. 624, 1429–1442.

Rott, E., Kofler, W., 2021. Planktonic centric diatoms from the eastern Alps: morphology, biogeography and ecology. Plant Fungal Systematics 66 (1), 1–36.

Ruppert, K.M., Kline, R.J., Rahman, M.S., 2019. Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: a systematic review in methods, monitoring, and applications of global eDNA. Glob. Ecol. Conserv. 17, e00547.

Salmaso, N., Tolotti, M., 2021. Phytoplankton and anthropogenic changes in pelagic environments. Hydrobiologia 848 (1), 251–284.

Salvi, G., Bertoli, M., Giubileo, C., Pastorino, P., Pavoni, E., Crosera, M., Pizzul, E., 2022. Testate Amoeba and Chironomid assemblages from Balma Lake (Piedmont, Italy): a multi-proxy record to identifying recent climate and environmental changes in alpine areas. Quat. Sci. Rev. 285, 107547.

Sánchez-Hernández, J., Cobo, F., Amundsen, P.A., 2015. Food web topology in high mountain lakes. PLoS One 10 (11), e0143016.

Santos, J.I., Vidal, T., Gonçalves, F.J., Castro, B.B., Pereira, J.L., 2021. Challenges to water quality assessment in Europe-is there scope for improvement of the current water framework directive bioassessment scheme in rivers? Ecol. Indic. 121, 107030.

Schabetsberger, R., Luger, M.S., Drozdowski, G., Jagsch, A., 2009. Only the small survive: monitoring long-term changes in the zooplankton community of an Alpine lake after fish introduction. Biol. Invasions 11 (6), 1335–1345.

Schirpke, U., Scolozzi, R., Kiessling, A., Tappeiner, U., 2021. Recreational ecosystem services of mountain lakes in the European Alps: preferences, visitor groups and management implications. J. Outdoor Recreat. Tour. 35, 100421.

Schmid, P., Kohler, M., Gujer, E., Zennegg, M., Lanfranchi, M., 2007. Persistent organic pollutants, brominated flame retardants and synthetic musks in fish from remote alpine lakes in Switzerland. Chemosphere 67 (9), S16–S21.

Schreder, S., Sommaruga, R., Psenner, R., Chimani, B., Ganekind, M., Koinig, K.A., 2023. Changes in air temperature, but not in precipitation, determine long-term trends in water chemistry of high mountain lakes of the Alps with and without rock glacier influence. Sci. Total Environ. 905, 167750.

Siddig, A.A., Ellison, A.M., Ochs, A., Villar-Leeman, C., Lau, M.K., 2016. How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in ecological indicators. Ecol. Indic. 60, 223–230.

Smits, A.P., Gomez, N.W., Dozier, J., Sadro, S., 2021. Winter climate and lake morphology control ice phenology and under-ice temperature and oxygen regimes in mountain lakes. Journal of geophysical research. Biogeosciences 126 (8), e2021JG006277.

Solimini, A., Argillier, C., Boggero, A., Böhmer, J., Gevrey, M., Urbanič, G., Wolfram, G., 2014. Alpine Lake Benthic Invertebrate Ecological Assessment Methods. Water Framework Directive Intercalibration Technical Report. Joint Research Centre, European Commission, Luxembourg. EUR 26511 EN. ISBN 978-92-79-35467-0.

Sommaruga, R., 2025. Survival strategies of planktonic organisms in alpine lakes and beyond. Inland Waters 15 (1), 1–31.

Sommer, F., Sonntag, B., Rastl, N., Summerer, M., Tartarotti, B., 2022. Ciliates in man-made mountain reservoirs. Front. Environ. Sci. 10, 903095.

Spellerberg, I.F., 2005. Monitoring Ecological Change, 2nd ed. Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511614690.

Stanić, I., Kajan, K., Selak, L., Orlić, S., 2025. Environmental drivers of microbial assembly and stability in lakes across biogeographical regions. Ecol. Indic. 172, 113324.

Steingruber, S.M., Bernasconi, S.M., Valenti, G., 2021. Climate change-induced changes in the chemistry of a high-altitude mountain lake in the Central Alps. Aquat. Geochem. 27 (2), 105–126.

Svitok, M., Kubovčík, V., Kopáček, J., Bitušík, P., 2021. Temporal trends and spatial patterns of chironomid communities in alpine lakes recovering from acidification under accelerating climate change. Freshw. Biol. 66 (12), 2223–2239.

Tartarotti, B., Sommaruga, R., Saul, N., 2022. Phenotypic and molecular responses of copepods to UV radiation stress in a clear versus a glacially turbid lake. Freshw. Biol. 67 (8), 1456–1467.

Tartarotti, B., Rastl, N., Sommer, F., 2025. Zooplankton Communities in Mountain Reservoirs of the Eastern Alps. Available at SSRN 4971841.

Tiberti, R., Brighenti, S., 2019. Do alpine macroinvertebrates recover differently in lakes and rivers after alien fish eradication? Knowl. Manag. Aquat. Ecosyst. 420, 37.

Tiberti, R., von Hardenberg, A., 2012. Impact of introduced fish on common frog (*Rana temporaria*) close to its altitudinal limit in alpine lakes. Amphibia-Reptilia 33 (2), 303–307.

Tiberti, R., Von Hardenberg, A., Bogliani, G., 2014. Ecological impact of introduced fish in high altitude lakes: a case of study from the European Alps. Hydrobiologia 724 (1), 1–19.

Tiberti, R., Bogliani, G., Brighenti, S., Iacobuzio, R., Liautaud, K., Rolla, M., Bassano, B., 2019. Recovery of high mountain Alpine lakes after the eradication of introduced brook trout Salvelinus fontinalis using non-chemical methods. Biol. Invasions 21 (3), 875–894.

Tiberti, R., Buscaglia, F., Armodi, M., Callieri, C., Ribelli, F., Rogora, M., Bocca, M., 2020. Mountain lakes of Mont Avic Natural Park: ecological features and conservation issues. J. Limnol. 79 (1).

Tiberti, R., Dory, F., Arthaud, F., Augé, V., Birk, C., Cavalli, L., Sommaruga, R., 2025. Long-term changes of zooplankton in alpine lakes result from a combination of local and global threats. Biol. Conserv. 308, 111222.

Tolotti, M., 2001. Phytoplankton and littoral epilithic diatoms in high mountain lakes of the Adamello-Brenta Regional Park (Trentino, Italy) and their relation to trophic status and acidification risk. J. Limnol. 60 (2), 171–188.

Tornimbeni, O., Rogora, M., 2012. An evaluation of trace metals in high-altitude lakes of the Central Alps: present levels, origins and possible speciation in relation to pH values. Water Air Soil Pollut. 223 (4), 1895–1909.

Trevisan, R., Pertile, R., Bronamonte, V., Dazzo, F.B., Squartini, A., 2012. Dinophyceae fluctuations in two alpine lakes of contrasting size during a 10-year fortnightly survey. J. Microbiol. Biotechnol. 22 (6), 754–762.

US EPA, 2002. A Framework for Assessing and Reporting on Ecological Condition: An SAB Report. EPA Science Advisory Board, Washington, DC. Available at: https://www.epa.gov/system/files/documents/2022-03/a-framework-for-assessing-and-reporting-on-ecological-condition.pdf.

Ventura, M., Tiberti, R., Buchaca, T., Buñay, D., Sabás, I., Miró, A., 2017. Why should we preserve fishless high mountain lakes?. In: High Mountain Conservation in a Changing World. Springer International Publishing, Cham, pp. 181–205.

Volta, P., Sala, P., Campi, B., Cerutti, I., 2014. Protocollo di campionamento della fauna ittica nei laghi italiani. In: Report CNR-ISE, 2. http://www.aiiad.it/sito/images/docs/manuali/3030-ProtocolloPesciLaghi_ISPRA2014.pdf.

Wall, A.A., Magny, M., Mitchell, E.A., Vannière, B., Gilbert, D., 2010. Response of testate amoeba assemblages to environmental and climatic changes during the Lateglacial–Holocene transition at Lake Lautrey (Jura Mountains, eastern France). J. Quat. Sci. 25 (6), 945–956.

Weisner, O., Arle, J., Liebmann, L., Link, M., Schäfer, R.B., Schneeweiss, A., Liess, M., 2022. Three reasons why the water framework directive (WFD) fails to identify pesticide risks. Water Res. 208, 117848.

Winder, M., Spaak, P., 2001. Carbon as an indicator of Daphnia condition in an alpine lake. Hydrobiologia 442 (1), 269–278.

Wögrath, S., Psenner, R., 1995. Seasonal, annual and long-term variability in the water chemistry of a remote high mountain lake: acid rain versus natural changes. Water Air Soil Pollut. 85 (2), 359–364.

Zhang, H., Huo, S., Yeager, K.M., He, Z., Xi, B., Li, X., Wu, F., 2019. Phytoplankton response to climate changes and anthropogenic activities recorded by sedimentary pigments in a shallow eutrophied lake. Sci. Total Environ. 647, 1398–1409.