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A Bibliometric Analysis of Lake Restoration with Submerged Macrophytes

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Abstract: Submerged macrophytes have attracted increasing attention in lake restoration due to the importance of their structuring communities and stabilizing functions in lake ecosystems. However, there is still a lack of systematic reviews on lake restoration with submerged macrophytes. Thus, we performed a systematic review based on a bibliometric analysis via analyzing and visualizing 934 published works from 1996 to 2023 from the Web of Science core collection. Publication characteristics were summarized, and keyword co-occurrence networks, reference co-citation analysis, and keyword burst tests were conducted. Our results suggest that the increasing attention in this field has partly resulted from the many water treatments and scientific schemes in Europe, China, and the USA and extensive international cooperation. The development of this field was divided into three stages based on keyword bursts (e.g., early, turning, and recent stages). Alternative stable states and biomanipulation laid the foundations of this field in the early stage. Progress in the field was discussed based on four aspects, the influence of environmental factors on submerged macrophytes, theory and mechanisms, targets, and evaluation and methods. Therefore, our results provide a new and comprehensive understanding of lake restoration with submerged macrophytes.

Keywords: keyword cluster; keyword co-occurrence; keyword burst; alternative stable states; biomanipulation

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1. Introduction

In recent decades, lake ecosystems worldwide have undergone intense artificial perturbations and climate change. On the one hand, lake eutrophication caused by expanding water demand and intensive industrial and rural activity has resulted in frequent algal blooms, which further lead to water quality deterioration, macrophyte vegetation and aquatic animal recession, impaired human health, and ecosystem function loss [1–4]. On the other hand, global warming can also induce water quality deterioration in lake ecosystems because of decreased dissolved oxygen and self-purification capacity [5,6]. Thus, governments, the public, and researchers have paid increasing attention to lake restoration.

Many methods, such as physical, chemical, and biological methods, have been exploited and applied in lake restoration. Physical methods (e.g., sediment dredging, artificial aeration, and water diversion dilution) are generally applied for severe water pollution because of their easy operation and long-term effectiveness. However, these physical methods are cost-intensive and may cause damage to water ecosystems [7]. Chemical methods (e.g., flocculation, sedimentation, and chemical removal) are applied for emergency disposal in water pollution incidents because of their quick and good effect, low cost, and easy operation. However, chemical methods easily cause secondary pollution and biotoxicity [7]. Compared with physical and chemical methods, biological methods (e.g., phytoremediation, animal and microbial repair) are considered more economical, effective, and environmentally friendly for lake restoration [7–10]. Lake restoration with submerged macrophytes has unique and comprehensive advantages among biological methods. For instance, submerged macrophytes, as major primary producers in lake ecosystems, can assimilate carbon and nutrients from water bodies [11]; provide refuge and food for microbes, fish, zooplankton, birds, and waterfowl [12–14]; inhibit phytoplankton [15]; control water velocity and sediment resuspension [16,17]; and provide recreational functions [18]. Thus, some large-scale water pollution control and treatment projects (e.g., the European Water Framework Directive) have set targets regarding submerged macrophytes and associated biodiversity [19].

There are existing research papers summarizing progress in the field related to submerged macrophytes. These reviews have focused on the relationships between submerged macrophytes and the water environment, macrophytes, phytoplankton, and restoration applications with submerged macrophytes [7,15,18,20–23]. For example, Wang et al. (2023) [7] reviewed the influence of water nutrients, light, depth, sediments, temperature, transparency, and flow on the growth of submerged macrophytes. Madsen et al. (2001) [23] reviewed the interaction between water movement, sediment dynamics and submerged macrophytes. Mohamed (2017) [15] summarized allelopathic interactions between macrophytes and toxic cyanobacteria, and Kibuye et al. (2021) summarized the knowledge on physical (artificial mixing, hypolimnetic aeration, dredging, sonication) and biological (biomanipulation, macrophytes, and straws) methods controlling cyanobacterial blooms. Hilt et al. (2006) [18] developed a step-by-step guideline to access the restoration of submerged vegetation in shallow eutrophic lakes, and Rodrigo (2021) [20] synthesized the knowledge in wetlands restoration with macrophytes. However, traditional review methods of analysis cannot extract and summarize all kinds of the information from large amounts of published literature, such as cooperative author relationships, development processes, and potential trends in specific research fields [24,25].

Bibliometric analysis, a scientific method using mathematical and statistical tests, was proposed by Pritchard (1969) [26]. It has been widely used to analyze quantitatively relevant knowledge carriers and explore the development and growth of a specific research field [27–29]. With the development of hardware and software, substantial reference and citation data can be efficiently handled via bibliometric analysis, and the results can be applied to different schemes to guide future data-processing practices [25,30,31]. Among these kinds of software, VOSviewer and CiteSpace are two popular tools for science mapping and have been used in many research fields, including ecological and environmental fields [25,29,32–34].

In this study, bibliometric and science mapping analyses were performed based on the Web of Science core collection database from 1996 to 2023 to provide a comprehensive understanding of the research development of lake restoration with submerged macrophytes,. Specifically, our objectives were to (1) investigate the characteristics of publications in this field, including annual productions, top authors, countries, institutions, and journals; (2) extract research hotspots and knowledge bases and explore their change trends over time; and (3) perform a systematic review of the development in the field based on this analysis.

2. Methods

2.1. Data Collection and Processing

Data were collected in the Science Citation Index Expanded (SCI-EXPANDED, in the Web of Science core collection database), in which the earliest literature was recorded in 1996. The search was conducted on 11 March 2023 using the following search terms: ((“submer* plant*” or “submer* macrophyte*” or “submer* aquatic plant*” or “submer* aquatic macrophyte*” or “submer* aquatic vegetation*” or “submer* vegetation*” or “submer* aquatic communit*” or “submer* communit*”) and (restor* or remediat* or recov* or reconstruct* or rebuild* or repair* or re-establish* or reestablish* or reviv*), and lake*). Consequently, 935 published works were obtained from 1996 to 2023, including 903 articles

(77 proceedings papers and 26 review articles), 5 editorial materials, and 1 correction. The correction was excluded in the following analysis because its content is less related to the keywords [25]. Finally, a database of 934 published articles was selected. The database files were exported as "plain text files" and "full record and cited references" was selected. The files were renamed as "download_xxx.txt" so they could be correctly recognized by the CiteSpace software. Two folders were constructed before data analysis processing. One folder was named "data" for depositing the database files, and the other was named "project" for storing the analysis process results.

2.2. Analysis Methods

To explore publication trends, we summarized the annual paper production and the top 10 publishing countries/regions, organizations, and authors. Then, collaborating network analyses of country/region, organization, and author were conducted in VOSviewer (V 1.6.19) [33]. The collaborating network of country/region was further processed in SCImago Graphica (V *Beta* 1.0.21).

To identify the core content of publications and popular topics in the field, keyword co-occurrence and cluster analyses were conducted to calculate the frequency of keywords and create a connection network in CiteSpace (V 6.2.2 Advanced) [25,27,29,35]. Some irrelevant keywords, such as "I." and "of the art" were excluded. Some synonyms were replaced by one keyword. Then, to distinguish the knowledge structure of the topic, reference co-citation and cluster analysis was performed [25]. Finally, burst detections were conducted to identify the burst keywords and references according to Kleinberg's method [36]. All the time slices were set from 1996 to 2023, with 1 year as a slice in the analysis. Node types were selected as keywords and references for visualization following the selection criteria g-index (k = 30). Clusters were pruned by the pathfinder and pruning sliced networks.

3. Results

3.1. Characteristics of Publications

In this study, 934 publication records were analyzed to determine the characteristics and trends in lake restoration with submerged macrophytes. The annual production of publications exhibited a linear increase from 1996 to 2022 (Figure 1, $R^2 = 0.82$, $p < 0.001$). As shown in Table 1, China played a critical role in the field, with 366 publications accounting for 39.2% of total publications, followed by the USA and Denmark. The top three contributing organizations were the Chinese Academy of Sciences, University of the Chinese Academy of Sciences, and Aarhus University. Erik Jeppesen, Zhenbin Wu, and Martin Söndergaard were the top three contributors to the publications. These publications were mainly published in *Hydrobiologia*, *Ecological Engineering*, *Freshwater Biology*, *Aquatic Botany*, and *Science of the Total Environment*.

3.2. Collaborating Networks

In the country/region collaborating network, the collaborating strength between China and Denmark and China and the USA was relatively the strongest (Figure 2). China had the highest publication production, while the USA and Denmark had the two most numerous publication citations. According to the collaborating networks of the organization and author, China benefited from the collaboration (Figures 3 and 4). For example, many organizations from China cooperated with Aarhus University (Aarhus, Denmark) and the University of Florida (Gainesville, FL, USA). In addition, many authors from China cooperated with Erik Jeppesen and Martin Söndergaard, who were both from Aarhus University, Denmark. However, Zhenbin Wu from China led a relatively independent author collaborating sub-network, indicating that China also played a pivotal role in lake restoration with submerged macrophytes.

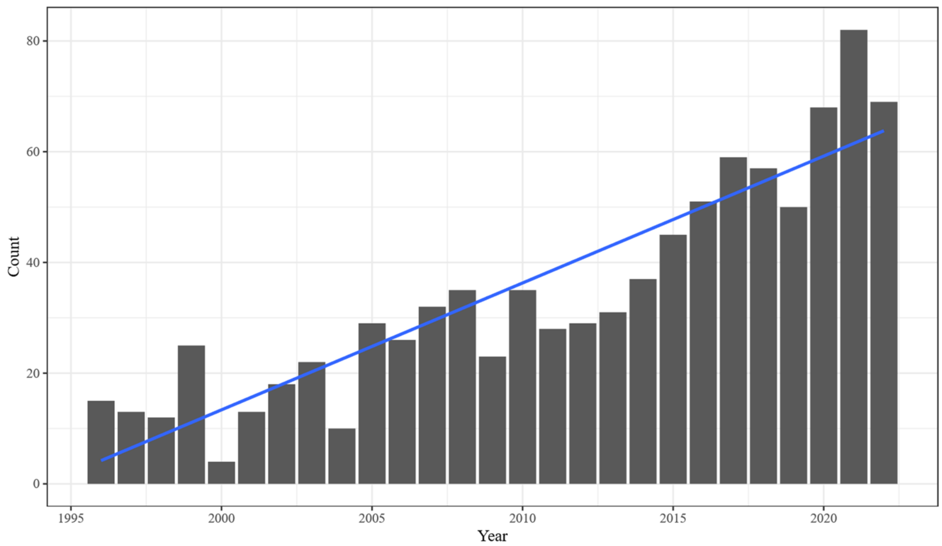

Figure 1. Annual literature production numbers during the period 1996–2022. The solid blue line is the fitting curve within the period 1996–2022.

Table 1. Top 10 countries/regions, institutions, authors, and journals with respect to publications related to lake restoration with submerged macrophytes from 1996 to 2023. The numbers in parentheses represent the number of publications.

Rank	Country/Region	Institution	Author	Article Source
1	China (366)	Chinese Academy of Sciences (224)	Erik Jeppesen (88)	*Hydrobiologia (135)*
2	USA (185)	University of the Chinese Academy of Sciences (128)	Zhenbin Wu (39)	*Ecological Engineering (49)*
3	Denmark (119)	Aarhus University (99)	Yi Zhang (35)	*Freshwater Biology (48)*
4	Netherlands (90)	State University System of Florida (42)	Martin Söndergaard (32)	*Aquatic Botany (46)*
5	England (68)	Netherlands Institute of Ecology (NIOO-KNAW) (36)	Zhengwen Liu (28)	*Science of the Total Environment (39)*
6	Germany (46)	Royal Netherlands Academy of Arts and Sciences (36)	Biyun Liu (24)	*Water (23)*
7	Canada (43)	Middle East Technical University (33)	Feng He (24)	*Journal of Paleolimnology (18)*
8	Spain (36)	University of Florida (32)	Torben L. Lauridsen (22)	*Ecological Indicators (18)*
9	Turkey (36)	Jinan University (31)	Qiaohong Zhou (20)	*Wetlands (17)*
10	Australia (35)	Wageningen University & Research (29)	Hu He (19)	*Environmental Science and Pollution Research (15)*

3.3. Keyword Co-Occurrence and Cluster

The keyword co-occurrence network was apparent (Modularity value = 0.464) and highly credible (Silhouette value = 0.740), including 596 keywords (author keywords and keywords plus) that were extracted from the 934 articles related to lake restoration with submerged macrophytes. In the network, 13 topics were generated by keyword clustering and labeled by keywords based on the log-likelihood ratio test, including great lakes, alternative stable states, photosynthesis, *Myriophyllum spicatum*, *Vallisneria natans*, n-alkanes, water clarity, seed bank, plants, remote sensing, ecological status, ecological restoration, and biomass (Figure 5 and Table S1). The topic alternative stable states appeared earlier and more frequently, indicating that this topic consisted of the basis of the research field. Recently, the topics biomass, *Vallisneria natans*, n-alkanes, and ecological status have also drawn ample attention. In summary, these 13 topics were related to submerged species and vegetation (photosynthesis, *Myriophyllum spicatum*, *Vallisneria natans*, n-alkanes, seed bank, plants, biomass, etc.), restoration mechanisms (alternative stable states) and methods (remote sensing, ecological restoration, etc.), and application scenarios (great lakes, etc.).

Figure 2. Collaborating network of countries/regions. The sizes of points and widths of lines scale with the literature production of each country/region and the cooperation strength between countries/regions, respectively.

The keyword burstiness denotes high occurrence frequency in a specific period. The higher the strength, the more exciting and attractive the keyword. As shown in Figure 6, keyword burstiness detection analysis indicated that the emergence of keywords could be divided into three stages. The period of "1996–2009" was the early stage when fish, biomanipulation, temperate lakes, alternative stable states, zooplankton, Danish lakes, top-down control, long-term, and chlorophyll a contents were the main research topics. The period of "2010–2017" was the developing stage. The keywords during the developing stage might be the turning point in this research field, including wetlands, species richness, model, ecological status, and organic matter. Water depth, nitrogen, *Vallisneria natans*, aquatic vegetation, and regime shifts were hot topics in the current period of 2018–2023.

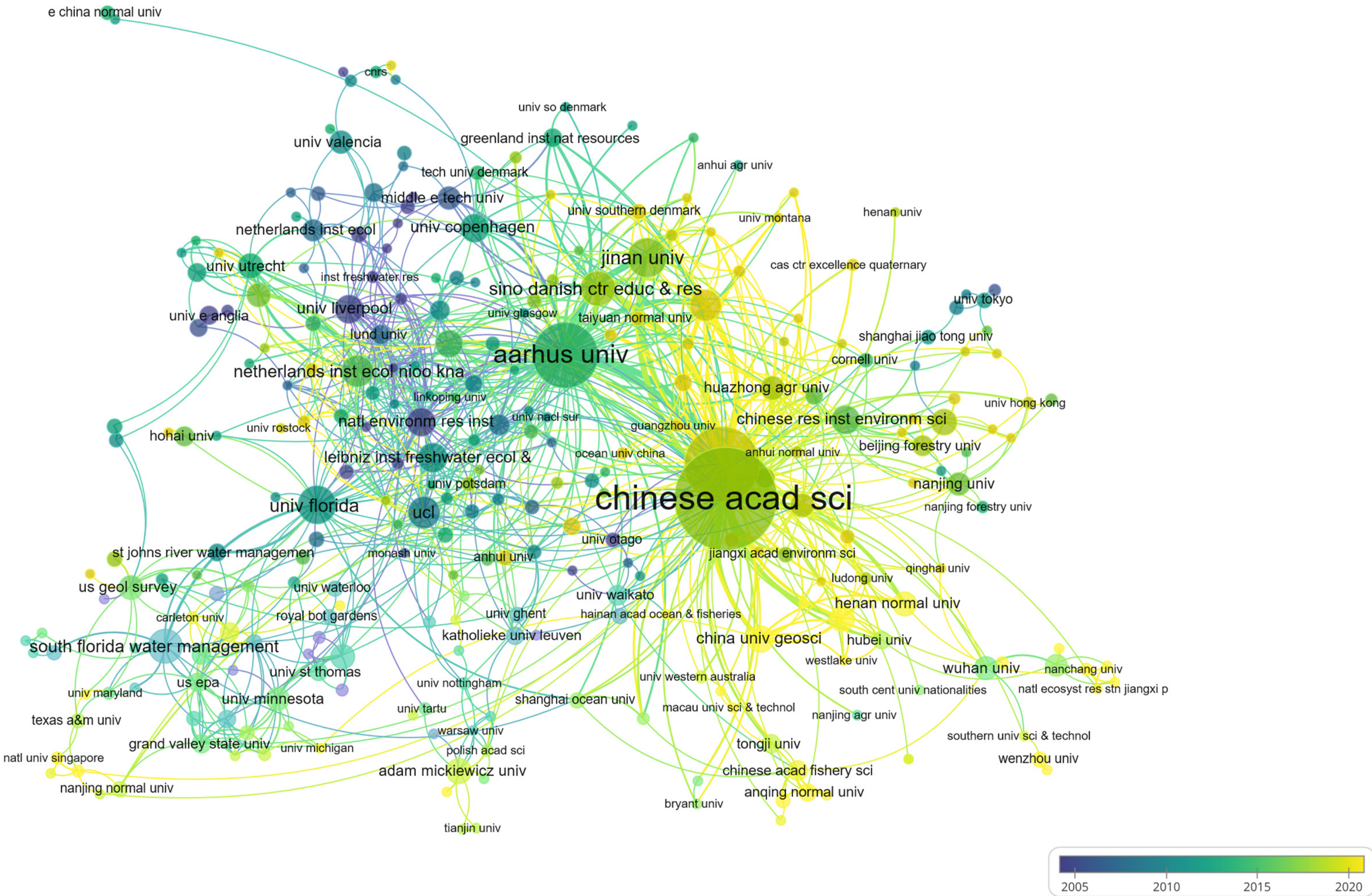

Figure 3. Collaborating network of organizations. The sizes of points scale with the literature production of each organization. The colors of points and lines scale with the mean published year of all literature for each organization.

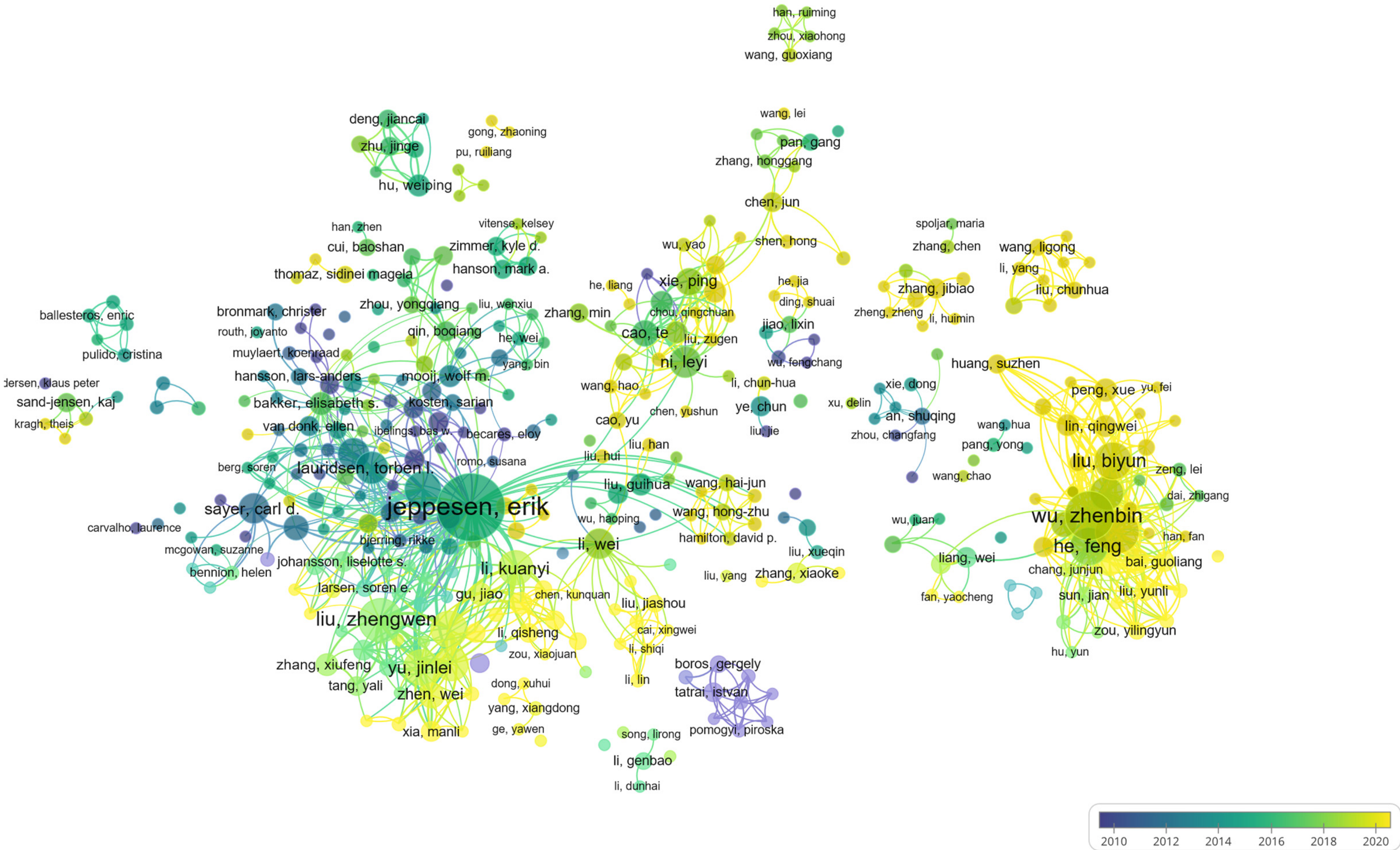

Figure 4. Collaborating network of authors. The sizes of points scale with the literature production of each author. The colors of points and lines scale with the mean published year of all literature for each author.

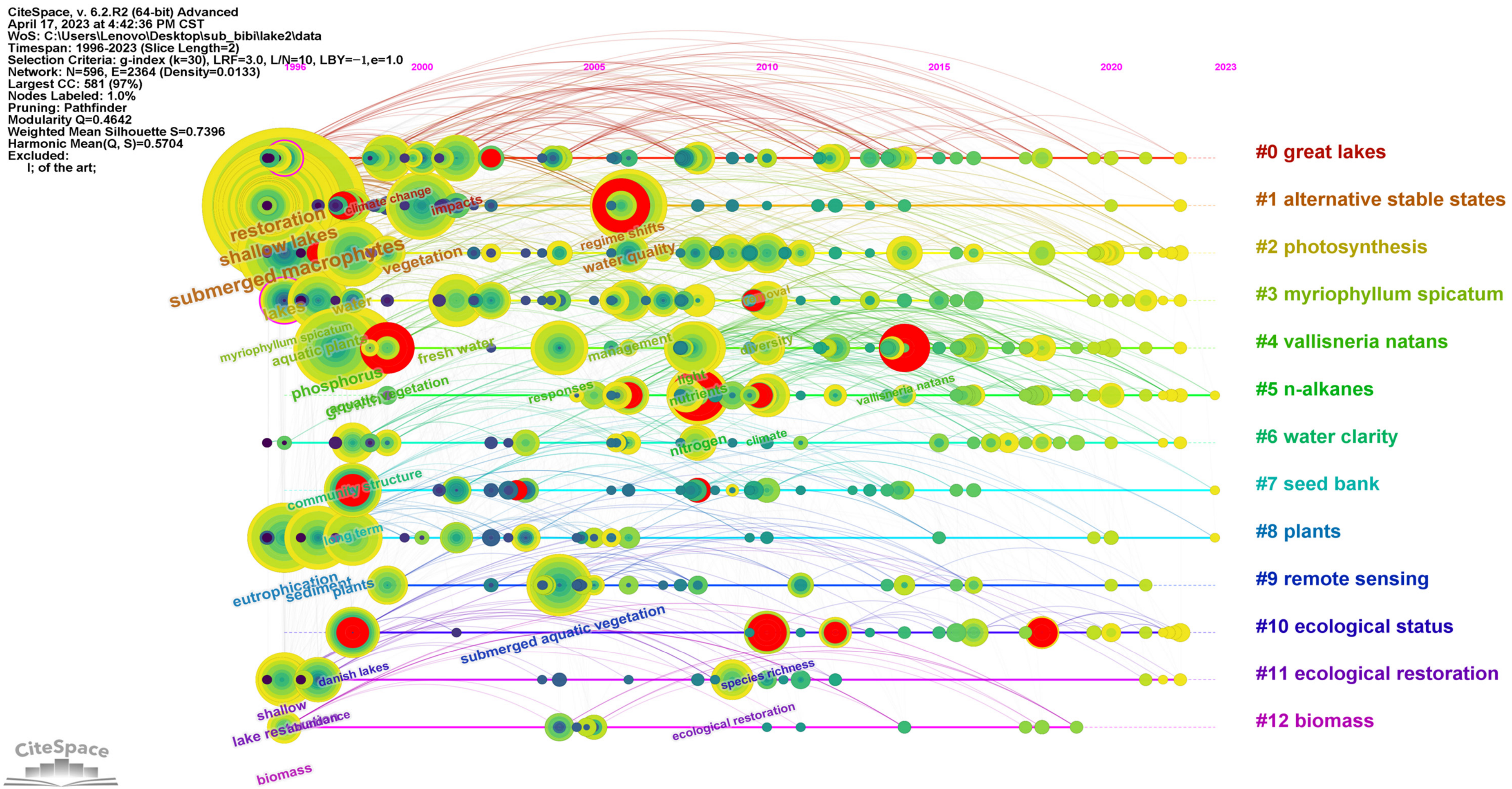

Figure 5. Keyword co-occurrence and cluster analysis related to lake restoration with submerged macrophytes. Clusters were labeled by the terms from keywords based on the log-likelihood ratio test. The sizes and colors of points scale with the frequency of keywords and mean published year for all the literature, respectively. The darker the color, the earlier the mean published year.

Figure 6. Top 22 keywords with the strongest citation bursts. The green and red lines denote existing and citation burst periods, respectively.

3.4. Reference Co-Citation and Cluster

The reference co-citation network was clustered into 16 groups (M = 0.653, S = 0.840, Figure 7, Table S2). The 16 clusters were labeled by keywords of references based on the log-likelihood ratio test, including biomanipulation, omnivore, zooplankton, nutrient removal, zooplankton community, *Myriophyllum spicatum*, fish, ecological status, diatoms, shallow lakes, aquatic weeds, *Cyprinus carpio*, clear water, turbid, root to shoot, and fatty acids. These clusters comprised the main knowledge domain in lake restoration with submerged macrophytes. Additionally, the knowledge structure had a marked shift from clear water, aquatic weeds, diatoms, fish, zooplankton community, root to shoot, nutrient removal, biomanipulation, and turbid to fatty acids, ecological status, *Myriophyllum spicatum*, zooplankton, *Cyprinus carpio*, and omnivore.

The network shows the top 10 most frequent co-citation references and strongest burst citation references from 1996 to 2023 in Tables 2 and 3, respectively. These top 10 and burst citation references were mainly concentrated on the following aspects: (1) responses of lakes to reduced nutrient loading and application in lake restoration [37–39]; (2) impact of submerged macrophytes on the abiotic environment, biota, and ecosystem processes [40,41]; (3) alternative stable states and application in lake restoration [42–45]; (4) biomanipulation and top-down control [46–51]; (5) submerged vegetation loss [45,52]; (6) restoration approaches and cases [48,53,54].

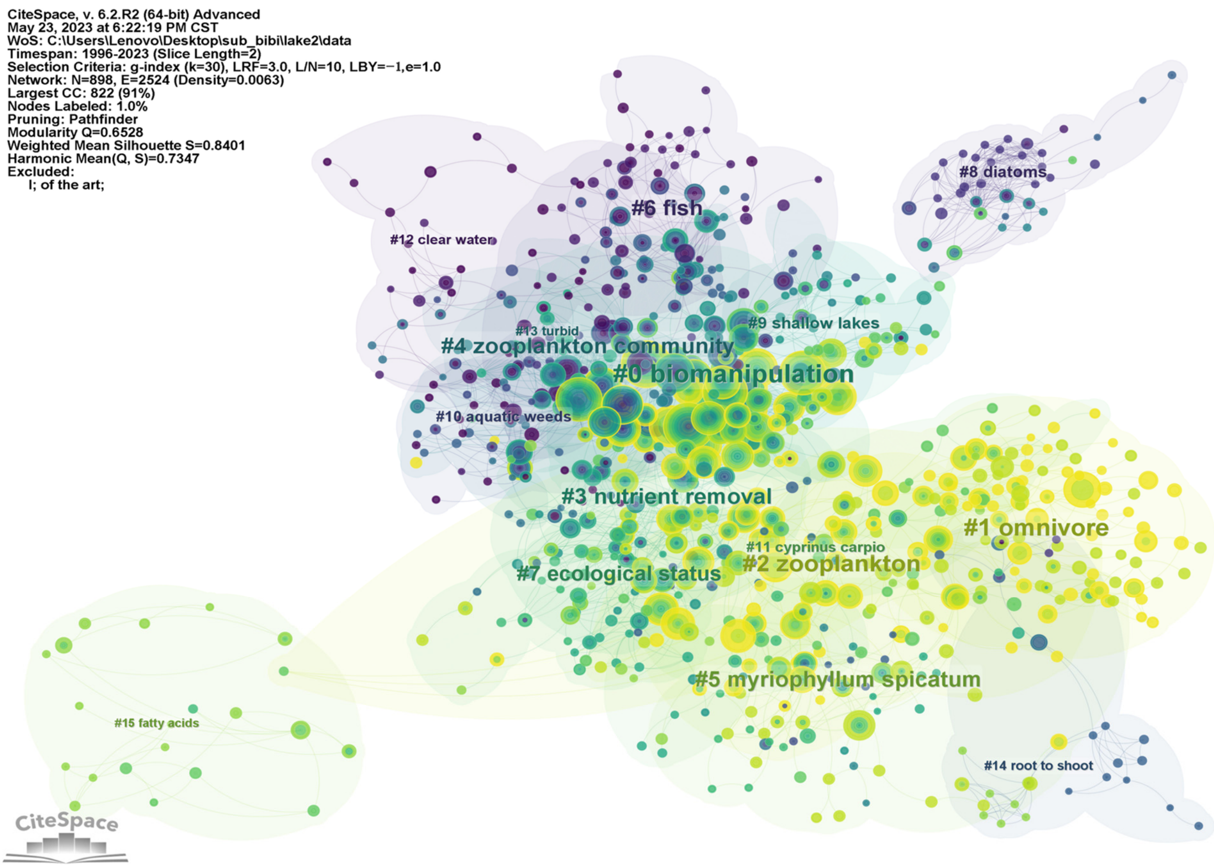

Figure 7. Reference co-citation and cluster analysis related to lake restoration with submerged macrophytes. Clusters were labeled by the terms from keywords. The size of cluster label scales with the proportion of references in each cluster. The sizes and colors of points scale with the citation frequency and year, respectively. The colors of clusters and their labels scale with mean citation year. The darker the color, the earlier the citation year.

Table 2. Top 10 citation references in the field from 1996 to 2023. CF represents the citation frequency. Cluster and reference ID denote the cluster of reference co-citation analysis and reference rank in the paper, respectively.

CF	Authors	Source	Cluster ID	Reference ID
266	Scheffer et al. (1993)	*Trends in Ecology & Evolution*	3	[42]
112	Scheffer (1998)	Book	12	[43]
102	Moss (1990)	*Hydrobiologia*	0	[53]
90	Carpenter and Lodge (1986)	*Aquatic Botany*	5	[40]
86	Scheffer et al. (2001)	*Nature*	3	[44]
85	Jeppesen et al. (1997)	*Hydrobiologia*	3	[49]
81	Jeppesen et al. (2005)	*Freshwater Biology*	0	[39]
80	Jeppesen (1990)	*Hydrobiologia*	3	[47]
77	Timms and Moss (1984)	*Limnology and Oceanography*	5	[46]
74	van Donke and van de Bund (2002)	*Aquatic Botany*	5	[50]

Table 3. Top 10 references with burst citations in the field from 1996 to 2023. CF represents the citation frequency. Cluster and reference ID denote the cluster of the reference co-citation analysis and the reference rank in this paper, respectively.

Rank	Bursts	Authors	Source	Cluster ID	Reference ID
1	19.07	Liu et al. (2018)	*Water Research*	8	[54]
2	16.02	Zhang et al. (2017)	*Earth-Science Reviews*	4	[52]
3	15.88	Scheffer (1998)	Book	12	[43]
4	14.8	Timms and Moss (1984)	*Limnology and Oceanography*	5	[46]
5	14.77	Phillips et al. (2016)	*Aquatic Botany*	3	[45]
6	12.94	Jeppesen (1990)	*Hydrobiologia*	3	[47]
7	12.36	Sas and Ahlgren (1989)	Book	0	[37]
8	11.4	Jeppesen et al. (2012)	Book	0	[51]
9	11.09	Moss et al. (1996)	Book	5	[48]
10	10.81	Jeppesen (1991)	*Memorie dell'Istituto Italiano di Idrobiologia*	6	[38]

4. Discussion

4.1. Publication Characteristics

The production of annual publications related to lake restoration with submerged macrophytes exhibited a linear increase from 1996 to 2022 (Figure 1), directly reflecting the field's concern level. Although the percentage of lakes and rivers in the water area of the biosphere is less than 1%, aquatic ecosystems have fundamental importance in the maintenance and survival of terrestrial life [55]. However, ecosystem deterioration caused by water pollution was paid more attention during industrialization, which might have resulted in more studies on lake restoration from Europe, the USA, and East Asia. For instance, publications from China, the USA, and Denmark account for nearly 71.7% of the field (Table 1). In these countries/regions, comprehensive treatment measures or scientific schemes have been implemented, such as the Clean Water Act of the USA (amended in 1972), the Water Framework Directive in European countries (implemented in 2000), and the National Water Pollution Control and Treatment Science and Technology Major Project in China, all of which have promoted the development of this field.

Moreover, extensive international cooperation may improve the research field's development. For example, the University of Chinese Academy of Sciences and some Danish universities (e.g., Aarhus University) have jointly set up the Sino-Danish Centre for Education and Research, which markedly promotes exchanges and cooperation regarding water and the environment between China and Denmark. As shown in Figures 2 and 3, the intensities between China and Denmark and between the Chinese Academy of Sciences and Aarhus University were the largest in the countries/regions and institutions' collaborating networks, respectively. Accordingly, Erik Jeppesen from Aarhus University collaborated most frequently with Chinese scientists (Figure 4).

4.2. Research Progress in the Field Related to Lake Restoration with Submerged Macrophytes

According to the cluster results, most of the literature is related to the influence of environmental factors on submerged macrophytes (light, photosynthesis, water clarity, water depth, biomass, root to shoot, etc.), restoration theory and mechanisms (alternative stable states, top-down control, bacterial community, biodegradation, etc.), restoration targets (nutrient removal, submerged aquatic vegetation, species richness, ecosystem restoration, etc.), and restoration and evaluation methods (biomanipulation, seed bank, remote sensing, n-alkanes, etc.). Thus, it is essential to understand all four aspects comprehensively.

4.2.1. Influencing Factors of the Growth and Distribution of Submerged Macrophytes

Submerged macrophytes are vital in maintaining the structures and functions of lake ecosystems. Numerous studies based on field and control experiments have discerned some essential environmental factors influencing the growth and distribution of submerged macrophytes, including light, nutrients, temperature, sediments, and water depth or level, further affecting the restoration function of submerged macrophytes. Thus, a comprehensive understanding of the effect of these factors on submerged macrophytes is crucial for better implementing lake ecological restoration.

Light

Light is a critical factor in determining the growth and distribution of submerged macrophytes. A previous study suggested that light conditions could explain as much as 77% of the variation in macrophyte presence frequency [56]. Based on a meta-analysis, Gao et al. (2023) [57] showed that the effect of light reduction on the growth rate of submerged macrophytes existed at a threshold value (*c.* 20%). Namely, slight light reduction promoted, but more than 20% light reduction inhibited the growth of submerged macrophytes.

Light affects the growth and distribution of submerged macrophytes mainly via photosynthesis, metabolism, and the rhizosphere microbial community [57]. First, low light decreases the photosynthesis rate, and then carbon assimilation decreases. In addition, low light stress is likely to trigger the detoxification process, and submerged macrophytes need higher antioxidant enzyme activities, implying that more carbon resources might be invested into metabolism to adapt to the stress [58–60]. Finally, low light might decrease the oxygen transportation from tissue to rhizosphere and the root exudations of submerged macrophytes [61,62], which will further induce the decrease in the abundance of some functional microbial groups (e.g., plant-growth-promoting bacteria, sulfide oxidizers, and nitrogen-fixing bacteria) [63,64]. These microbial groups benefit submerged macrophytes' growth, nutrient acquisition, and antioxidants.

Submerged macrophytes can adapt to low-light stress via tolerance and avoidance strategies [65]. The tolerance strategy is characterized by high investment in leaf area and photosynthetic efficiency to increase light utilization, and greater investment in vertical growth, characterized as the avoidance strategy to acquire more light in shallow water bodies [57,65]. However, a meta-analysis revealed that the response of the relative growth rate to light reduction is mainly driven by the tiller ability rather than the photosynthesis capability of submerged macrophytes [57].

Nutrients

Nitrogen (N) and phosphorus (P) are also essential factors for the growth of submerged macrophytes. Appropriate nutrient supplies can promote, but excessive nutrients can inhibit, the growth of submerged macrophytes. For example, a low concentration of ammonium-N (0–4 mg/L) can promote, but higher than 8 mg/L ammonium-N can inhibit, the growth of *Vallisneria natans* [66]. The effects of P on submerged macrophytes depend on the N concentration. In one study, when total N was 1.0–2.0 mg/L, low total P (<0.1 mg/L) inhibited, but 0.1–0.4 mg/L P increased, the macrophyte cover [67]. However, when total N was less than 1 mg/L or more than 2 mg/L, the increase in P was accompanied by decreased macrophyte cover [67]. Moreover, the effects of nutrients were species-specific. The addition of 10 mg/L ammonium-N inhibited the growth of *Ceratophyllum demersum* and *Myriophyllum spicatum*, but the addition of 20 mg/L ammonia-N still promoted the growth of *Myriophyllum aquaticum* [68].

The inhibiting effect of high nutrient levels on the growth of submerged macrophytes might be attributed to the following mechanisms. First, excessive ammonia might be toxic to plants. Excess-free ammonia can suppress the uptake and transportation of Mg^{2+}, the synthesis of photosynthetic pigments, and the photosynthesis process [69–71], and impede plant respiration and photophosphorylation [72]. Second, plankton and epiphytes benefiting from high nutrient levels have the advantage of competing for light with submerged macrophytes, which thus reduces macrophyte growth [45]. Third, high nutrient levels stimulate the growth of epiphytes, which generally shape the microenvironment with high pH and low CO_2 concentrations on the host leaf surface to inhibit the photosynthesis process of submerged macrophytes [73]. Finally, allelopathic substances (e.g., microcystin) secreted from plankton suppress the growth of submerged macrophytes by preventing synthesis or speeding the decomposition of chlorophyll a [74].

Temperature

Temperature is crucial in governing submerged macrophytes' germination, growth, and distribution. Although the temperature fluctuation in a water body is relatively small, its seasonal variation can markedly influence submerged macrophytes, especially under global climate warming scenarios. Previous studies have indicated that the lethal water temperatures of submerged macrophytes are generally less than 3 °C or higher than 45 °C [75,76]. In the temperature range of 10–20 °C, the seed germination rates of *V. natans* increase with temperature, but higher temperatures (e.g., 28 °C) may decrease the rates and speed up the germination [77]. This result might be attributed to the higher temperature increasing the metabolism rate to accelerate the germination and decreasing the energy stored in seeds to decrease the germination rate [77].

The responses of the growth of submerged macrophytes to temperature are also species-specific. In previous studies, the light compensatory points of five submerged macrophytes increased with temperature in the range of 4–30 °C, while *C. demersum* and *V. natans* had the highest and lowest compensatory points, respectively [77,78]. Moreover, biotypes can also influence the temperature effects on submerged macrophytes. The growth of overwintering tubers of monoecious *Hydrilla verticillata* depends on a lower threshold temperature of 8 °C and an upper threshold temperature of 16 °C [76]. However, dioecious *H. verticillata* showed lower and upper threshold temperatures of 12 °C and 21 °C, respectively [76].

Global climate warming might have diverse effects on the growth and distribution of submerged macrophytes. On the one hand, climate warming is conducive to the germination and growth of submerged macrophytes. For example, early-season warm temperatures increased the biomass and cover of submerged macrophytes in Canada [79]. On the other hand, climate warming inhibited the growth of submerged macrophytes by increasing the frequency and intensity of algal blooms in eutrophic lakes [7]. Nevertheless, some studies have shown that warming had no significant effect on the biomass and abundance of submerged macrophytes but changed the community composition [80,81].

Sediments

Sediments are the primary sources of nutrients (e.g., N, P, and other micronutrients) and the basis of root fixation of submerged macrophytes. Thus, sediments are also likely to influence submerged macrophytes' growth, reproduction, and distribution, which might depend on the nutrient content. Specifically, when nutrient contents are relatively low, sediments can promote the growth of submerged macrophytes. For instance, sediment structure and organic matter composition affected the growth of *H. verticillata* by influencing the supply of potassium [82]. Changes in the biomass and spatial distribution of *Elodea nuttallii* were linked positively with the extracted P content of sediments in an oligomesotrophic lake [83].

However, sediment with high nutrient contents might suppress the growth of submerged macrophytes. Barko and Smart (1986) [82] found that an increased organic matter content could promote the growth of *M. spicatum* and *H. verticillate*. However, there were 10- and 20-fold declines in growth with increasing the sediment organic matter up to 20% dry sediment mass. The result might be attributed to the following mechanisms. First, relatively high organic matter generally leads to anaerobic microcosms that decrease pH and redox potential, and the generation of toxins (e.g., sulfide and acetic acid), which prevents the growth of roots for submerged macrophytes [84]. Second, high organic matter content generally reduces the root anchorage strength in sediments, which is not conducive to the fixation of submerged macrophytes [85].

Moreover, sediment density can also affect the growth of submerged macrophytes. Increased sediment density with no change in organic matter still stimulates the growth of submerged macrophytes [82], which might be attributed to the low nutrient diffusion and exchange rate and low nutrient status in low-density sediments [82].

Water Depth

Water depth plays a crucial role in submerged macrophytes' growth, distribution, and community structure, mainly by affecting the underwater light climate [86,87]. Thus, water depth is a crucial limited parameter of lake restoration with submerged macrophytes. For example, the depth (i.e., 1.5 times the water clarity) is recommended as the reference line, above which submerged macrophytes can be restored successfully in shallow lakes [88]. Liu et al. (2016) [56] further found that the ratio of euphotic depth to water depth determined the growth of submerged macrophytes in Lake Taihu. Specifically, the ratio value of 0.8 can be regarded as the critical threshold for growth. When the ratio value ranges from 0.57 to 0.8, the lake should be considered for recovery and environmental management [56].

Water depth mainly influences underwater light via the exponential attenuation of irradiance with depth, resulting from water color and suspended matter. Among these factors, the suspended matter is relatively important. The relative contributions of non-phytoplankton particulate matter and water-color-related substances (i.e., chlorophyll a and chromophoric dissolved organic matter) to light attenuation were 82.6% and 16.5%, respectively [89]. Havens (2003) [90] also found that nonvolatile suspended solids were relatively more important in attenuating light than chlorophyll a or water color in Lake Okeechobee.

Additionally, water depth can also affect water nutrient dynamics. Based on a global database, Qin et al. (2020) [91] found that N and P limitations differed in shallow and deep lakes. Specifically, in shallow lakes, enhanced denitrification and inhibited sedimentation and P supply in sediments led to a decrease in N/P with frequent N limitation, while only water-surface denitrification that reduced nitrogen loss and P removal via sedimentation were enhanced in deep lakes, which resulted in an increase in N/P with frequent P limitation [7,91].

4.2.2. Progress of Theory and Mechanisms of Lake Restoration with Submerged Macrophytes

4.2.2.1. Alternative Stable State Theory

Alternative stable states are contrast states of an ecosystem's characteristics, including its functions, processes, components, and interrelationships [42,44,92]. These contrast states are maintained through different types of stabilizing feedback, with sudden drastic switches between these states [44,92]. A theory was first proposed in the 1960s as to whether two or more stable communities could be found in a given habitat [93]. Then, increasing empirical evidence supported the theory [94–97]. Until Scheffer (1989) [98] developed a simple mathematical model, the theory attracted increasing attention regarding shallow lakes.

According to the bifurcation model of alternative stable states proposed by Scheffer et al. (1993) [42], shallow lakes exist in two alternative stable states: a clear-water state dominated by submerged macrophytes and a turbid-water state dominated by algae [44,99]. Transitions between clear- and turbid-water states are sometimes called regime shifts, induced by the interaction between internal processes and external fluctuations [44,99,100]. To simplify the analysis, the critical assumption for alternative stable states in lakes is that internal processes are stronger than external fluctuation [101]. Thus, internal control mechanisms of alternative stable states in lakes have been studied more frequently.

The clear-water state is mainly stabilized by ecological feedback mechanisms referring to submerged macrophytes, such as reduced sediment resuspension, increased sedimentation, providing refuge against planktivorous fish for phytoplankton-grazing zooplankton, and inhibiting the growth of phytoplankton via competing for nutrients and excreting allelochemicals [46,102–104]. However, the stabilized mechanisms of a turbid-water state include algal blooms caused by eutrophic water, easily resuspended matter during eutrophication owing to the absence of macrophytes and the disturbance of benthivorous fish, and zooplankton predation by planktivorous fish [99,100,105].

Verifying alternative states is vital because it involves markedly different lake restoration and management options [99]. The methods of verification include experimental observation (i.e., long time series and large-scale spatial observation), statistical analysis (i.e., bootstrap, vector autoregressive models, recurrence quantification analysis, and Bayesian latent variable regression), and model stimulation (i.e., static model, minimal dynamic model, complex dynamic model, structural dynamic model, individual-based model) [106–109]. These alternative states have been checked via field studies of shallow lakes worldwide, e.g., Denmark [110], USA [111], China [112,113], Netherlands [114], England [48], and Germany [115]. Based on field investigations, three hints of alternative stable states have been summarized as follows: (1) abrupt fluctuations of variables in time series; (2) multimodality of the frequency distribution of states; (3) dual relationships between variables and control factors [99,116]. However, some large shallow lakes might have no alternative stable states. For example, alternative stable states do not exist in Taihu Lake (surface area > 500 km^2), resulting from unfavorable conditions caused by wind (e.g., plant uprooting, high resuspension, low underwater light availability), high water-level fluctuations, and excessive grazing pressure from herbivorous fish [116].

4.2.2.2. Mechanisms of Lake Restoration with Submerged Macrophytes

Submerged macrophytes could be used for lake restoration by improving water quality and stabilizing the ecosystem structure and functions. First, submerged macrophytes could absorb N and P from the water body and sediment to relieve eutrophication stress. For example, the efficiency of N and P removal by *Potamogeton malaianus* could be as much as 80% [117]. Further, submerged macrophytes could mitigate surface sediment resuspension and reduce P release by oxidizing the rhizosphere sediment and improving the ability to bind Fe- and Ca-bound P [118–120].

Submerged macrophytes could also inhibit the growth of phytoplankton via several mechanisms. First, as major primary producers, submerged macrophytes compete for nutrients, light, and other resources with phytoplankton in lake ecosystems [121]. Second, denitrification might be increased in the submerged macrophyte beds owing to microbe gathering in the rhizosphere [122], intensifying the nitrogen limitation for phytoplankton growth [50,123]. Third, submerged macrophytes could provide refuge against predation pressure for zooplankton (e.g., Cladocera), which could graze small and rapidly growing phytoplankton [41,46]. Finally, submerged macrophytes could secrete allelochemicals, such as polyphenols, fatty acids, and alkaloids, inhibiting phytoplankton [50,124,125].

4.2.3. Targets of Lake Restoration with Submerged Macrophytes

Improving Water Quality

Lake restoration of submerged macrophytes could significantly improve water quality. For instance, enough submerged macrophyte coverage of a lake's surface area could lead to low algal biomass, reduction in chlorophyll a, and higher water transparencies [126–128]. Artificial planting of submerged macrophytes resulted in the removal of half of the P content in sediment and water in Lake Datong (>80 km^2) [119]. The N uptake by submerged macrophytes was 5.13 tons per year in the Daihai Lake, with a large area of 9.91 km^2 [129].

However, the restoration of submerged macrophytes also has some drawbacks. The removal efficiency of N and P for submerged macrophytes declines along with the biomass and coverage [130]. Moreover, the senescence and decomposition of submerged macrophytes might release nutrients (i.e., N and P) and dissolved organic matter and cause algal blooms in late spring [131]. Thus, some low-temperature-tolerant species (e.g., *Potamogeton crispus* and *Ceratophyllum demersum*) and adaptive management options (e.g., mowing and harvesting) should be applied for lake restoration with submerged macrophytes [18].

Increasing Species Diversity

High species diversity could stabilize the community and increase ecosystem resilience [132,133], improving water quality and clarity [134]. Enhanced purifying ability with high species richness might be attributed to the following mechanisms. On the one hand, the facilitation process among submerged macrophytes might increase stress tolerance or improve their ambient environment [134,135]. The facilitation processes mainly reflect the facilitative response and effect. Specifically, the submerged macrophytes benefit from the tolerance to shade from both their macrophyte neighbors and phytoplankton and indirectly improve the underwater climate owing to competition for nutrients with phytoplankton [135].

On the other hand, species with different growth forms promote the water purification ability of the macrophyte community [134]. For example, charophytes can reduce sediment resuspension [118], while the canopy forms (e.g., *Myriophyllum spicatum* and *Potamogeton maackianus*) are more beneficial for nutrient removal [113]. Of course, the species diversity of submerged macrophytes should also be appropriate, and an excess of species richness might not increase the purifying effect of macrophyte communities resulting from functional overlap and interspecific competition [136,137]. Zhang et al. (2019) [138] and Liu et al. (2020) [134] found that three species might be a threshold value of species richness for increasing the water transparency of lakes.

Stabilizing Ecosystem Structure and Function

Submerged macrophytes, as major primary producers, can influence lake ecosystem components, including microbes, phytoplankton, zooplankton, macroinvertebrates, and fish via trophic cascades. For example, submerged macrophytes can recruit unique microbial communities in sediments and the phyllosphere, resulting in changes in biogeochemical cycles and further influencing water quality and clarity [64,139]. Submerged macrophytes can also inhibit phytoplankton through several mechanisms, as mentioned in Section 4.2.2.2. Submerged macrophytes can increase the habitat complexity and decrease the foraging ability of predators such as piscivorous fish, zooplanktivorous fish, or macroinvertebrates [22,140–142], leading to the increased abundance and size of the respective prey. Then, the effects of submerged macrophytes on other ecosystem components are beneficial in improving water quality and clarity, controlling algal blooms, and maintaining a clear-water state. Thus, stabilizing the ecosystem structure and function is the main target for lake restoration with submerged macrophytes.

4.2.4. Progress of Evaluation and Methods of Lake Restoration with Submerged Macrophytes

Biomanipulation

Biomanipulation, proposed by Shapiro et al. (1975) [143], refers to the manipulation of the fish community to reduce the predation pressure on herbivorous zooplankton, therefore increasing the grazing pressure on phytoplankton through the food web [144–146]. Trophic cascade interactions and top-down/bottom-up effects in lakes were proposed by Carpenter et al. (1985) [147] and McQueen et al. (1986) [148], respectively, which supplemented the potential mechanisms of biomanipulation. Carpenter et al. (1985) [147] suggested that trophic cascade interactions could alter the primary production of lakes via altering consumer populations based on food web theory. McQueen et al. (1986) [148] considered that the maximum biomass at each trophic level was controlled from below (bottom-up) by nutrient availability and the low trophic level could be limited by the high trophic level above (top-down control).

Some common methods of biomanipulation include controlling phytoplankton via removing zooplanktivorous and benthivorous fish, stocking predatory and pelagic herbivorous fish, macrophyte transplantation and protection, and introducing mussels [51]. Although these methods have been used worldwide, biomanipulation is only partially valid. Only 44.4% of 18 biomanipulated lakes exhibited significant improvements in water clarity and promoted submerged macrophytes' development in the Netherlands [127]. Mehner et al. (2002) [149] also found that only 60% of lake restorations with biomanipulation were successful.

Nonetheless, submerged macrophyte establishment and protection are crucial for the long-term effects of biomanipulation owing to their fundamental roles in lake ecosystem structure and function [51]. Some restoration experiments with submerged macrophytes have been conducted, such as the introduction of shoots and seed banks, transplantation, protection from grazing birds and fish, removal of herbivores and herbivorous fish, and establishment of artificial submerged macrophyte beds [150–153]. However, these restoration methods seem to be more effective in temperate lakes than subtropical or tropical ones [154], which could result from the increased grazing pressure posed by fish with higher species richness, more diverse communities, increased numbers of large fish, and more young individuals in the subtropics or tropics [155,156]. Thus, protecting submerged macrophytes against herbivory is vital for successful manipulation.

Moreover, biomanipulation with submerged macrophytes might have some drawbacks, such as increasing N and P release in water, leading to less effective pollutant removal during the nongrowth season and conflicting with recreational users [18,51,157]. Thus, in the future, how to formulate management options for submerged macrophytes to improve the effects and efficiencies of restoration with submerged macrophytes should be considered.

Remote Sensing

Mapping the distribution and monitoring the dynamics of submerged macrophyte vegetation (SAV) is labor-intensive and time-consuming [158]. Remote sensing could be used to map and monitor effectively the distribution and abundance of SAV, detecting the relationships between environmental factors and SAV, and is thus crucial for the management of lake restoration [158–160]. Specifically, remote sensing could be used to interpret SAV on large spatial scales and for long time series using satellite spectral data (e.g., Sentinel-2, HJ-CCD).

For example, Ghirardi et al. (2022) [161] and Xia et al. (2022) [162] explored the decade scale of SAV dynamics using remote sensing images, providing a reference area for restoration. The classification accuracy of SAV changed from 60% to nearly 95% in existing studies [158,163–165], which were mainly limited by the resolution of images, water depth, water color, and spectral traits of specific submerged macrophytes [158,166]. With the increase in the resolution of satellite images, the dynamics of specific aquatic macrophyte species can also be interpreted. Luo et al. (2017) [167] classified the seven submerged macrophyte species in Taihu Lake, and the overall classification accuracy was 68.4% (62–75%). Thus, more detailed field data about SAV and higher-resolution satellite images might be conducive to an increase in the overall classification accuracy.

Biomarkers

Biomarkers in sediments are broadly used to reconstruct the paleoclimate, paleoenvironment, paleoecosystem, and paleoproduction [168–170]. Biomarkers related to aquatic macrophytes are mainly aliphatic hydrocarbons that are reliable markers for recording the origin of sediments due to their resistance to diagenesis and the specific source [171,172]. It is widely accepted that middle-chain n-alkanes (i.e., C20–C25) in sediments are derived from submerged and floating macrophytes [171,173]. However, emerged macrophytes had similar n-alkane distributions to terrestrial plants, dominated by long-chain homologs (>C29) [173]. A proxy ratio (Paq) was proposed to reflect the composition of terrestrial and aquatic plants [173]. In addition, the combined applications of lipid biomarkers, stable isotopes, and spectroscopic indices are highly recommended and could more accurately trace the sediment origin and dynamics in aquatic ecosystems [169,173,174].

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w15132411/s1. Table S1: Cluster information of keyword co-occurrence analysis; Table S2: Cluster information of reference co-citation analysis.

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