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Review

A Review on the Driving Mechanism of the Spring Algal Bloom in Lakes Using Freezing and Thawing Processes

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Abstract: Spring algal blooms in mid–high-latitude lakes are facing serious challenges such as earlier outbreaks, longer duration, and increasing frequency under the dual pressure of climate warming and human activities, which threaten the health of freshwater ecosystems and water security. At present, the freeze-thaw processes is the key to distinguishing spring algal blooms in mid- to high-latitude lakes from low-latitude lakes. Based on the visualization and an analysis of the literature in the WOS database during 2007–2023, we clarified the driving mechanism of the freeze-thaw process (freeze-thaw, freeze-up, and thawing) on spring algal bloom in lakes by describing the evolution of the freeze-thaw processes on the nutrient migration and transformation, water temperature, lake transparency and dissolved oxygen, and physiological characteristics of algae between shallow lakes and deep lakes. We found that the complex phosphorus transformation process during the frozen period can better explain the spring-algal-bloom phenomenon compared to nitrogen. The dominant species of lake algae also undergo transformation during the freeze-thaw process. On this basis, the response mechanism of spring algal blooms in lakes to future climate change has been sorted out. The general framework of "principles analysis, model construction, simulation and prediction, assessment and management" and the prevention strategy for dealing with spring algal bloom in lakes have been proposed, for which we would like to provide scientific support and reference for the comprehensive prevention and control of spring algal bloom in lakes under the freezing and thawing processes.

Keywords: freezing and thawing processes; spring algal bloom; climate change; driving mechanism; prevention and control strategies

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1. Introduction

Lakes are important carriers of surface water resources, playing a role in protecting biodiversity, maintaining ecological balance within the watershed, and supplying fresh water [1–4]. The migration pathways and rates of nitrogen and phosphorus nutrients to lakes have exhibited diversity and variability under the dual pressure of global warming and human activities [2,5]. The algal blooms in mid- to high-latitude lakes are facing challenges such as earlier outbreak times, longer duration, and increased frequency of occurrence [3,6]. Previous studies have found that the presence of freeze-thaw processes is the key to promoting the mechanism of algal blooms in mid- to high-latitude lakes, which is different from that in low-latitude lakes [4–6]. Hence, how to reveal the impact mechanism of freeze-thaw processes on the occurrence and development of spring algal blooms is crucial for water-environment management.

Compared to low-latitude lakes, the growth and melting of lakes' ice would change the living environment of algae in mid–high-latitude lakes [5,6]. The water temperature structure, hydrodynamic conditions, sunshine conditions, and eutrophication degree will change with the freeze-thaw process. These factors will promote changes in the growth mechanism of the plankton and microbial communities in the lake [6,7]. Among them, the freeze-thaw process affects the migration and transformation of nutrients in the lake, and the competition for algae growth is more complex and variable. Taking Lake Washington in the United States as a typical seasonally covered shallow lake, the concentration of nutrients is actually the highest in winter. This situation encourages algae to receive a lot of light and nutrients after the lake's ice melts in the spring [7–9]. Subglacial water not only increases nutrients through concentration, it also increases the conductivity of the water by a factor of 1.7–2.7 compared to summer. This phenomenon increases the risk of spring algal blooms. [10,11]. However, there was insufficient research on the competitive living environment and self characteristics of algae growth during different periods such as freeze-thaw, freeze-up, and thawing [11]. Therefore, it is urgent to propose future mechanisms and prevention and control strategies for spring algal blooms by reviewing existing research on the impact of freeze-thaw processes on spring algal blooms. In the current study, the survival of plankton and nitrogen and phosphorus substances in lakes during the ice-covered period has been richly researched, but the changes in these substances during the whole process from freeze-thaw to thawing of lakes have not been sufficiently researched [5,8,9]. Meanwhile, a set of effective preventive measures for spring algal bloom in lakes has not been proposed. This paper proposed some theories and strategies to address these shortcomings.

In order to sort out the driving mechanism of the spring algal bloom in lakes with freezing and thawing processes, the literature during 2007–2023 in the Web of Science (WoS) database were summarized and analyzed. The objectives of this study are (i) to summarize the hotspots and difficulties of the freeze-thaw process on the driving mechanism of spring algal blooms through visual analysis of the number of publications and hot vocabulary; (ii) to sort out the response mechanism of spring algal blooms in lakes to the freeze-thaw process' effects using the migration and transformation of nutrient, the transparency and dissolved oxygen, and the succession and renewal of the algal community structure; (iii) to provide the strategies for prevention and control of spring algal bloom in lakes.

2. Data and Methods

CiteSpace was used to analyze the historical literature from 2007 to 2023 on the effect of freeze-thaw processes on spring algal bloom in lakes. Research hotspots and future research trends will be further revealed in our study. The advantage of CiteSpace is it uses mathematical and statistical methods to conduct in-depth literature mining, through visualizing the structural and hot-topic relationships between massive amounts of data, clarifying the development process of the field [12–16]. This study mainly utilized time-slicing technology to construct a time-varying model of time series, integrating a single network into an overview network. In addition, this study achieved the visualization effect of the literature through dynamic time-series mapping, including keyword recognition, extraction of research hotspots, and correlation between publishing units.

2.1. Data Sources

The literature was obtained from the Web of Science's (WoS's) core-collection database in the Clarivate Analytics website and was citation indexed from SCI-E (Science Citation Index Extend). The search date was 28 November 2023, and the search time was 2007–2023. The search keywords were "eutrophication", "eutrophication Lakes", "algal bloom", "water bloom", "phytoplankton", "spring algal blooms", "spring bloom", "lake bloom" and "freeze", "freeze thawing", "seasonal freeze-thaw" and "freezing and thawing". In order to accurately discover the relevant literature in this field, the retrieved studies were further screened and eliminated in terms of title, abstract and keywords.

2.2. Methods of Analysis

The study information such as year of publication, number of documents, keywords and other information were screened and extracted. The trend and keyword maps of the effect of freeze-thaw processes on spring algal blooms in lakes in various countries over the years have been drawn using a bibliometric functional analysis method. The hotspot and tendencies were analyzed using visualization software based on the year of publication, the number of papers, and keywords.

3. Hotspots Revisited

3.1. Statistical Analysis of the Volume of Publications

The number of publications on the impact of freeze-thaw processes on spring algal blooms in lakes has been increasing since 2007 based on WoS database. Especially after 2014, the number of publications has sharply increased. An analysis was conducted based on 519 papers from 2007 to 2023 on the mechanisms of the influence of freeze-thaw processes on spring algal blooms in lakes. The top 5 countries (The United States of America (USA), China, Canada, the United Kingdom (UK), Germany) with the highest number of publications and the greatest extent of impacts from spring algal blooms were extracted for statistical analysis (Figure 1) [7,12,15]. At the same time, these countries are located at high latitudes, where lake freeze-thaw phenomena and spring algal blooms are common. The results showed that the average annual publication volume in the United States was the highest in the world regarding the impact of freeze-thaw processes on spring algal blooms. The average annual publication volume of China had the highest growth rate compared to other countries. The tendency of publication numbers in Germany and the United Kingdom were relatively stable.

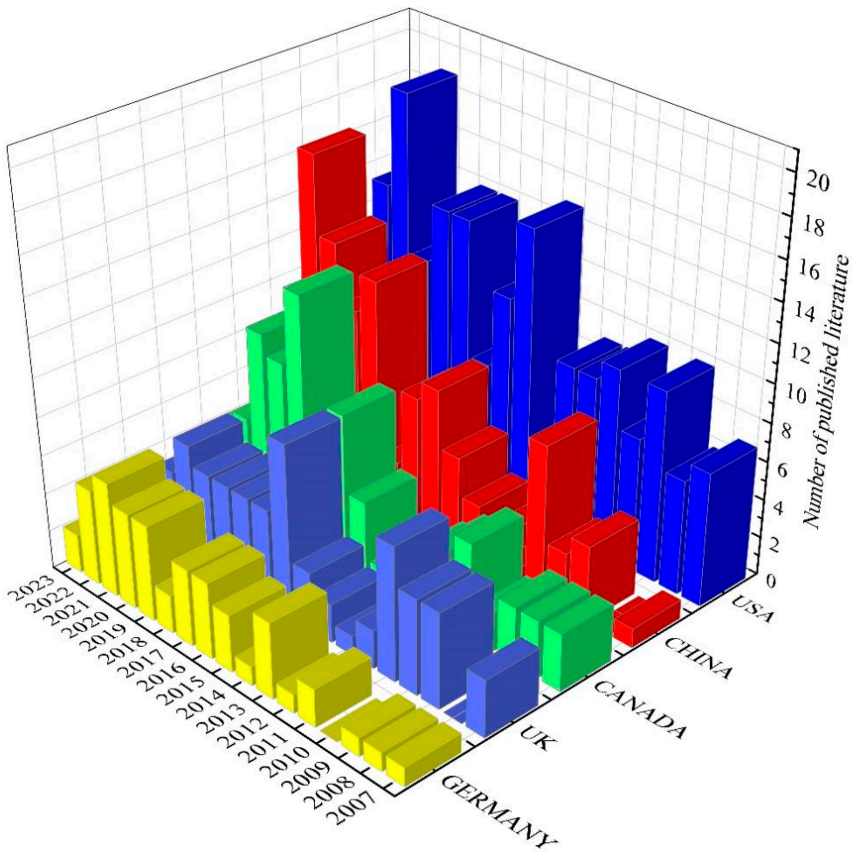

Figure 1. Statistical chart of annual publication volume in the top five countries with the highest publication volume.

3.2. Statistical Analysis of Keywords

The study on the impact of freeze-thaw processes on spring algal bloom in lakes has broad and focal differences based on keywords. There were 298 keywords that appeared during 2007–2023 in the WoS database. Among these keywords, there were nine keywords that appear at least 15 times. The top five keywords with the highest frequency of occurrence were phytoplankton (77 times), climate change (38 times), nitrogen (27 times), water (19 times), and sea ice (19 times) (Table 1). The top five keywords for centrality were phytoplankton, climate change, water, nitrogen, and temperature. The research hotspots also began to shift from the earlier hydrodynamic characteristics, and there were changes in nitrogen and phosphorus levels and phytoplankton growth mechanisms. The research hotspots gradually migrated to mechanisms affecting water-quality changes, aquatic-plant tolerance, and the phytoplankton-growth processes. Based on the keyword co-occurrence map, studies on the effects of freeze-thaw processes on spring algal blooms mainly focus on two aspects: exploring the hydrodynamic characteristics under climate change and studying the growth mechanism of phytoplankton. (Figure 2). In summary, international research on the effects of freeze-thaw processes on spring algal blooms has focused on the physicochemical properties of ice-water bodies (nutrients, light, dissolved oxygen (DO), etc.). Research is also directed at the effects of their changes for phytoplankton growth mechanisms.

Table 1. Mapping of keyword frequency, centrality, and high-frequency burst analysis in the WoS database (top9).

No.	Order of Occurrence		Order of Centrality		Sudden-Appearance Analysis				
	Keywords	Frequency	Keywords	Centrality	Keywords	Strength	Begin	End	2007–2023
1	phytoplankton	77	phytoplankton	0.67	dynamics	4.62	2009	2010	
2	climate change	38	climate change	0.23	southern ocean	2.44	2009	2017	
3	nitrogen	27	water	0.18	phytoplankton	3.15	2011	2014	
4	water	19	nitrogen	0.17	eutrophication	3.99	2018	2020	
5	sea ice	19	temperature	0.15	water quality	3.27	2019	2021	
6	eutrophication	19	harmful algal blooms	0.11	cold hardiness	3.01	2019	2023	
7	temperature	18	sea ice	0.1	loesses	2.44	2019	2021	
8	dynamics	17	ocean	0.1	damage	2.41	2019	2021	
9	growth	16	dynamics	0.07	organic matter	2.39	2020	2023	

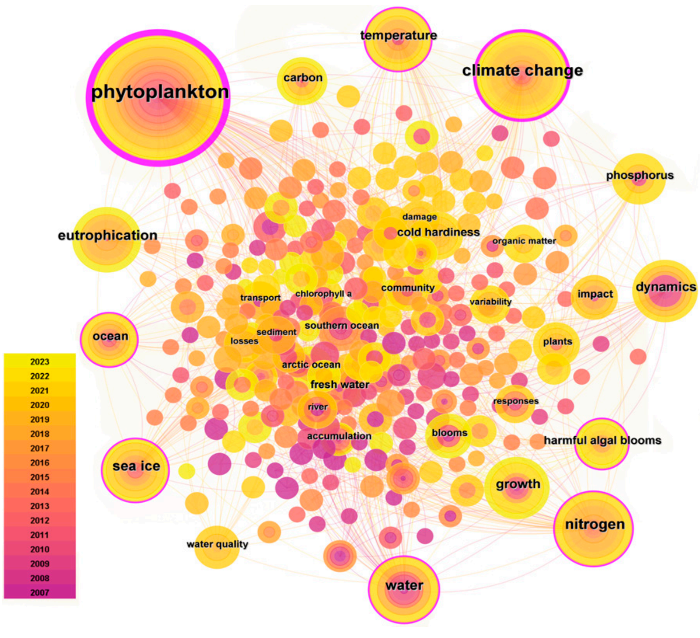

Figure 2. Keyword-co-occurrence-analysis mapping.

4. Results of Driving Mechanism Analysis

4.1. Effects of Freeze-Thaw Processes on Nutrient Migration and Transformation

Nitrogen and phosphorus were the major drivers of phytoplankton growth, competition, and succession, and directly affect primary productivity in lakes [17]. Excess nutrients could contribute to lake algal blooms [18]. Lakes' spring algal bloom has been expanding to the middle and high latitudes, and the scale, frequency, and intensity of its occurrence are all increasing under the dual pressures of climate change and human activities [19]. The algal blooms in lakes at mid to high latitudes arounds the world are also showing an increasing trend. Most of the studies focused on the mechanism of algal blooms in low-latitude lakes, with a lack of studies on the driving mechanism of algal blooms in mid–high-latitude lakes, especially those with seasonal ice and freeze-thaw phenomena. Therefore, it was important to analyze the mechanism of nutrient transport and transformation during freeze-thaw processes on spring algal bloom in lakes [20]. The freeze-thaw processes of lakes include freeze-thaw, freeze-up, and thawing [21]. During this period, the physical (water temperature, solar radiation, gas release, etc.), chemical (dissolved oxygen, CO_2 concentration, etc.), and hydrology factors (hydrodynamic conditions, water velocities, water circulation, etc.) of the lakes would change significantly, which will directly or indirectly drive the migration and transformation of nutrients [22]. The freeze-thaw effect on the migration and transformation of nutrients in lakes will affect the stability and development of the entire lake ecosystem [23]. During the freezing period of the Ulansuhai Lake in Inner Mongolia, due to the thickness of the snow cover and the shallow depth of the lake, the organisms at the bottom of the water body are able to carry out photosynthesis to promote the migration and transformation of nutrients; as represented by Woods Lake, the nutrient concentration replaces the temperature of the water body as an important controlling factor affecting the stability of the lake ecosystem (Table 2) [24,25]. The growth and melting of ice sheets altered the growth of phytoplankton by affecting physical and biogeochemical processes in the water beneath the ice [26]. The study of Norfolk Lake in the UK and Rappbode Reservoir in Germany found that the increase of nutrient concentration caused by ice sheet freezing led to the decrease of plant abundance and biomass in the water [27,28]. Therefore, the effects of the freeze-thaw processes on the nutrient-transport mechanism, transparency, and dissolved oxygen, and the physiological and ecological characteristics of algae in the water column should be considered [29].

Table 2. Eutrophication in selected high-latitude lakes.

No.	Country	Lake	Algae Bloom State	References
1	USA	Great-salt-sea	Escalation	[30,31]
2	China	Hulun	Sharply escalate	[32,33]
3	Canada	Winnipeg	Escalation	[34,35]
4	UK	Lough Neagh	In grave difficulty	[36,37]

4.1.1. Effects of Freeze-Thaw Processes on Nutrient Transport in Lakes

Nutrients were mainly distributed on the surface and bottom sediment layers of the water during the non-freezing period of lakes, which was an obvious vertical stratification phenomenon [38]. The dissolved oxygen concentration at the bottom of the water column was relatively low, while the content of organic matter and particulate matter was higher than that at the top of the water column [39]. The formation of ice sheets promoted the transportation of nutrients in ice concentration into the water, resulting in higher nutrient concentrations in the water than during the non-freezing period [40]. Of particular note is the formation of thermocline in deep-water lakes located in cold or temperate regions during freezing and thawing. It is difficult to exchange material between the upper mixed layer (epilimnion) and the lower stagnant layer (hypolimnion) within the lake. Large quantities of particulate organic matter and nutrients are difficult to resuspend into the upper layers of the water column through re-suspension after settling to the bottom of the lake. On the other hand, in shallow lakes, wind, waves, and turbulence can reach the bottom of the lake directly before the ice cap forms. There is an impact on organic matter and nutrients deposited on the lake bottom. These substances can enter the overlying water column through re-suspension, creating a nutrient cycle on the sediment–water inner surface (Figure 3) [41].

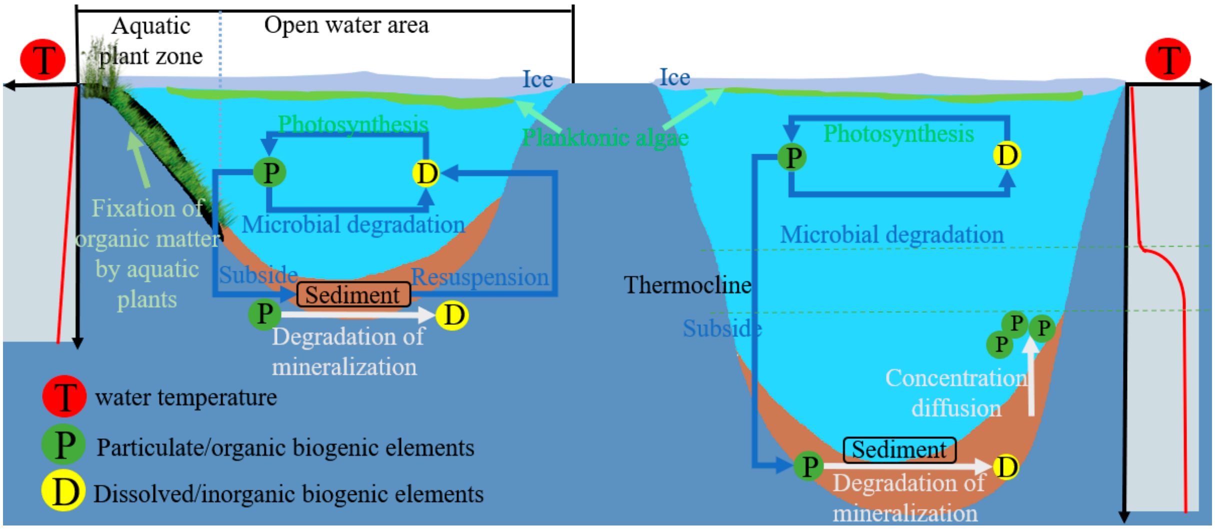

Figure 3. Patterns of nutrient cycling in shallow (left) and deep-water (right) lakes during the freezing period.

When the lake was in the frozen period, the presence of ice sheets and snow promoted significant differences in the physical and chemical environment compared to other periods [42]. The water flow rate was slow, while the nutrient concentration varied greatly in multiple media. Nutrient concentration showed a "C-shaped" distribution in sub glacial water bodies [43]. The concentration of ammonia nitrogen and nitrate nitrogen in water was higher than those in sediment, while the tendency of available phosphorus was opposite [42]. The distribution characteristics of nitrogen and phosphorus at the sediment water interface were relatively different [44]. The concentration of ammonia nitrogen and nitrate nitrogen decreased with the increase of sedimentation depth. However, the concentration of effective phosphorus showed a tendency to increase and then decrease with the increase of sedimentation depth [45]. The presence of lake ice promotes the slowed rheological behavior of ice water, changing disturbance between sediment, and promoting a different distribution of nutrients between ice, water, and sediment compared to other periods [46]. There was a critical value for external factors such as flow velocity and disturbance in water bodies under ice caps, and both above and below this threshold will have different effects on nitrogen and phosphorus releasing [47].

During the thawing period, nutrients in snow quickly entered the water body, which resulted in a sudden increasing of nutrient concentration in the water body [17]. The increasing of water temperature accelerated the metabolism of algae [21]. During the thawing period, the water flow rate increased, and the nutrient cycling rate and biogeochemical reaction rate both accelerated [48]. In addition, studies had shown that the comprehensive eutrophication index of water during the freezing and thawing periods was higher than that during non-freezing period [40]. These variations will lead to the spring algal blooms [49].

4.1.2. Effects of Freeze-Thaw Processes on Nutrient Transformation

Nitrogen and phosphorus, as important components of biogeochemical cycles in lakes, are the material basis for the growth and reproduction of phytoplankton and microorganisms [50]. At present, studies showed that a variety of factors such as temperature, dissolved oxygen content, acidity, alkalinity, and solar radiation were subject to change. Regrettably, there were fewer studies on the polymorphic transformation of nitrogen and phosphorus in lakes with the freezing and thawing process. The response of each substance was difficult to quantify, which greatly restricted an in-depth understanding of the mechanism of spring algal bloom in mid–high latitude lakes [51].

The main chemical reaction mechanisms of nitrogenous nutrients in lakes included anaerobic denitrification, anaerobic ammonium oxidation, aerobic denitrification, and anaerobic methane oxidation [52]. The transformation of nitrogen forms in water mainly includes processes of ammonification, nitrification, and denitrification [53]. The existence of freeze-thaw processes in lakes led to lower water temperature and dissolved oxygen concentration in the lake [5]. Anaerobic and low-temperature environments led to a decrease in microbial activity, promoting a decrease in the rates of nitrification, denitrification, and ammonification reactions [54]. Anaerobic environment also promoted further reduction of nitrate into nitrogen and nitrous oxide [55]. However, the contribution of freezing and thawing processes to ammonification and nitrification can not be specifically quantified.

Phosphorus is an essential macronutrient for phytoplankton growth, which plays a more important role in phytoplankton succession than nitrogen in lakes. The occurrence forms of phosphorus included orthophosphates ($H_2PO_4^-$, HPO_4^{2-}, PO_4^+), polymerized phosphates ($P_2O_7^{4-}$, $P_3O_{10}^{5-}$), and organophosphates (phosphatidylinositol) [56,57]. The rate phosphorus migration and its transformation in lakes was higher than that of nitrogen and silicon [58]. The phosphorus content decreased below the critical value required for algae growth (2 µg/L) due to the long-term low-temperature and hypoxic environment during the frozen period [57]. The process of converting organic phosphorus into inorganic phosphorus and orthophosphate into adenosine triphosphate (ATP) was greatly inhibited due to the decrease in microbial activity during the frozen period [58]. Phosphate can form insoluble precipitates with metal cations Fe_3^+, Al_3^+, Ca_2^+, Mg_2^+, and the reaction speed was also affected by the temperature and oxygen content (Figure 4). Phosphate exhibited vertical stratification due to the decomposition of dead vegetation residues by microorganisms during the frozen period [59]. The anaerobic environment promoted the transformation of insoluble $Fe(ON)_3$ into soluble $Fe(ON)_2$, providing a material-source basis for the improvement of primary productivity in spring [60]. Some anaerobic microorganisms in the frozen sediments accelerated the conversion of organic to inorganic phosphorus in the sediments. This phenomenon also increases phosphorus levels in the overlying water column [61]. Hence, the complex phosphorus transformation process during the frozen period can better explain the spring-algal-bloom phenomenon compared to nitrogen.

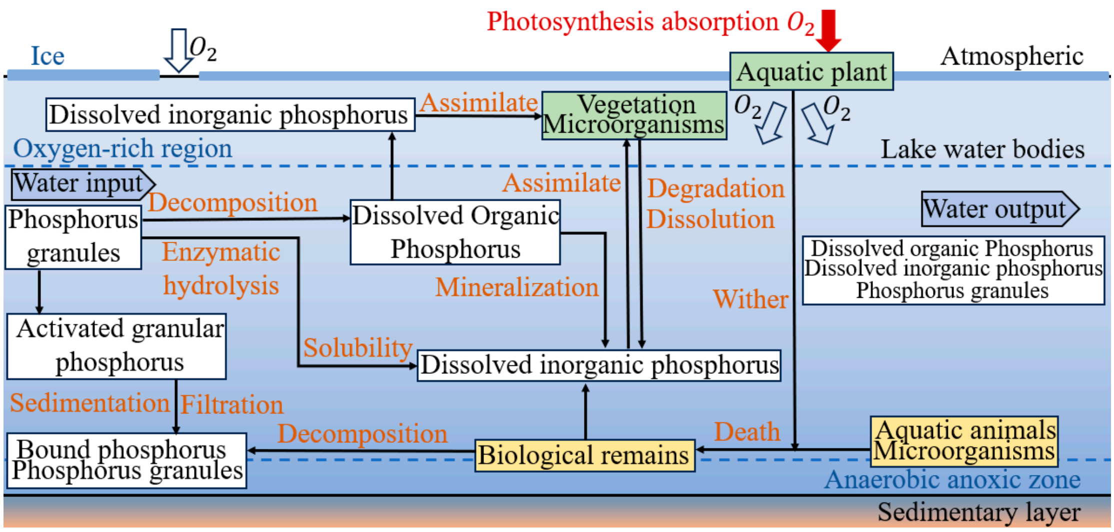

Figure 4. Mechanisms of phosphorus-containing nutrient transformation in lakes during freezing and thawing processes.

4.2. Effect of Freeze-Thaw Processes on Transparency and Dissolved Oxygen

The presence of snow and ice layers weakened the intensity of solar radiation entering sub-glacial water bodies, promoting a decrease in sub-glacial light intensity to inhibit algal photosynthesis [62,63]. The lake ice also temporarily buffered atmospheric sedimentation and reduced wind disturbance, suppressing the resuspension of sediment [64].

Ice caps are influenced by a number of factors during their formation. The freezing temperature of the ice, the rate of ice growth, and the salinity of the water together determine the density, crystal structure, and internal microstructure of the ice. They lead to a decrease in the transparency of the ice, making less light receivable under the ice [65]. The weakening of photosynthesis led to a further decrease in dissolved-oxygen content [66]. In addition, the nutrient concentration in the ice and the freezing separation coefficient also increased with the decreasing of freezing temperature, promoting the release of nutrients from the ice into the water body [67]. Ice caps redistributed nutrients between water bodies and ice layers through freezing, salt discharge, and melting dilution [68]. The research found that the formation of ice sheets redistributed nutrients among ice, water, and sediment [69]. The ice sheet weakened the disturbance of wind, blocks the exchange of substances between the atmosphere and water, and reduced the re-suspension of particles caused by wind [68,69]. The pollutants in the overlying water became more uniform during the frozen period, which promoted the increasing of transparency [69–71]. Hence, transparency of different lakes reacts differently during freeze-thaw processes, while it all led to a decreasing of dissolved oxygen due to the ice sheets.

4.3. Effect of Freeze-Thaw Processes on Algae Physiology

Phytoplankton, as the basis of material circulation and energy flow in lake ecosystems, plays an important role in maintaining the balance of the entire ecosystem [72]. Freezing and thawing had direct or indirect effects on the physiological and ecological characteristics of planktonic algae from physical (temperature, light intensity, dissolved sample content), chemical (nutrient salt concentration, metabolic rate) and hydrological (hydrodynamic conditions, water circulation) [71].

According to the previous research, the freeze-thaw process greatly limited the activity of underwater organisms [73]. However, scholars found that the diversity of benthic phytoplankton species during the frozen period was still relatively high in recent years [74–76]. Currently, the research has found that the freezing period promoted a decreasing of phytoplankton diversity over time [77]. However, the driving mechanism of phytoplankton population succession during the freezing period was not clear (Figure 5). Cyanobacteria had the greatest dominance during the freeze-up period; with the further reduction in temperature and the extension of the freeze-up time, the cyanobacteria entered into a dormant period [78]. Diatoms had a clear dominance during the freeze-up period, which had a direct relationship to their physiological characteristics of regulating the water, sugar, and fat in the cells to increase the ability of drought resistance [79]. During the thawing period, cyanobacteria and green algae dominate, due to maximal photosynthesis [80].

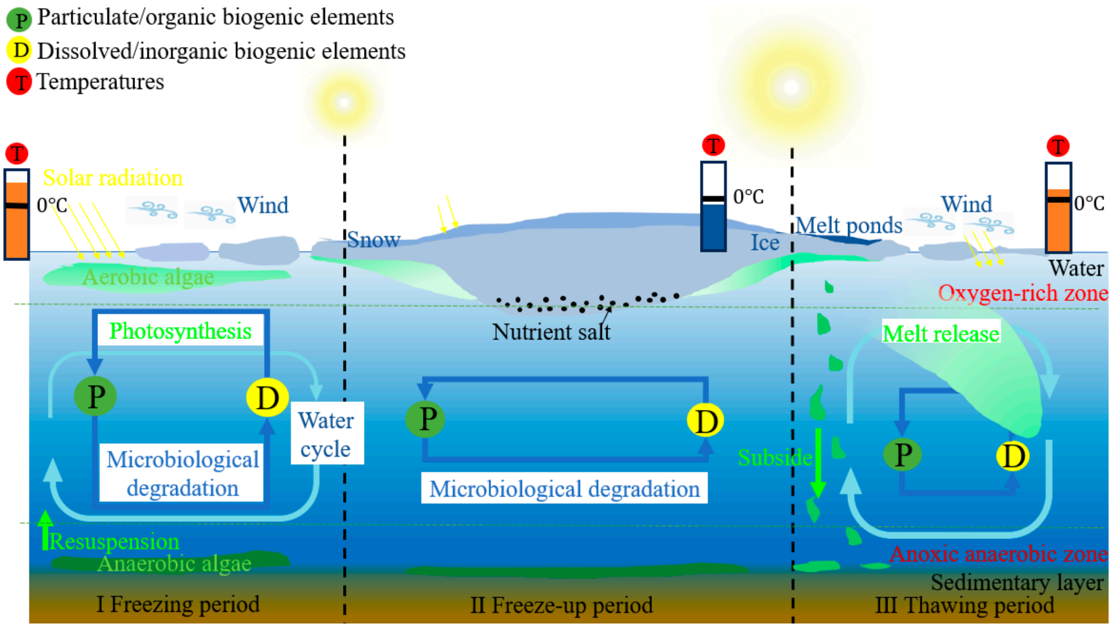

Figure 5. Mechanisms of lake-algal-bloom occurrence during freezing and thawing processes.

5. Response Mechanism of Lake Algal Bloom to Climate Warming and Prevention Strategies

5.1. Response Mechanisms of Lake Algal Blooms to Climate Warming

The response mechanism to climate change mainly manifested in the study of the effect of warming and increasing CO_2 concentration on algal blooms. Rising temperatures directly affected lake-water temperature, vertical mixing between suspended and insoluble particles, thermal stratification of water bodies, and biological-community structure [80,81]. Rising air temperature increased the concentration of nutrients and the absorption efficiency of algae by increasing water temperature and reducing the concentration of dissolved oxygen near sediments, thereby exacerbating the scale, frequency, and intensity of algal blooms [82]. The increase in the duration of thermal stratification in deep-water lakes exacerbated the phenomenon of hypoxia [83], and reducing the thickness of the mixed layer in water further promoted the expansion of cyanobacteria blooms [84]. The shortening of freezing period led to the advancement of spring-algal-bloom phenology [78]. All studies confirm that warmer temperatures lead to higher water temperatures, longer vertical stratification of the water column, thinner mixed layers, and earlier melting of the ice cap. Together, these phenomena led to earlier spring algal blooms and longer bloom durations. In addition, higher CO_2 concentrations also increased algal photosynthesis to increase phytoplankton biomass accumulation [85–87]. A portion of the carbon dioxide present in the lake was dissolved in the water, changing the pH of the water and having an effect on the nutrient-cycling process, with the water becoming less hard and the concentration of calcium ions decreasing [88]. The growth of some acid-loving cyanobacteria in this environment was promoted [89]. Furthermore, CO_2 can also improve the absorption and utilization efficiency of Microcystis for nutrients rather than other algae [90]. In summary, cyanobacteria had a more positive response to climate change.

5.2. Prevention and Control Strategies

Based on the driving factors, of occurrence principles and response mechanisms to climate change, we proposed the prevention and control strategies for lake spring cyanobacteria blooms in response to future climate change in terms of (i) improving the predictive ability of spring algal blooms in lakes, and (ii) strengthening spring-algal-bloom prevention and control in river basin lakes. Traditional ecological prediction models focus on calculating probability distributions between phytoplankton and nitrogen, and phosphorus and water-quality factors. However, this model lacks the mechanistic analysis of cyanobacterial blooms under the synergistic effect of multiple environmental factors. It also generates large errors in simulation prediction under long-term series and multi-temporal dynamic changes [84,91]. In the future, it will be necessary to establish a cyanobacterial-bloom-prediction and -warning model dominated by meteorological factors, the synergistic effects of multiple environmental factors, and the integrated effects of biochemical reaction processes. We hope to improve the ability of predicting the risk of spring algal blooms in lakes in this way [92]. The quantification of endogenous pollution in the watershed pollution load should be further strengthened, in order to develop more scientific thresholds and strategies for reducing pollutants in watershed [93,94].

5.3. A New Comprehensive Framework

Based on the comprehensive research on the effect of freeze-thaw processes on lake algal blooms, an overall framework was constructed with "principles analysis-model construction-simulation prediction-evaluation management" (Figure 6). At present, most of the existing studies used the control variable method to quantify the contribution of a single environmental factor, which made it difficult to effectively predict the evolution of algal blooms in complex scenarios in the future. There was a lack of climate-change-driven ecological and environmental risk assessment and socio-economic impact analysis of algal blooms in lakes, which restricted the prevention, control, and management of the hazards of algal blooms in lakes. Therefore, it is of great significance to construct an integrated lake-climate hydrodynamics–water-quality algal-bloom model to simulate and predict the development trend of algal bloom in lakes.

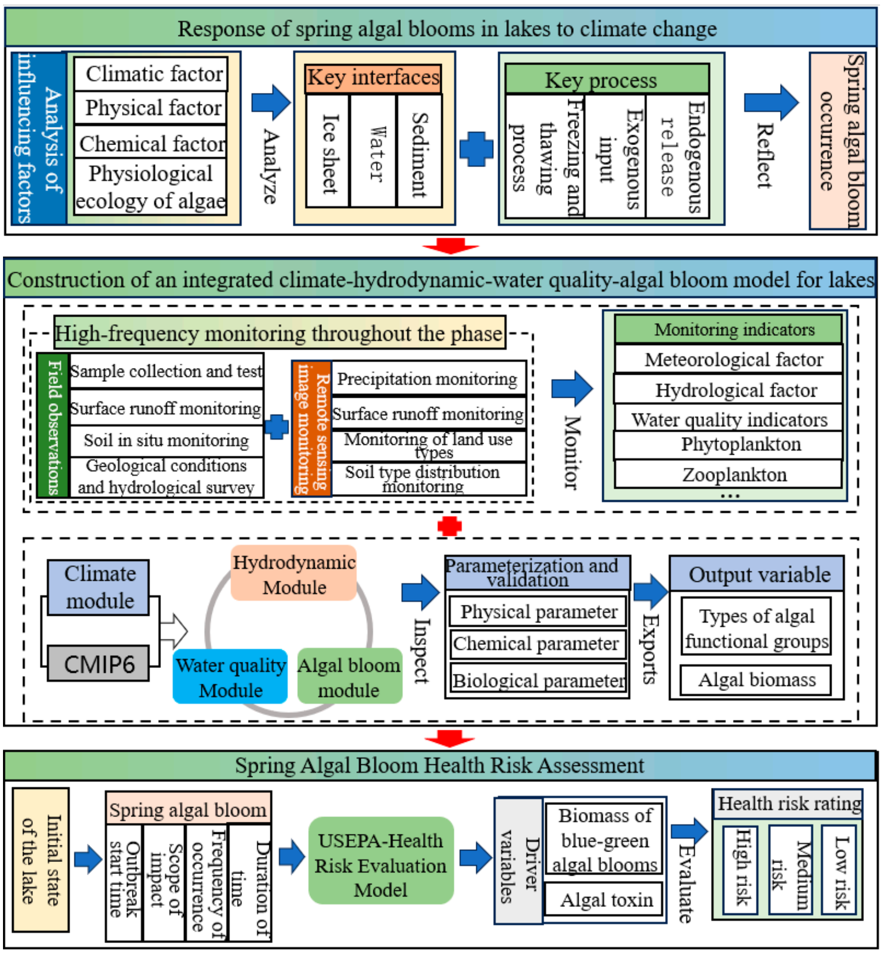

Figure 6. A framework for studying the effects of freezing and thawing on spring algal blooms in lakes under climate change.

In order to construct a comprehensive model of lake-climate hydrodynamics–water-quality algal blooms, it is necessary to first clarify the driving mechanism of freeze-thaw processes on spring algal blooms under historical conditions. Secondly, coupled with climate models, potential risks of spring algal blooms under future climate scenarios should be predicted. The key to this framework is to clarify the mechanisms of functional and representational levels of spring algal blooms in lakes, with the biomass and density of the main algal communities that trigger algal blooms as constraint indicators, effectively simulating the development and evolution process of the scale, frequency, and duration of algal blooms driven by climate conditions. The evaluation indicators for health-risk assessment are algal biomass and the accumulative-risk index. Algal toxin content takes tourism revenue, causes fishery-resource loss, requires algal-bloom-control cost, and impacts urban gross domestic product which are evaluation indicators for socio-economic development. We must minimize the disaster-risk levels caused by spring algal blooms in lakes, improve public awareness and understanding of the disaster problem, and effectively promote the synergistic effect of pollution reduction and carbon reduction.

6. Conclusions and Outlook

Based on 16 years of analysis of the literature, hot topics of research have shifted from the impact of freeze-thaw processes on lake nutrients, physicochemical properties, and hydrodynamic characteristics to the competitive driving mechanism of freeze-thaw processes on spring phytoplankton growth. The freeze-thaw process (freeze-thaw, freeze-up, thawing) directly or indirectly affects the occurrence of spring algal blooms by affecting biogeochemical process. Phosphorus conversion in lakes during freeze-thaw processes explains spring algal blooms better than nitrogen. Therefore, monitoring and controlling of phosphorus-containing substances needs to be strengthened throughout the freeze-thaw and thawing processes in lakes. It is pointed out that spring algal blooms in lakes will face problems such as expanding their scope, increasing their intensity, advancing their occurrence time, and prolonging their duration under climate change and human activities. We propose prevention and control strategies for spring algal blooms in lakes under future changing environments.

(1) Strengthening the monitoring of high-frequency lake-water-quality and -plankton data, which is necessary in order to accurately determine the limiting nutrient threshold for spring algal blooms.
(2) It is recommended to remove the snow on the surface of the ice sheet during the freeze-up period to reduce the input of external pollutants in spring.
(3) During the thawing period, attention should be paid to the release of nutrients, especially phosphorus, caused by sediment re-suspension.
(4) Installing circulating pumps in areas with high concentrations of lake pollutants during the thawing period to increase the hydrodynamic circulation in local areas.

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