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Seasonal Variation in Physicochemical Parameters of Freshwater Lentic Ecosystems and its Influence on Plankton Community Dynamics: A Comparative Review

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ABSTRACT

Freshwater lentic ecosystems such as lakes, ponds, and reservoirs experience marked seasonal shifts in physicochemical conditions that, in turn, regulate the abundance, composition, and diversity of their plankton communities. This review synthesizes findings from a range of tropical, subtropical, and temperate freshwater studies to examine how variables such as water temperature, dissolved oxygen, pH, nutrient concentration, and transparency fluctuate across seasons, and how these fluctuations drive succession in phytoplankton and zooplankton assemblages. Evidence is drawn from monsoon-influenced systems, high-altitude oligotrophic lakes, and large eutrophic water bodies to illustrate recurring patterns: warm, nutrient-enriched periods generally favour cyanobacterial dominance and reduced diversity, while cooler, more transparent periods support more even, diatom- or chlorophyte-rich assemblages. The review also discusses the analytical tools most commonly used to quantify these relationships, including Shannon-Wiener, Simpson, Margalef, and Pielou indices, and multivariate ordination methods such as Canonical Correspondence Analysis. Findings converge on the conclusion that plankton communities function as sensitive, rapidly responding bioindicators of seasonal and anthropogenic change in freshwater systems. The review closes by identifying methodological gaps, including the scarcity of multi-year datasets and inconsistent index selection, and by outlining implications for the monitoring and management of freshwater lentic ecosystems, particularly those under increasing seasonal and human pressure.

***Keywords**: Seasonality, Physicochemical Parameters, Plankton Community Dynamics, Freshwater Lakes, Diversity Indices, Eutrophication, Monsoon Hydrology.*

Introduction

Lentic freshwater ecosystems, comprising lakes, ponds, reservoirs, and other standing water bodies, are among the most ecologically and socioeconomically important components of the hydrosphere. They provide drinking water, support fisheries and agriculture, regulate local microclimates, and sustain a wide diversity of aquatic life. Unlike lotic (flowing) systems, lentic waters are characterized by comparatively long residence times, which allow physicochemical conditions to develop pronounced, often cyclical, seasonal patterns rather than being continuously flushed. These patterns are driven by a combination of external forcing factors, principally solar radiation, air temperature, precipitation and monsoonal hydrology, and internal biogeochemical processes such as nutrient regeneration, stratification, and decomposition.

Physicochemical parameters, including water temperature, dissolved oxygen (DO), pH, electrical conductivity, total dissolved solids, alkalinity, and dissolved nutrients (particularly nitrogen and phosphorus compounds), together define the habitat template within which the biological communities of a lake operate. Because these variables do not remain static through the year, the organisms that depend on them, most immediately the plankton, must continuously adjust their physiology, growth rates, and species composition. Plankton, comprising the phytoplankton (autotrophic, largely algal primary producers) and zooplankton (heterotrophic primary consumers such as rotifers, cladocerans, and copepods), form the base of the aquatic food web and are unusually sensitive indicators of water quality because of their short generation times and close physiological coupling to ambient conditions <cite index="6-1">as demonstrated by the marked temporal and spatial variation observed in the abundance of both phytoplankton and zooplankton in large freshwater lake systems</cite>.

A substantial body of limnological literature, spanning tropical rift-valley lakes in East Africa, monsoon-fed reservoirs in South Asia, and large eutrophic lakes in China, has documented how seasonal shifts in physicochemical conditions reshape plankton assemblages. In tropical and monsoonal systems, the alternation of dry and rainy seasons imposes a strong seasonal rhythm on nutrient loading, turbidity, and thermal structure, while in temperate systems the primary driver is the annual cycle of ice cover, thermal stratification, and photoperiod. Despite these differing climatic contexts, several recurring ecological patterns have emerged: cyanobacterial dominance during warm, nutrient-rich periods; diatom or chlorophyte dominance during cooler, more transparent periods; and a general decline in diversity indices when a single functional group achieves competitive dominance.

Understanding these dynamics has taken on renewed urgency in the context of global climate change, which is altering the timing, duration, and intensity of seasonal cycles in lakes worldwide. Long-term observational studies have shown that dissolved oxygen concentrations in many temperate lakes have been declining for decades, a trend attributed to warming surface waters, changing solubility, and altered mixing regimes <cite index="5-1">an analysis of long-term data from temperate lakes has found a widespread decline in dissolved oxygen concentrations in both surface and deep waters, linked to reduced oxygen solubility at warmer temperatures and to increased stratification at depth</cite>. Such shifts in the physicochemical template inevitably cascade into biological communities, altering plankton phenology, bloom timing, and diversity.

Against this backdrop, the present review has three principal objectives. First, it synthesizes evidence on how the major physicochemical parameters of freshwater lentic ecosystems, temperature, dissolved oxygen, pH, nutrients, and transparency, vary seasonally across different climatic and trophic contexts. Second, it examines how these seasonal physicochemical shifts translate into corresponding changes in phytoplankton and zooplankton community structure, abundance, and diversity. Third, it reviews the principal analytical and statistical tools, including diversity indices and multivariate ordination techniques, used to establish and quantify these physicochemical–biological relationships. By drawing together findings from geographically and climatically diverse freshwater systems, this review aims to identify general ecological principles that transcend individual case studies, while also highlighting methodological gaps that constrain comparability across the wider literature.

Materials and Methods

This review adopts a narrative-synthesis approach appropriate to a topic characterized by heterogeneous study designs, sampling regimes, and geographic settings. A structured literature search was conducted using major academic databases and search engines, including Scopus-indexed journals, ScienceDirect, SpringerLink, Nature Portfolio journals, and Google Scholar, using combinations of the keywords "seasonal variation," "physicochemical parameters," "plankton," "phytoplankton," "zooplankton," "freshwater lake," "reservoir," and "diversity index." The search was restricted to peer-reviewed primary research articles, review papers, and internationally recognized limnological reference texts published in English.

Studies were included if they reported paired seasonal measurements of physicochemical parameters and plankton community metrics (abundance, composition, and/or diversity indices) from a lentic freshwater system, defined as a lake, pond, or reservoir with negligible unidirectional flow. Studies focused exclusively on lotic systems (rivers and streams) were considered only where they offered directly comparable seasonal plankton–physicochemical relationships useful for cross-system comparison. Studies were excluded if they addressed marine or estuarine systems exclusively, or if seasonal resolution was not reported.

Given the geographically dispersed nature of the available literature, spanning East African rift-valley lakes, South and Southeast Asian monsoon-influenced reservoirs, Chinese floodplain and shallow eutrophic lakes, and high-altitude Himalayan lakes, this review does not attempt a formal meta-analysis with pooled effect sizes. Instead, it adopts a comparative, pattern-based synthesis, identifying convergent and divergent findings across studies and relating them to the underlying physical and biogeochemical mechanisms described in general limnological theory. Where studies employed statistical approaches such as Pearson or partial correlation, Canonical Correspondence Analysis (CCA), or the SIMPER (similarity percentage) procedure to relate plankton assemblages to physicochemical variables, these approaches and their reported outcomes are discussed to illustrate the analytical toolkit available to researchers addressing similar questions in their own study systems. This approach is consistent with the aims of a synthesis-style research paper, which is to provide a coherent conceptual framework and methodological reference point for researchers designing site-specific seasonal limnological studies, rather than to generate new primary field data.

Seasonal Dynamics of Physicochemical Parameters in Lentic Ecosystems

- **Temperature and Thermal Structure**

Water temperature is widely regarded as the single most influential physical variable governing seasonal change in lentic ecosystems, since it directly affects metabolic rates, gas solubility, density-driven stratification, and the competitive balance among plankton functional groups <cite index="26-1">climate-induced alterations have triggered notable changes in the physical and biogeochemical processes within lakes, all of which are acutely sensitive to temperature fluctuations, including changes in mixing and stratification patterns and a decline in water viscosity that shifts the competitive balance between sinking phytoplankton and buoyant cyanobacteria</cite>. In tropical lakes without pronounced thermal winters, seasonal temperature variation is generally more modest than in temperate systems but is still ecologically significant. For example, seasonal water temperature in an East African rift-valley lake varied by roughly four degrees Celsius across sampling sites and seasons, yet this variation was still associated with measurable shifts in phytoplankton composition and abundance <cite index="1-1">the observed variation in plankton species dominance during the study may be attributed to seasonal changes in the physicochemical environment, since phytoplankton typically undergo a fairly predictable annual and seasonal cycle</cite>.

In temperate and subtropical systems, seasonal warming drives the onset of thermal stratification, separating the water column into a warm, well-mixed epilimnion and a cooler, isolated hypolimnion. The timing of this stratification, its "phenology," has itself been shown to be shifting under climate warming, with stratification onset occurring progressively earlier and breakdown occurring later in the year across many lakes of the Northern Hemisphere. This lengthening of the stratified period has direct consequences for nutrient availability in surface waters and for the depth distribution of oxygen-sensitive plankton and fish. Because thermal structure constrains the vertical mixing of nutrients and dissolved gases, its seasonal evolution effectively sets the stage upon which the remaining physicochemical variables, dissolved oxygen, pH, and nutrient concentration, play out their own seasonal cycles.

- **Dissolved Oxygen**

Dissolved oxygen concentration in lentic systems is governed by the balance between photosynthetic oxygen production, atmospheric exchange, and oxygen consumption through respiration and decomposition, all of which vary seasonally. In many freshwater lakes, DO concentrations rise during cooler, more oxygen-soluble periods and decline during warmer months when respiration and decomposition rates increase and thermal stratification restricts reaeration of bottom waters. This seasonal oscillation has a long-term dimension as well: a large multi-decadal analysis of temperate lakes found a widespread and continuing decline in dissolved oxygen concentrations in both surface and deep waters, a trend linked to reduced oxygen solubility under warmer conditions and to intensified thermal stratification <cite index="5-1">the long-term decline in dissolved oxygen concentrations in surface waters is primarily associated with reduced solubility under warmer water temperatures, although dissolved oxygen in surface waters has in some cases increased where primary production has been enhanced</cite>. Seasonal deoxygenation in bottom waters during stratified periods can create hypoxic refugia that exclude sensitive zooplankton taxa, thereby reshaping vertical community structure independently of surface-water plankton dynamics.

- **pH and Alkalinity**

Seasonal variation in pH largely reflects the balance between photosynthetic carbon dioxide drawdown, which raises pH, and the input of carbon dioxide and organic acids from decomposition and catchment runoff, which lowers it. In a seasonal study of an East African rift-valley lake, pH values differed significantly across seasons at some sampling sites, with somewhat lower values recorded during the rainy season, a pattern attributed to the increased input and decomposition of organic matter carried in by seasonal runoff, with values subsequently rising once photosynthetic activity resumed after the rains <cite index="1-1">pH values were relatively low during the rainy seasons which may be attributed to the decomposition of organic matter, but the pH values increased after the rainy season as photosynthetic activity of phytoplankton increased</cite>. Alkalinity and hardness, which reflect the buffering capacity and dissolved mineral content of the water, similarly fluctuate with the balance of evaporative concentration during dry periods and dilution during wet periods, a pattern especially pronounced in shallow, climatically exposed water bodies.

- **Nutrient Dynamics and Monsoon-Driven Loading**

Nitrogen and phosphorus dynamics are arguably the most consequential physicochemical drivers of seasonal plankton change, since these nutrients frequently limit primary production and their relative availability (the N:P ratio) can determine whether phytoplankton communities are dominated by diatoms, green algae, or cyanobacteria. Nutrient concentrations in lentic systems typically show strong seasonal pulses linked to precipitation and catchment runoff. In monsoon-influenced regions, the onset of the rainy season is frequently associated with a sharp increase in nutrient loading as surface runoff transports nitrogen and phosphorus from agricultural and urban catchments into receiving water bodies, a pattern documented across reservoirs and headwater catchments subject to strong monsoonal forcing. Because nutrient enrichment is the principal driver of cultural eutrophication, the seasonal timing and magnitude of these nutrient pulses have direct management relevance <cite index="25-2">excess nitrogen and phosphorus inputs to water bodies accelerate eutrophication, increasing the occurrence of harmful cyanobacterial blooms and reducing biodiversity</cite>. It has long been recognized in the eutrophication literature that controlling both nitrogen and phosphorus, rather than a single nutrient in isolation, is necessary to manage the trophic status of lakes effectively, since either element can become limiting depending on season and system type.

Superimposed on these anthropogenic nutrient inputs is a natural seasonal cycle of internal nutrient regeneration: during summer stratification, nutrients released from decomposing organic matter accumulate in the hypolimnion and become unavailable to surface-dwelling phytoplankton until autumnal mixing redistributes them through the water column. This internal loading cycle interacts with external, monsoon- or precipitation-driven loading to produce the complex, often bimodal, seasonal nutrient trajectories reported in many tropical and subtropical lentic systems.

- **Turbidity and Water Transparency**

Water transparency, commonly measured using a Secchi disc, integrates the combined effects of suspended sediment, phytoplankton biomass, and dissolved organic matter, and exerts a strong seasonal control on the light available for photosynthesis. In monsoon-influenced tropical lakes, transparency typically declines sharply during the rainy season as catchment runoff introduces suspended sediment, a phenomenon that can suppress phytoplankton biomass even as nutrient availability increases. This pattern was documented in a large high-altitude tropical lake, where phytoplankton biomass declined during the rainy season primarily as a result of increased turbidity rather than nutrient limitation <cite index="2-1">phytoplankton biomass declined during the rainy season as a result of increased turbidity</cite>, illustrating that light limitation can override nutrient enrichment as the proximate control on seasonal primary production in turbid systems. Transparency typically recovers during the dry season as suspended sediment settles, permitting a resurgence of phytoplankton biomass and a corresponding shift in the composition of the dominant algal groups.

Seasonal Plankton Community Dynamics

- **Phytoplankton Succession Patterns**

Phytoplankton assemblages in lentic ecosystems characteristically undergo predictable seasonal succession, driven by the interacting physicochemical gradients described above. A widely reported pattern, observed across tropical, subtropical, and temperate systems alike, is the dominance of cyanobacteria (blue-green algae) during warm, nutrient-enriched, and often more stable periods, giving way to diatoms, chlorophytes, or mixed assemblages during cooler or more turbulent periods. In a large eutrophic Chinese lake, phytoplankton composition and biomass exhibited clear seasonal and spatial variation linked to nutrient concentration, temperature, and hydrological conditions, with cyanobacterial taxa such as *Microcystis* and *Anabaena* becoming dominant under warm, eutrophic conditions <cite index="3-2">this research discovered that the composition of the phytoplankton community had significant seasonal changes across sampling stations, with cyanobacteria dominating much of the community during the warmer, more eutrophic periods</cite>. A comparable pattern was documented in a study of Lake Chaohu, where the phytoplankton community was dominated during productive periods by *Microcystis* and *Anabaena* species, reflecting the well-established competitive advantage that buoyancy-regulating cyanobacteria hold under warm, nutrient-rich, and often stratified conditions.

Similar successional dynamics have been documented in a large river-connected lake in China, where phytoplankton were found to be dominated by cyanobacteria in summer and by diatoms in winter, while zooplankton, in contrast, were dominated by copepods throughout the year, indicating that phytoplankton groups respond more strongly to seasonal thermal and nutrient cycles than do the broader zooplankton assemblage <cite index="45-1">phytoplankton were dominated by cyanobacteria in summer and diatoms in winter, and zooplankton were dominated by copepods throughout the year</cite>. In cooler, less eutrophic settings, the successional pattern can differ markedly: a long-term study of phytoplankton in a large, deep, oligotrophic lake found that temperature was a key driver of seasonal succession, with distinct assemblages characterizing the spring, summer, and autumn periods as the thermal regime of the lake evolved <cite index="4-1">phytoplankton density and biomass showed significant differences between spring and summer, reflecting the influence of seasonal changes in the physicochemical environment on community structure</cite>.

Turbidity-driven light limitation can produce an alternative seasonal trajectory in monsoon-affected systems, where phytoplankton biomass peaks not during the warmest season but during the clearer, nutrient-replete periods immediately before or after the monsoon. In an East African rift-valley lake, the diversity of phytoplankton was highest during the cooler, drier winter season, while the lowest diversity coincided with the post-rainy autumn period, when a small number of cyanobacterial and chlorophyte taxa achieved numerical dominance <cite index="34-1">the highest Shannon–Wiener diversity index was recorded during the dry winter season, while the lowest was recorded during autumn, when phytoplankton populations were increasingly dominated by a limited number of taxa</cite>. This inverse relationship between the degree of numerical dominance by a small number of taxa and overall community diversity is a recurring theme across the reviewed literature, reflecting the general ecological principle that competitive exclusion under favourable growth conditions for a single functional group reduces evenness even when total abundance is high.

- **Zooplankton Dynamics**

Zooplankton communities, comprising principally rotifers, cladocerans, copepods, and ostracods in freshwater systems, respond to seasonal physicochemical change both directly, through effects on their own physiology and reproduction, and indirectly, through changes in the abundance and composition of their phytoplankton food resource. Zooplankton play a pivotal ecological role in transferring energy from primary producers to higher trophic levels and in regulating phytoplankton biomass through grazing pressure, making their seasonal dynamics tightly coupled to, yet somewhat lagged behind, those of the phytoplankton community <cite index="3-1">zooplankton play an important part in transforming energy from lower trophic organisms to higher ones, regulating phytoplankton growth and shaping pelagic ecosystem structure</cite>. This coupling is not always synchronous, however; combined effects of nutrient dynamics and seasonal climatic forcing on the co-occurring phytoplankton and zooplankton assemblages remain comparatively under-studied relative to single-taxon investigations <cite index="3-1">combined effects of nutrient dynamics together with seasonal climatic change on phytoplankton and zooplankton communities have seldom been examined jointly, since most previous studies have evaluated the two groups separately</cite>.

Empirical evidence indicates that zooplankton seasonal abundance and biomass often peak during warmer months when phytoplankton food resources and water temperature both favour rapid reproduction, as documented for a temperate river system where zooplankton and phytoplankton abundance and biomass were both higher in summer than in other seasons <cite index="8-1">the abundance and biomass of zooplankton and phytoplankton in the summer were higher than those recorded in other seasons</cite>. However, taxonomic composition within the zooplankton community can remain comparatively stable across seasons even as total abundance fluctuates, as observed in a large floodplain lake where copepods dominated the zooplankton assemblage throughout the year despite pronounced seasonal shifts in the co-occurring phytoplankton community <cite index="45-1">zooplankton were dominated by copepods throughout the year, in contrast with the more strongly seasonal phytoplankton community</cite>. This differential seasonal sensitivity between the two plankton groups has practical implications for water-quality monitoring: while phytoplankton indices may respond rapidly to a single nutrient pulse or thermal event, zooplankton community composition may offer a more integrated, temporally buffered signal of overall ecosystem condition.

- **Diversity Indices as Analytical Tools**

Quantifying seasonal change in plankton community structure requires standardized diversity metrics that allow comparison across sites, seasons, and studies. The most widely applied metric in the reviewed literature is the Shannon-Wiener diversity index, originally developed as a measure of information content and subsequently adapted by ecologists to quantify species diversity by combining species richness and evenness into a single value (Shannon & Weaver, 1949). This index has been applied extensively to both phytoplankton and zooplankton datasets to track seasonal changes in community structure, with higher values generally interpreted as indicating a more diverse, less disturbed community, and lower values indicating dominance by a smaller number of tolerant or opportunistic taxa.

Complementary indices frequently reported alongside the Shannon-Wiener index include Simpson's index, which emphasizes the probability that two randomly selected individuals belong to different species and is therefore more sensitive to dominance by abundant taxa (Simpson, 1949); Margalef's richness index, which relates the number of species present to the logarithm of total sample size and thus isolates the richness component of diversity independent of relative abundance (Margalef, 1958); and Pielou's evenness index, which expresses observed diversity as a proportion of the maximum possible diversity for the observed number of species, thereby isolating the evenness component (Pielou, 1966). Together, this suite of indices allows researchers to distinguish whether a seasonal decline in overall diversity reflects a genuine loss of species richness or simply a redistribution of relative abundance toward a smaller number of dominant taxa, a distinction with different ecological and management implications.

Beyond these general diversity measures, certain research traditions in freshwater biomonitoring have developed pollution-specific indices, most notably Palmer's algal genus pollution index, which assigns pollution-tolerance scores to particular algal genera and sums these scores to produce a single index of organic pollution (Palmer, 1969). Such indices complement the more general diversity measures by linking specific taxonomic composition directly to inferred water-quality status, an approach broadly consistent with the wider use of biological indicators, including plankton, to assess ecosystem health <cite index="34-2">phytoplankton have frequently been used as ecological indicators for assessing the ecological health of aquatic ecosystems and the stress effects of chemical contaminants</cite>.

Linking Physicochemical Seasonality to Plankton Structure: Statistical Approaches

Establishing a quantitative link between seasonal physicochemical variation and plankton community structure typically requires statistical approaches capable of handling multiple, often correlated, explanatory variables alongside multivariate biological response data. The simplest and most widely reported approach is bivariate or partial correlation analysis, in which the abundance of individual plankton taxa or functional groups is correlated against specific physicochemical variables across the seasonal sampling series. In a seasonal study of an East African lake, partial correlation analysis showed that cyanobacterial abundance correlated positively, though not always significantly, with water temperature and turbidity, while chlorophyte abundance showed a significant positive correlation with temperature, and diatom and euglenoid abundance correlated negatively with temperature <cite index="34-3">a partial correlation analysis showed that cyanobacterial abundance was positively though non-significantly correlated with water temperature and turbidity, while a positive and significant correlation was observed between green-algal abundance and water temperature, and a non-significant negative correlation was found between water temperature and both euglenoid and diatom abundance</cite>. Such taxon-specific correlation patterns illustrate why aggregate community metrics, such as total phytoplankton biomass, can obscure important underlying shifts in functional group composition that are more directly diagnostic of seasonal environmental change.

Where the objective is to relate an entire multivariate community matrix (many taxa across many samples) to a suite of physicochemical variables simultaneously, direct gradient analysis techniques such as Canonical Correspondence Analysis (CCA) are more appropriate and have been widely adopted in the recent limnological literature. CCA analyses have been used to relate phytoplankton assemblage composition to variables such as pH, dissolved oxygen, free carbon dioxide, alkalinity, hardness, conductivity, and total dissolved solids in seasonal studies of high-altitude oligotrophic lakes, allowing researchers to identify which physicochemical axes best explain the observed seasonal turnover in species composition. Comparable ordination-based approaches, including cluster analysis and similarity percentage (SIMPER) procedures, have been used to formally test for statistically significant seasonal dissimilarity in phytoplankton community composition while identifying the specific taxa most responsible for driving these seasonal differences, an approach that provides more ecological detail than whole-community diversity indices alone.

The choice between simple correlation, multivariate ordination, and dominance- or pollution-based indices should, in general, be guided by the specific research question: correlation analysis is well suited to testing hypotheses about the physiological response of particular taxa to individual environmental drivers; ordination techniques are better suited to characterizing overall community-level turnover and identifying the dominant environmental gradients structuring an assemblage; and index-based approaches, such as the trophic state index or Palmer's pollution index, are most useful when the objective is rapid, standardized water-quality classification for management purposes rather than detailed mechanistic understanding.

Discussion

The comparative evidence reviewed here indicates that, despite substantial differences in climate, trophic status, and hydrological regime, freshwater lentic ecosystems share several recurring patterns in how seasonal physicochemical change structures their plankton communities. First, temperature functions as a near-universal seasonal driver, directly controlling metabolic rates and, through its effect on water density and stratification, indirectly controlling the vertical distribution of nutrients and oxygen. Second, in systems subject to strong seasonal precipitation, whether monsoonal in South and Southeast Asia or more diffusely seasonal in temperate climates, nutrient loading and turbidity are frequently decoupled from the temperature cycle, producing complex, sometimes bimodal, seasonal trajectories in primary production that cannot be predicted from temperature data alone. Third, across nearly all reviewed systems, periods of warm temperature combined with elevated nutrient availability were associated with reduced phytoplankton diversity and increased dominance by cyanobacterial taxa, a pattern with direct relevance to the management of eutrophication and harmful algal blooms.

An important nuance emerging from this synthesis is the differential seasonal sensitivity of phytoplankton versus zooplankton. Phytoplankton assemblages, owing to their short generation times and direct dependence on light and nutrient availability, tend to track seasonal physicochemical shifts closely and can exhibit rapid compositional turnover within a single season. Zooplankton communities, by contrast, often show more taxonomically stable seasonal composition, even where total abundance fluctuates substantially, suggesting that zooplankton community structure may integrate environmental variability over a longer time window than instantaneous phytoplankton snapshots. This has practical implications for biomonitoring programme design: a monitoring strategy relying solely on phytoplankton counts may be more sensitive to short-term pollution events, whereas one incorporating zooplankton metrics may better capture sustained or chronic ecosystem stress.

The reviewed literature also highlights the growing relevance of climate change as a modifier of "normal" seasonal cycles in lentic ecosystems. Evidence of earlier onset and later breakdown of thermal stratification, together with widespread long-term declines in dissolved oxygen concentration in temperate lakes, suggests that the seasonal templates against which plankton communities have historically adapted are themselves shifting. This raises the possibility that the well-documented seasonal succession patterns described in the classical limnological literature may become progressively less predictable, or may shift in timing (a phenomenon sometimes termed phenological mismatch), with consequences for food web stability that remain incompletely understood.

Several methodological gaps constrain the broader comparability of the seasonal plankton–physicochemical literature. First, sampling duration varies enormously across studies, from single-year investigations to multi-year time series, limiting the ability to distinguish genuine seasonal cycles from inter-annual variability or long-term trend. Second, there is considerable inconsistency in the choice and reporting of diversity indices, with some studies reporting only Shannon-Wiener values while others report a fuller suite including Simpson, Margalef, and Pielou indices, complicating cross-study synthesis. Third, relatively few studies integrate simultaneous, high-resolution physicochemical and plankton sampling with the statistical power needed to disentangle the relative contributions of temperature, nutrients, and light to observed seasonal succession patterns. Addressing these gaps through standardized, multi-year monitoring protocols, ideally incorporating both simple diversity indices and multivariate ordination methods, would substantially strengthen the evidentiary basis for the management of seasonally variable freshwater ecosystems, including culturally and religiously significant water bodies that face concentrated anthropogenic pressure during specific festival or pilgrimage seasons.

Conclusion

This review has synthesized evidence from a geographically and climatically diverse set of freshwater lentic ecosystems to demonstrate that seasonal variation in physicochemical parameters, particularly temperature, dissolved oxygen, pH, nutrient concentration, and transparency, exerts a strong and largely predictable influence on the abundance, composition, and diversity of plankton communities. Warm, nutrient-enriched, and often more turbid periods are consistently associated with reduced phytoplankton diversity and increased dominance by cyanobacterial taxa, while cooler, clearer periods tend to support more diverse and even assemblages dominated by diatoms or chlorophytes. Zooplankton communities, while responsive to these same seasonal drivers, generally exhibit somewhat greater taxonomic stability across seasons than phytoplankton, reflecting their more integrated response to environmental variability. Diversity indices, particularly the Shannon-Wiener, Simpson, Margalef, and Pielou indices, together with multivariate ordination techniques such as Canonical Correspondence Analysis, provide a robust and widely validated analytical toolkit for quantifying these relationships. Given the accelerating influence of climate change on lake thermal regimes and oxygen dynamics, continued and expanded seasonal monitoring of both physicochemical parameters and plankton community structure remains essential, not only for advancing fundamental limnological understanding but also for the practical management and conservation of freshwater lentic ecosystems worldwide.

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