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Knowledge domain of greenhouse gas emissions from hydropower reservoirs: Hotspots, frontiers and future perspectives

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Research on greenhouse gas (GHG; CO_2, CH_4, N_2O) emissions from hydropower reservoirs has attracted widespread attention due to the potential effect on global climate change. However, few attempts have been made to conduct the research progress in this field from a global perspective. In this study, knowledge mapping research was conducted by applying scientometric analysis to explore research hotspots, frontiers and emerging trends of this field from 1993 to 2021, and five research priorities were recommended for the further study. The results showed that the research on GHG emissions from hydropower reservoirs was interdisciplinary, and there was an exponential increase in yearly publication outputs. Additionally, China, Brazil, Canada, America, and France were the leading contributors with high publication outputs, and the Chinese Academy of Science was the most productive and influential institution. Furthermore, the research hotspots in the field mainly focused on CO_2, CH_4, and N_2O emissions and their spatiotemporal characteristics due to great contributions to greenhouse effect and heterogeneities of the GHG emissions from hydropower reservoirs. Research frontiers mainly concentrated on the Three Gorges Reservoir, bubble-mediated gas exchange, GHG emissions across different interfaces and gas transfer velocity. Meanwhile, the first three research frontiers were regarded as emerging trends in recent years. Although great progress has been made in the field, there were still some research challenges. Future research priorities were recommended to strengthen: 1) Application of remote sensing in the research on GHG emissions from hydropower reservoirs, 2) improvement of life cycle assessment research, 3) standardization research on the measurement methods, 4) anthropogenic impacts on carbon dynamics, and 5) international cooperation and database construction. Finally, several mitigation measures were suggested to provide useful insights into the management and control of GHG emissions. In contrast to previous reviews, this paper provides an insight for the visual study of the research on GHG emissions from hydropower reservoirs, helping researchers understand the current research status and future perspectives from a global perspective.

KEYWORDS

greenhouse gases, hydropower reservoirs, citespace, research hotspots, future perspectives

1 Introduction

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the three major greenhouse gases (GHGs) in the atmosphere (Raymond et al., 2013), contributing 66%, 16%, and 7% of the total radiative forcing, respectively (World Meteorological Organization, 2021). By the end of 2020, their average concentrations reached new highs (CO_2: 413.2 ppm, CH_4: 1889 ppb, N_2O: 333.2 ppb), which were 149%, 262%, and 123% of pre-industrial levels (World Meteorological Organization, 2021). The increasing concentration of GHGs in the atmosphere intensifies global climate change, which has become a global environmental problem of great concern (Anas et al., 2015; Zhao et al., 2017). Therefore, how to reduce GHG emissions has become a challenge.

Hydropower has been promoted as climate-friendly energy in the past for effectively reducing GHG emissions compared with fossil fuels (Giles, 2006; Barros et al., 2011; Almeida et al., 2019b; Zhao et al., 2019). However, the inundation of land and vegetation and the retention of organic matters make reservoirs become places for carbon processing, transportation and burial (Guerin et al., 2006; Deemer et al., 2016). Organic matter and nitrogen sources retained in reservoirs produce GHGs under the action of microorganisms, especially in the first decade after reservoir construction (Abril et al., 2005; Barros et al., 2011), and the "green" certifications of hydropower reservoirs have been challenged (Giles, 2006). Therefore, research on GHG emissions from hydropower reservoirs has aroused growing worldwide concern among researchers due to the potential to increase global warming (de Sousa Brandao et al., 2019; Zhang et al., 2022b).

Related research on GHG emissions from hydropower reservoirs (GHG-HR) began with Rudd et al. (1993), who commented that GHG emissions from hydropower reservoirs were not zero. It was found that some tropical reservoirs in Brazilian Amazonia even emit more GHGs than fuel-fired power plants (Fearnside, 1995), which aroused international concern about the clean energy properties of hydropower. In recent years, many reviews have been published to promote the research on GHG-HR, and these reviews fell into two categories. From a micro-perspective, researchers reviewed the GHG emission pathways (Yang et al., 2014), influencing factors (Zhao et al., 2008), and measurement methods (Kumar et al., 2019a). From a macro-level, they studied the impacts of reservoir construction on global climate change in certain countries, such as China (Zhang et al., 2015a; Zhang et al., 2015b), Brazil (dos Santos et al., 2019; Rocha Lessa et al., 2015), the United States (Song et al., 2018), and India (Kumar and Sharma, 2016; Kumar and Sharma, 2017; Kumar et al., 2018; Kumar et al., 2019b; Kumar et al., 2021). However, to the best of our knowledge, relatively little attention have been paid to the research hotspots and frontiers on GHG-HR over the past 3 decades from a global perspective. Additionaly, traditional literature reviews tended to be conducted by reading massive amounts of literature, while researchers could not keep up with the rapidly growing number of available studies (Liu et al., 2021). Moreover, the review contents depended much more on the researchers' knowledge structures, leading to non-objectivity to some extent (Wang et al., 2019).

Scientometrics, as an important tool for quantitatively characterizing knowledge maps, can overcome the non-objective drawback to obtain reliable conclusions about a certain field (Li et al., 2021b). Importantly, scientometric analysis have been conducted with regards to research on GHG monitoring (Chen et al., 2021), carbon emissions (Udara Willhelm Abeydeera et al., 2019), lakes and reservoirs (Dehdarirad et al., 2014), and hydropower (Jiang et al., 2016). However, few studies have focused on quantitatively analyzing GHG-HR, especially in the context of global change and carbon neutralization. Therefore, it is of great urgency to adopt the scientific method to systematically analyze GHG-HR from a macro-to micro-perspective.

Given the limitations mentioned above, this paper aims to conduct a systematic and quantitative analysis of GHG-HR research using scientometric analysis. Based on the retrieved publications from 1993 to 2021 in the Web of Science Core Collection, the CiteSpace software was used to visualize and analyze the current research status and future developments in the field. This paper provides an overview of this field from the following perspectives: 1) Analyzing the current research status in GHG-HR field, including the spatiotemporal distribution, popular subject categories and journals, cooperation dynamics among authors and institutions, highly cited journals and references; 2) identifying research hotspots in the field; 3) exploring research frontiers and emerging trends; and 4) proposing future research priorities for the further study.

2 Materials and methodology

2.1 Data collection and search strategy

The Web of Science Core Collection, a comprehensive and multidisciplinary database of peer-reviewed scientific publications, contains a vast number of influential academic journals (Huang et al., 2020). Given the advantages of its comprehensiveness, high impact, and strict screening criteria, the Web of Science Core Collection was chosen to ensure the representativeness of the retrieved literature (Dehdarirad et al., 2014). The required publications used in this paper were obtained by a combination of retrieved results from the advanced retrieval method to the Web of Science (Table 1).

TABLE 1 Key word retrieval history for GHG-HR.

Set	Results	Retrieval history
#7act	1,579	#1 OR #2 OR #3 OR #4 OR #5 Refined by: [excluding] Publication years: (1992 OR 1991 OR 1990 OR 1977) AND [excluding] Web of Science Categories: (Reproductive Biology OR Cell Biology OR Physiology OR Medicine Research Experimental OR Nutrition Dietetics or Infectious Diseases OR Veterinary Sciences OR Food Science Technology OR Parasitology OR Pediatrics or Neurosciences or Surgery OR Telecommunications OR Tropical Medicine OR Zoology OR Behavioral sciences OR Genetics heredity OR Dentistry oral surgery medicine OR Endcrinology metabolism OR Entomology OR Sport Sciences OR Evolutionary
#6	1,682	#1 OR #2 OR #3 OR #4 OR #5
#5	338	Topic: ("carbon footprint*" OR "carbon cycl*" OR "carbon budget" OR "carbon emission") AND Topic: (hydropower reservoir OR dam OR hydroelectric reservoir OR hydro project OR hydroreservoir OR hydropower plant) AND Document types: (Article OR Review) AND Language: (English)
#4	99	Topic: (N_2O OR "nitrous oxide") AND Topic: (hydropower reservoir OR dam OR hydroelectric reservoir OR hydro project OR hydroreservoir OR hydropower plant) AND Document types: (Article OR Review) AND Language: (English)
#3	482	Topic: (CH_4 OR methane) AND Topic: (hydropower reservoir OR dam OR hydroelectric reservoir OR hydro project OR hydroreservoir OR hydropower plant) AND Document types: (Article OR Review) AND Language: (English)
#2	1,020	Topic: (CO_2 OR "carbon dioxide") AND Topic: (hydropower reservoir OR dam OR hydroelectric reservoir OR hydro project OR hydroreservoir OR hydropower plant) AND Document types: (Article OR Review) AND Language: (English)
#1	708	Topic: (GHG OR "greenhouse gas*" OR "green house gas*") AND Topic: (hydropower reservoir OR dam OR hydroelectric reservoir OR hydro project OR hydroreservoir OR hydropower plant) AND Document types: (Article OR Review) AND Language: (English)

The comprehensive peer review process involved makes the journal articles more reliable than other sources (Olawumi et al., 2017). As a result, the document types used in this study were limited to "article" and "review", and the language of the documents was limited to English. Rudd et al. (1993) initiated the research on GHG-HR, so documents published before 1993 were excluded when refining the publications retrieved. After refining the publication year and subject categories, a total of 1,579 records were retrieved. Since some irrelevant records were inevitably retrieved from the Web of Science Core Collection through the above retrieval strategies (Li and Chen, 2016), these 1,579 records were further manually screened. The exclusion criteria of the publications were as follows: 1) Exclude the non-related records of GHG emissions, carbon emissions and reservoirs that are not included in the title, abstract and keywords; 2) Refine the research field, and exclude the literature related to medicine and petroleum; 3) Refine the research contents, and articles related to carbon storage are excluded.

According to the above criteria, 338 publications from 1995 to 2021 were obtained after manual screening, including 326 articles (96.4%) and 12 reviews (3.6%). The retrieved publications were downloaded on 8 December 2021, and saved as plain text files in the format of "Full Records and Cited References" for subsequent analysis.

2.2 Scientometric analysis

In this study, CiteSpace software (5.8 R3 version), designed and developed by Professor Chaomei Chen, was selected to conduct the scientometric analysis. It is a visualization software package based on Java, and focuses on discovering the development hotspots and citation hotspots in a certain research field (Chen, 2006). CiteSpace includes four analysis functions: cooperation analysis, co-occurrence analysis, co-citation analysis and coupling analysis. According to the co-occurrence analysis of keywords, the research hotspots and frontiers in corresponding fields can be determined (Ouyang et al., 2018).

CiteSpace takes a series of bibliographic records as the input files to generate complex knowledge maps for statistical analysis and visual exploration (Chen et al., 2012). To ensure the effectiveness of all the bibliographic records, it is necessary to remove the duplicates before running CiteSpace. No duplicate documents were found in the records downloaded in this study. As a result, the number of available records was still 338. This paper selected the top 20 items for analysis, and the time slice was 1 year.

The module value and silhouette value are regarded as the evaluation basis of the knowledge map drawing effect. The clustering effect is considered significant when modularity value is greater than 0.3, and the clustering effect is convincing when the silhouette value is greater than 0.7 (Chen, 2006). The nodes in the map, representing the analysis objects, are marked by a series of tree-rings in this paper. The thickness of the ring is directly proportional to the frequency of occurrence in the corresponding period. Among them, the centrality and burst are indicators used to measure the importance of the nodes in the network. Nodes with high centrality and burst are highlighted by purple and red circles, respectively, making it easier to identify the key points.

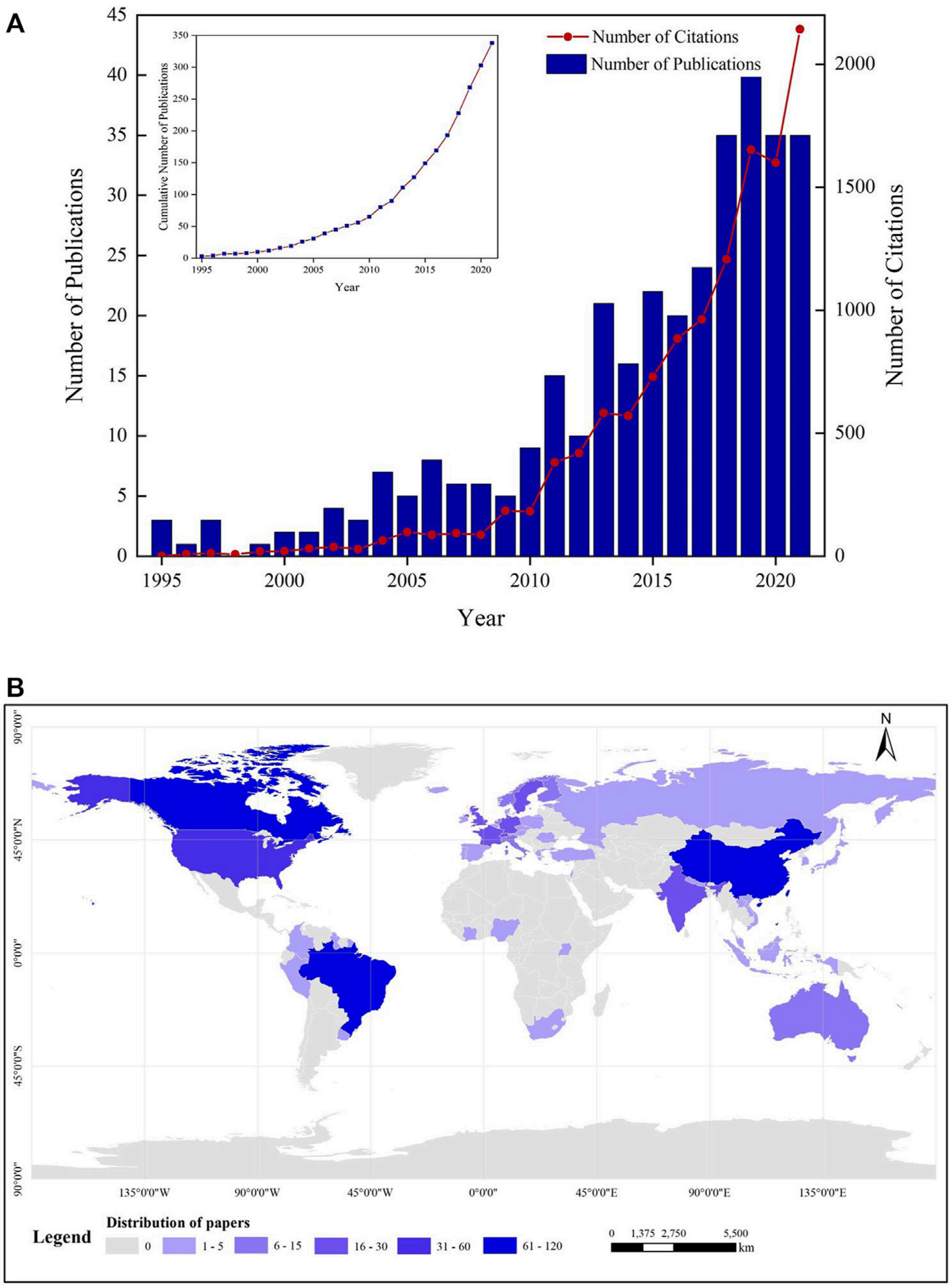

FIGURE 1
Spatiotemporal characteristics of annual publications in GHG-HR research field. (A) is the trends of publications in GHG-HR research field; and (B) is the global distribution of publications in GHG-HR research field.

3 Results and discussion

3.1 Current research status

3.1.1 Spatiotemporal distribution

The publication entitled "Are hydroelectric reservoirs significant sources of greenhouse gases?" by Rudd et al. (1993) is a landmark initiating research on GHG-HR. Therefore, 1993 was chosen as the year to begin the scientometric research. However, the document type of the publication is "note", not the required "article" or "review", so this publication was filtered out during the retrieval. As a result, based on the retrieved records, the time span was set to 1995–2021.

TABLE 2 Top five most productive countries in GHG-HR research field.

Ranking	Country	Frequency	Year*
1	China	120	2007
2	Brazil	66	2001
3	Canada	61	1995
4	United States	58	2002
5	France	26	1996

Note: * indicates the first time the country published articles in the field.

The number of yearly publications can directly reflect the research activity in a certain field (Hu et al., 2017; Wu et al., 2021). The trends of publications in GHG-HR research field are presented in Figure 1A. Although the yearly publication outputs in this field fluctuated slightly, they generally exhibited an increasing trend, indicating that GHG-HR research has gradually attracted more concern. With the growing attention to global climate change and clean energy, GHG-HR research has received increasing interest over the last decade. The increasing interest in this field has inspired researchers to explore the impact of reservoir construction and operation on global climate change. Furthermore, it was found that the number of publication citations increased exponentially from 1995 to 2021, indicating that the depth and breadth of research on GHG-HR have grown rapidly over the past 30 years. The total number of citations was 12,088 during 1995–2021, and the average number of citations per publication was 35.76.

Based on the affiliations of the authors, analysis of the countries helps understand the spatial distribution of countries researching GHG-HR and the contributions of the different countries at the geographical level (Ouyang et al., 2018). The global distribution is shown in Figure 1B. It can be seen that GHG-HR research has attracted different degrees of attention from different countries, and the top five countries contributing to GHG-HR research field were China, Brazil, Canada, the United States and France (Table 2). China ranked first with 120 publications on GHG-HR, much ahead of other countries, accounting for 35.5% of the total number of publications. Although China accounts for only 7% of the global land area, China has the largest number of reservoirs in the world (Li et al., 2018). By the end of 2020, China had 98,566 reservoirs, with a total storage capacity of 930.6 billion m^3 (Ministry of Water Resources of the People's Republic of China, 2020). Considering the vast number of reservoirs in China and the potential greenhouse effect of reservoirs, it is of great necessity to determine the source-sink relationship of reservoir GHGs for exploring the clean property of hydropower, especially in the context of China's "carbon neutrality" target. As can be seen from Table 2, previous studies on GHG-HR have mainly focused on Brazil, Canada, the United States and France. Since 2007, the number of research cases on GHG-HR in China has increased rapidly, which has greatly enriched the related research from a global perspective. Although China started researching GHG-HR much later than other countries, the follow-up development in China was rapid, becoming the most productive and influential country so far in the field.

3.1.2 Popular subject categories and journals

Through co-occurrence analysis of the subject categories in CiteSpace, the popular disciplines involved in the field can be detected (Ouyang et al., 2018). Figure 2 shows the co-occurrence analysis network of the subject categories and the top 10 subject categories. As can be seen from Figure 2, GHG-HR research is an interdisciplinary topic, and covers a wide range of disciplines, including Environmental Sciences and Ecology, Environmental Sciences, Geosciences, Geology, Engineering, Water Resources, Ecology and so on. Among all the disciplines, Environmental Sciences and Ecology and Environmental Sciences were the top two subject categories in the domain, contributing 42% of all the publications in this field, indicating that the research contents in the field are highly related to the research directions of the two subject categories. In addition, Environmental Sciences and Ecology and Environmental Sciences had the highest centrality, showing that these two disciplines played an important role in GHG-HR research. As a result, Environmental Sciences and Ecology and Environmental Sciences were the most popular subject categories in the field.

The 338 selected publications on GHG-HR research were published in 115 journals. Table 3 displays the top nine most popular journals in GHG-HR research field. A total of 123 publications were published in the nine journals, accounting for 36.4% of all publications. When it comes to the scopes of the journals, the top nine journals cover a range of disciplines, including environmental sciences, geology, water resources, and geoscience. This also implies that GHG-HR research is interdisciplinary. As Table 3 shows, *Science of the Total Environment* is the most popular and influential of the journals related to GHG-HR research, followed by *Biogeosciences, Global Biogeochemical Cycles, Environmental Science and Technology* and *Water Research.* Indentifying the most popular journals in GHG-HR field can help researchers quickly choose the right journals for the publication of their research.

3.1.3 Cooperation dynamics among authors and institutions

The influence of an author in a certain field is directly related to the number of papers published. Authors with higher publication outputs tend to have greater influence, and will promote the research in the field. Table 4 shows the top five most productive authors in GHG-HR research field. Among these representative researchers, Baoli Wang from the Institute of Geochemistry, Chinese Academy of Sciences, ranked first with 14 publications. He mainly focused on the GHG emissions from

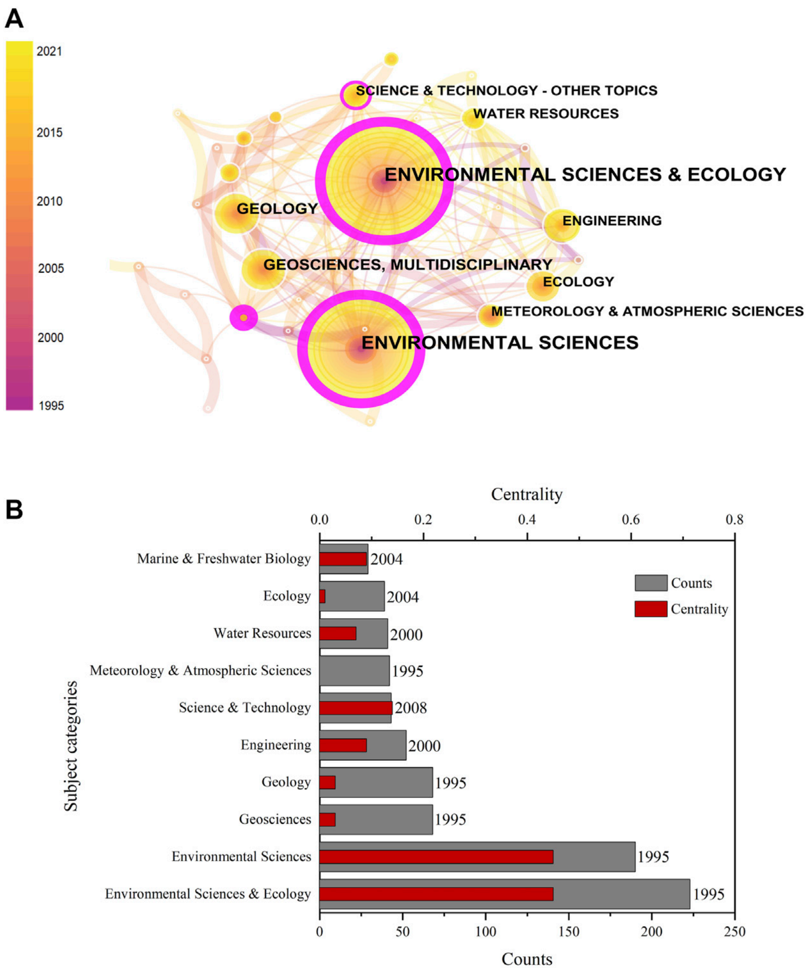

FIGURE 2
Subject categories: **(A)** Subject categories network; and **(B)** Top 10 subject categories. The numbers on the bar chart represent the years of the first occurrence.

TABLE 3 Top nine most popular journals in GHG-HR research field.

Ranking	Journals	Counts	% Of 338 publications
1	Science of the total environment	26	7.7
2	Biogeosciences	19	5.6
3	Global biogeochemical cycles	15	4.4
4	Environmental science and technology	13	3.8
5	Water research	12	3.6
6	Journal of geophysical research	11	3.2
7	Journal of cleaner production	10	3
8	Inland waters	9	2.7
9	Environmental monitoring and assessment	8	2.4

TABLE 4 Top five most productive authors in GHG-HR research field.

Ranking	Author	Frequency	Year
1	Baoli Wang	14	2008
2	Fushun Wang	13	2008
2	Sebastian Sobek	13	2009
4	Yves T Prairie	12	2011
5	Nathan Barros	11	2011

cascade power stations in southwestern China. As Figure 3 shows, there is close cooperation between Fushun Wang, Baoli Wang, Siliang Liu and Congqiang Liu. They focused on the carbon cycle in cascade reservoirs in the Wujiang River Basin (southwestern China), and carried out research on GHG-HR from the perspectives of river-reservoir hydrochemical characteristics, dissolved inorganic carbon and pCO_2 migration and transformation (Sun et al., 2020). Except for Fushun Wang, Baoli Wang, Siliang Liu, Congqiang Liu, M. P Sharma and Amit Kumar, the rest of the authors exhibited relatively close research cooperation (Figure 3).

Cooperation among institutions is not only conducive to the optimal allocation of scientific research resources, but it also promotes innovations and improvements in global reservoir carbon cycle research. As Figure 4 shows, there has been close international cooperation in GHG-HR field. As can be seen from Table 5, the top five most productive institutions were the Chinese Academy of Science (57 publications), University of Quebec (24 publications), University Fed Juiz de Fora (18 publications), Chongqing University (17 publications) and Shanghai University (16 publications). Significantly, the number of publications produced by the Chinese Academy of Sciences far exceeds those produced by the other institutions, indicating the non-negligible importance of the Chinese Academy of Sciences in GHG-HR research field. In terms of the distribution of the institutions, the top five institutions are located in China, Canada and Brazil, with four of the institutions (Chinese Academy of Sciences, Chongqing University, Shanghai University, Tianjin University) located in China, demonstrating the diversity of the cooperation among institutions in GHG-HR research field in China.

Burst detection of institutions can be used to identify the institutions that are particularly active for a certain period (Yu and Xu, 2017). The top five institutions with the strongest citation bursts are shown in Figure 5. The University of Quebec is the institution with the earliest research start year, the strongest burst strength and the longest burst duration, which indicates that researchers from University of Quebec paid great attention to the research on GHG-HR from 2000 to 2013. Of the

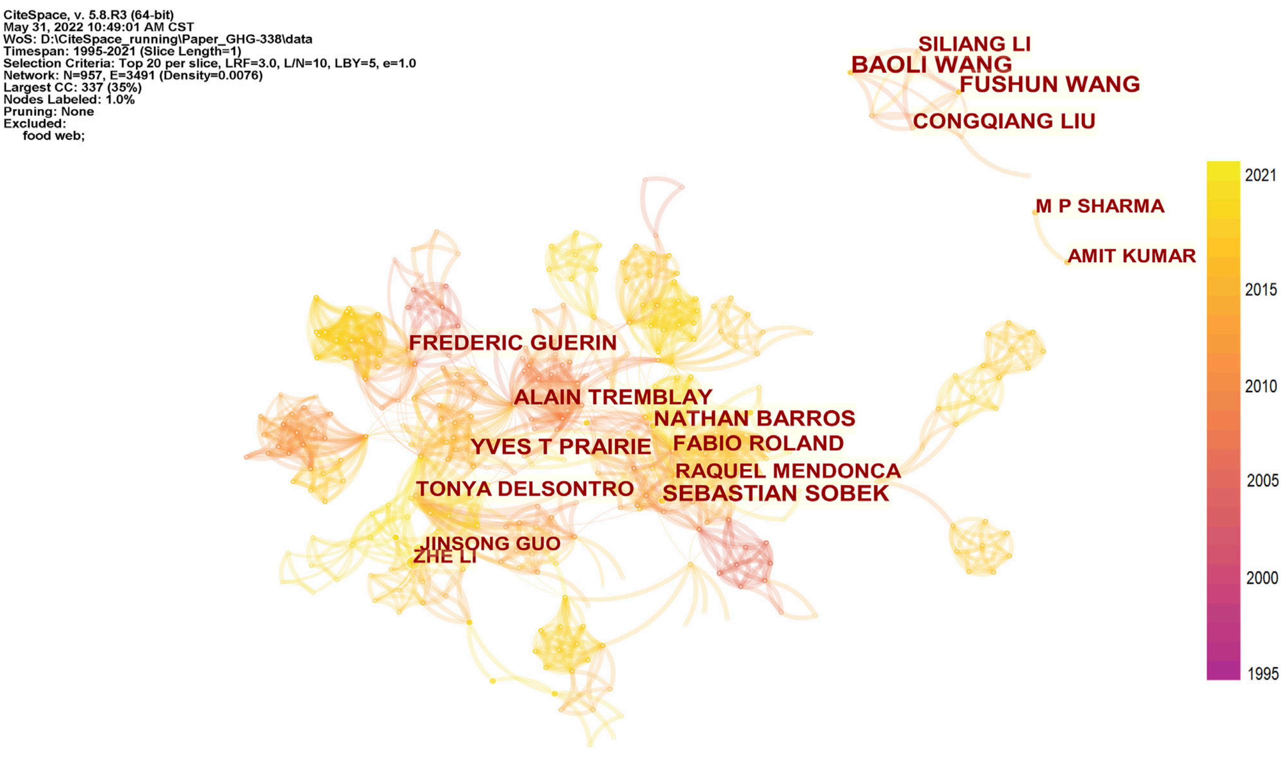

FIGURE 3
Author collaboration network.

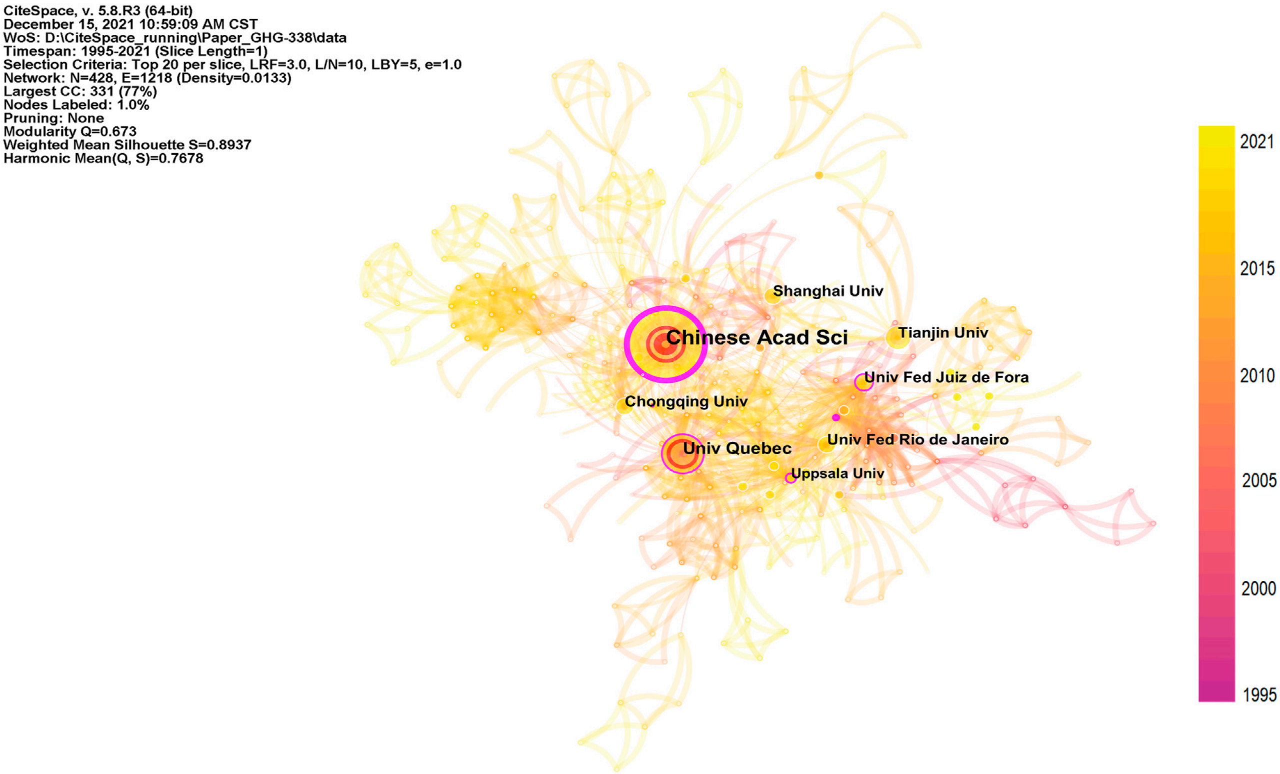

FIGURE 4
Cooperation network among institutions in GHG-HR research field.

TABLE 5 Top five institutions in GHG-HR research field.

Ranking		Institutions	Count	Centrality	Year
Sorted by counts	1	Chinese Academy Science (China)	57	0.57	2008
	2	University of Quebec (Canada)	24	0.14	2000
	3	University Fed Juiz de Fora (Brazil)	18	0.17	2010
	4	Chongqing University (China)	17	0.01	2009
	5	Shanghai University (China)	16	0.01	2008
Sorted by centrality	1	Chinese Academy Science (China)	0.57	57	2008
	2	CSIRO Land and Water (Australia)	0.2	3	2009
	3	University Fed Juiz de Fora (Brazil)	0.17	18	2010
	4	University of Quebec (Canada)	0.14	24	2000
	5	Uppsala University (Sweden)	0.12	14	2004
	5	SINTEF Energy Research (Norway)	0.12	6	2011

top five institutions with the strongest citation bursts, two institutions are located in Canada, demonstrating that Canada had a great influence on GHG-HR research.

Based on the above analysis, the Chinese Academy of Sciences is the institution with the largest number of publications, the highest centrality and the second-highest burst strength. Thus, it can be

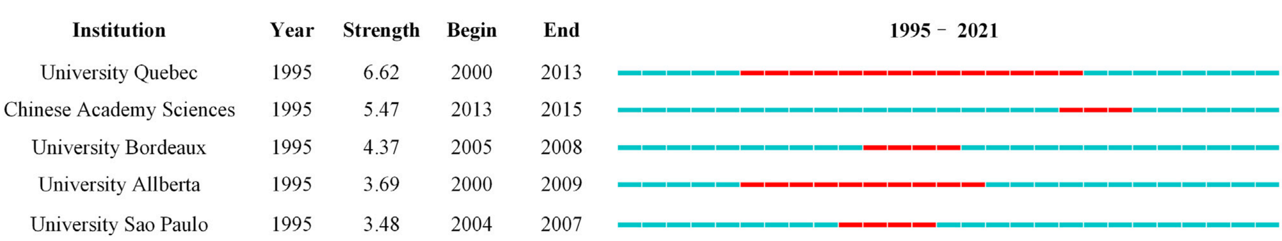

FIGURE 5
Top five institutions with the strongest citation bursts.

TABLE 6 Top 10 cited journals in GHG-HR research field.

Ranking	Cited journals	Counts	Year
1	Global biogeochemistry cycles	272	1995
2	Limnology oceanography	231	1995
3	Environmental science and technology	231	2000
4	Bioscience	217	2003
5	Nature	209	1995
6	Nature geoscience	189	2012
7	Geophysical research letter	183	2002
8	Science	178	1995
9	Journal of geophysical research-biogeosciences	177	2008
10	Ecosystems	161	2003

concluded that the Chinese Academy of Sciences has been the most productive and influential institution in GHG-HR research field, playing an important role in institutional cooperation.

3.1.4 Highly cited journals and references

Top 10 most cited journals in this field are listed in Table 6. All of the 10 journals have been cited more than 160 times, demonstrating that these journals are influential in GHG-HR field. Among these journals, *Global Biogeochemistry Cycles* (272 citations) was the most cited journal, followed by *Limnology Oceanography* and *Environmental Science and Technology* (231 citations). From the perspective of the impact factor, *Nature* and *Science* were the most profound and influential journals, with 209 and 178 citations, respectively.

Highly cited references can help researchers better grasp the research core contents, and reflect the knowledge base of the field (Wang et al., 2021). Table 7 lists the top 10 references cited in GHG-HR research field. Notably, the most cited article refers to the number of citations in the 338 articles, not the number of citations in the Web of Science. Obviously, "Greenhouse gas emissions from reservoir water surfaces: A new global synthesis" published by Deemer et al. (2016) in *Bioscience* was the most cited publication in the database, demonstrating that this publication has a certain guiding role in the development of this field. The publication estimated the total GHG emissions from global reservoirs water surfaces (0.8 PG $CO_{2equivalents}$/year). Methane emissions from global reservoirs water-air interface account for 79% of the total radiative forcing over the 100-year scale, CO_2 and N_2O account for 17% and 4% respectively. As an important component of inland water carbon cycle, the quantification of carbon emissions from global reservoirs are essential to global carbon budgets. Among the top 10 references, the publication time is mainly concentrated in the past decade. This indicates that GHG-HR research has developed rapidly, and breakthroughs have been made over the last decade, laying a solid foundation for future research. In addition, the highly cited publications are mainly published in *Environmental Science and Technology*, *Nature* and its series, showing that these journals have made important contributions in GHG-HR research field.

3.2 Research hotspots

Keywords are the concentration of the research core in an article, and they can fully describe the main contents of an article

TABLE 7 Top five references cited in GHG-HR research field.

Ranking	Frequency	Cited References	Authors	Source
1	93	Greenhouse gas emissions from reservoir water Surfaces: A new global synthesis Deemer et al. (2016)	Bridget R. Deemer, John A. Harrison, Siyue Li, Jake J. Beaulieu, Tonya Delsontro, Nathan Barrros, Jose F. Bezerra-Neto, Stephen M. Powers, Marco A. Dos Santos, J. Arie Vonk	Bioscience
2	54	Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude Barros et al. (2011)	Nathan Barros, Jonathan J. Cole, Lars J. Tranvik, Yves T. Prairie, David Bastviken, Vera L. M. Huszar, Paul del Giorgio and Fábio Roland	Nature Geoscience
3	36	Greenhouse gas emissions from freshwater reservoirs: What does the atmosphere see? Prairie et al. (2018)	Prairie, Y. T., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J, Del Giorgio, P., DelSontro, T., Guerin, F., Harby, A., Harrison, J, Mercier-Blais, S., Serca, D., Sobek, S., Vachon, D	Ecosystems
4	31	Global carbon dioxide emissions from inland waters Raymond et al. (2013)	Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., Guth, P	Nature
5	29	Reservoir water-level drawdowns accelerate and amplify methane emission (Harrison et al. (2017)	John A. Harrison, Bridget R. Deemer, M. Keith Birchfield, Maria T. O'Malley	Environmental Science and Technology
6	25	Sediment trapping by dams creates methane emission hot spots Maeck et al. (2013)	Andreas Maeck, Tonya DelSontro, Daniel F. McGinnis, Helmut Fischer, Sabine Flury, Mark Schmidt, Peer Fietzek, Andreas Lorke	Environmental Science and Technology
7	25	A global boom in hydropower dam construction Zarfl et al. (2014)	Christiane Zarfl, Alexander E. Lumsdon, Jurgen Berlekamp, Laura Tydecks, Klement Tockner	Aquatic Sciences
8	23	Freshwater methane emissions offset the continental carbon sink Bastviken et al. (2011)	David Bastviken, Lars J. Tranvik, John A. Downing, Patrick M. Crill,4 Alex Enrich-Prast	Science
9	23	Greenhouse-gas emissions from tropical dams Fearnside and Pueyo. (2012)	Philip M. Fearnside and Salvador Pueyo	Nature Climate Change
10	19	Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China Zhao et al. (2013)	Y. Zhao, B. F. Wu, and Y. Zeng	Biogeosciences

(Su and Lee, 2010). The co-occurrence analysis of keywords helps identify the main research areas (Shrivastava and Mahajan, 2016), and detect research hotspots and emerging trends in a certain knowledge field (Yu et al., 2017; Wang et al., 2018). In this study, the keywords and keywords plus from 338 records were selected for co-occurrence analysis to determine the research hotspots in GHG-HR research field.

As shown in the co-occurrence network map (Figure 6), the modularity value and silhouette value are 0.5293 and 0.8188, respectively, indicating that the mapping effect is convincing. The higher frequency of keywords shows a higher research interest. Table 8 lists the top 10 keywords with high frequencies. Not surprisingly, "hydroelectric reservoirs" (195 times) and "greenhouse gas" (192 times), as the keywords in this paper, had the highest frequency. "Carbon dioxide" (164 times) and "methane" (156 times) ranked third and fourth, respectively, and had much higher frequencies than nitrous oxide (42 times). This was due to the significantly higher carbon dioxide and methane emissions from reservoirs compared to nitrous oxide. Although carbon dioxide, methane and nitrous oxide are the main GHGs produced by reservoirs, nitrous oxide emissions are low unless there is a nitrogen source (Hu and Cheng, 2013; Yang et al., 2014). Therefore, nitrous oxide has been studied less than methane and carbon dioxide. However, the global warming potential of N_2O is 298 times that of CO_2 on the 100-years scale (Baena-Moreno et al., 2019). Combined with the significant impact of anthropogenic activities over the years, N_2O emissions from reservoirs may be a potential research focus, especially for reservoirs significantly affected by agricultural activities. Finally, "lake" ranked fifth (93 times), which is because reservoirs have some characteristics of limnology, and many researchers associate research with reservoirs and lakes. Moreover, lakes are considered an important source of GHGs in the atmosphere (Bastviken et al., 2004; Raymond et al., 2013; Li et al., 2018; Rosentreter et al., 2021).

Keywords with high centrality are regarded as the key points of the transition from one time period to another in the network. They are the research focus, and have certain theoretical innovations. The top five keywords with high centrality in this field are shown in Table 8. Significantly, N_2O ranked second with a centrality of 0.18, which confirmed the above speculation before. In addition to the high global warming potential, nitrous oxide is also a destroyer of the stratospheric ozone (Ravishankara et al., 2009; Cavigelli et al., 2012), seriously exacerbating global climate change. Following N_2O, the

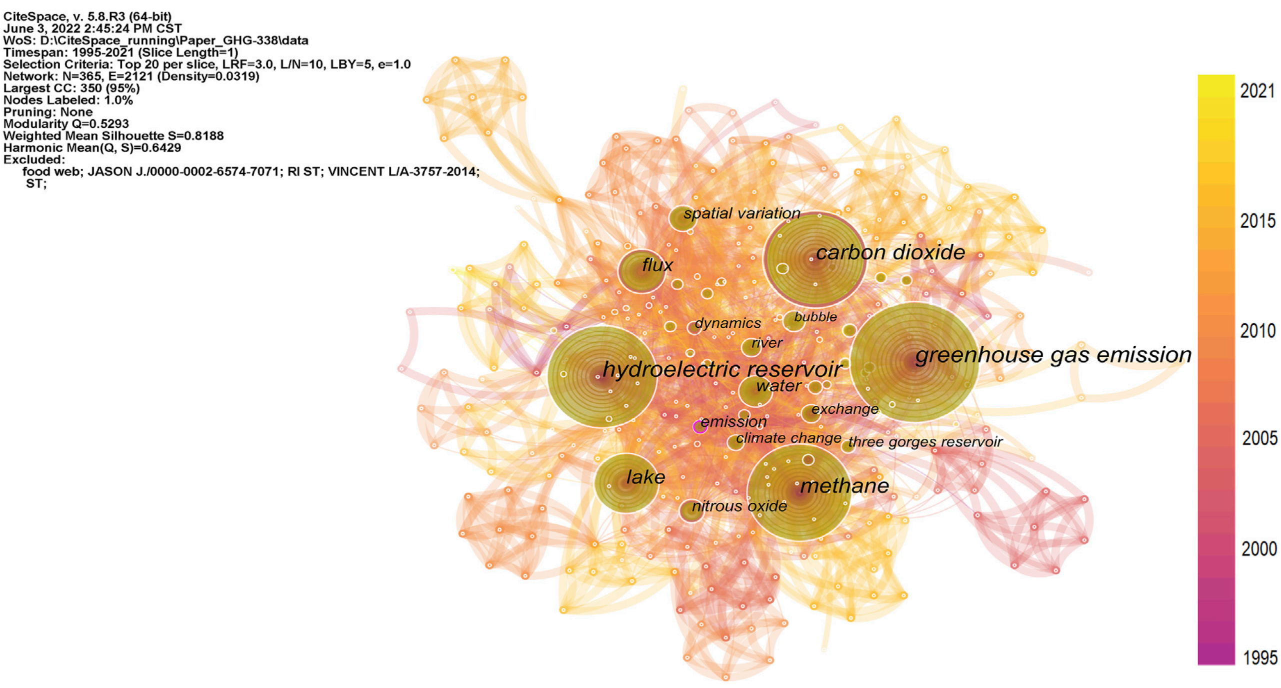

FIGURE 6
Keyword co-occurrence network in GHG-HR research field.

TABLE 8 Keywords with a high frequency and centrality in GHG-HR research field.

Ranking		Keywords	Frequency	Centrality
Sorted by counts	1	hydroelectric reservoir	195	0.08
	2	greenhouse gas emission	192	0.09
	3	carbon dioxide	164	0.15
	4	methane	156	0.05
	5	lake	93	0.08
	6	flux	80	0.14
	7	water	62	0.06
	8	nitrous oxide	42	0.18
	9	spatial variation	41	0.08
	10	emission	38	0.21
Sorted by centrality	1	emission	38	0.21
	2	nitrous oxide	42	0.18
	3	carbon dioxide	164	0.15
	4	flux	80	0.14
	5	dynamics	31	0.14

centrality of CO_2 (0.15) was the second-highest. Interestingly, CO_2 ranked in the top three in terms of both centrality and frequency, demonstrating the importance of research on CO_2 in exploring the carbon cycle mechanism of reservoirs. Dynamics ranked fifth with a centrality of 0.14. The large spatiotemporal heterogeneity of GHG emissions and the limited sampling points

Keywords	Year	Strength	Begin	End
Three Gorges Reservoir	1995	6.83	2019	2021
surfacce	1995	5.08	2018	2021
bubble	1995	5.02	2018	2021
sediment	1995	4.33	2017	2018
atmosphere	1995	4.19	2003	2011
wind	1995	3.97	2017	2019
gas transfer velocity	1995	3.86	2014	2016
emission	1995	3.44	1995	2008
carbon	1995	3.36	2004	2010

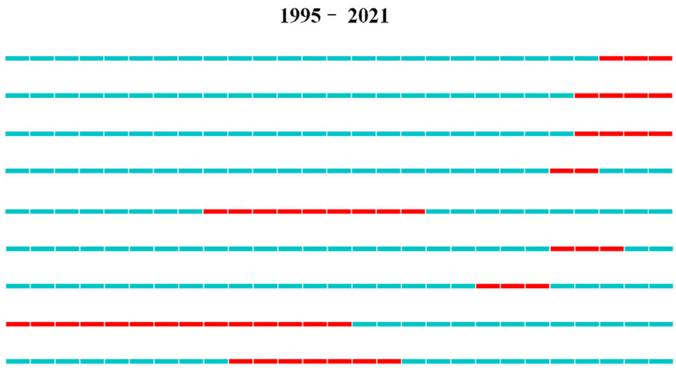

FIGURE 7
Top nine keywords with the strongest citation bursts in GHG-HR research field.

bring significant uncertainty in the estimation of the global carbon budget (Zheng et al., 2011; Paranaiba et al., 2021). Studying the temporal and spatial patterns of GHG emissions not only helps researchers accurately identify the GHG emission hotspot areas, but also enables reliable evaluation of the total emissions from reservoirs (Descloux et al., 2017; Paranaiba et al., 2018). Through analysis of the keyword co-occurrence network, it was found that the research hotspots in GHG-HR research field mainly focused on CO_2, CH_4, N_2O emissions, and their temporal and spatial characteristics, which has greatly improved our understanding of the global carbon cycle.

3.3 Research frontiers and emerging trends

Although frequency analysis of keywords provides some information about the hot topics in a certain field, it cannot be used to analyze the emerging trends (Cui et al., 2019). Burst detection on keywords refers to an abrupt change of the frequency during a certain period (Chen et al., 2014a; Chen et al., 2014b), and it indicates that the keywords receive great attention in a short time, which can reflect research frontiers (Huang et al., 2020).

Figure 7 shows that there are nine keywords with the citation bursts in GHG-HR research field. It was found that “Three Gorges Reservoir” ranked first with the strongest citation bursts in 2019–2021. On the one hand, Chen et al. (2009) extrapolated that the GHG emissions from the Three Gorges reservoir were not less than those from the South American hydropower reservoirs. In the same year, Nature reported the above achievements under the title of “Chinese Dam Maybe A Methane Menace” (Qiu, 2009), which aroused the high concern of the international community about the potential climate change effects of the Three Gorges Reservoir. This event has become an important starting point for the research on GHG emissions from reservoirs in China, and has opened an important development period in this field for the next years (Sun et al., 2020). Follow-up research on the Three Gorges Reservoir was indirectly prompted due to the concern on regional climate change and the production of clean energy (Zhao et al., 2019). In terms of the “clean” property of the hydropower generated by the Three Gorges Reservoir, it was estimated that the power density of the Three Gorges Reservoir is 35.6 W/m^2 (Sun et al., 2020). According to the threshold set by the United Nations Framework Convention on Climate Change on clean development mechanisms, the GHG emissions from hydropower reservoirs with energy densities of greater than 10 W/m^2 can be ignored (UNFCCC, 2006). Moreover, in contrast to previous studies that only considered GHG emissions from the Three Gorges Reservoir areas, from the perspective of the range of 4,300 km along the Yangtze River upstream and downstream of Three Gorges Reservoir, Ni et al. (2022) found that the Three Gorges Dam has caused significant reductions in annual average GHG emissions over the 4,300 km range along the Yangtze River.

On the other hand, China announced the “carbon peaking” and “carbon neutrality” targets in 2020 and its intention to actively respond to global climate change. The issue of GHG emissions from the Three Gorges Reservoir is directly related to China’s national strategy for energy security, sustainable development of hydropower and the realization of the dual-carbon targets. Therefore, exploring the carbon cycle mechanism of the Three Gorges Reservoir provides an important scientific basis for objectively evaluating the green property of hydropower.

Following “Three Gorges Reservoir”, “surface” ranked second, demonstrating that the GHG emissions across the water-air interface have attracted significant attention. The three keywords with burst— “sediment”, “atmosphere” and “surface”— all indicate the importance of GHG research at different interfaces of reservoirs, such as water-air interface, soil-air interface and sediment-water interface. However, existing research has mainly focused on GHG emissions at the water-air interface (Yang and Tong, 2015). Research on GHG emissions at the sediment-water interface and the soil-air interface needs to be strengthened. "Bubble" ranked third with a burst strength of 5.02. As the main methane emission pathway, great importance has been attached to research on methane bubbling. Compared with diffusive flux, ebullition is much more challenging to measure as the bubbles are more stochastic (Bastviken et al., 2004; Wik et al., 2016). Due to the significant spatiotemporal variability of bubbles, accurate estimates of ebullition emissions require intensive spatial and continuous temporal sampling (Wik et al., 2016). "Wind" and "gas transfer velocity" ranked sixth and seventh, respectively, which are both factors influencing GHG diffusion. The diffusion of GHGs is driven by the gas concentration gradient and the gas transfer velocity at the water-air interface (Cole and Caraco, 1998). Wind affects the contact area between the water and air, and changes the concentration gradient of GHGs at the water-air interface (Wanninkhof, 1992), which increases the research uncertainty. In addition, the gas transfer velocity directly determines the magnitude of the GHG fluxes across the water-air interface (Zhang et al., 2021a). It has been found that the gas transfer velocity strongly depends on the water surface motion (e.g., the wind speed, rainfall, and surface turbulence), and it varies greatly with time and under different flow conditions (Cole et al., 2010; Hall and Ulseth, 2020). Generally, the gas transfer velocity is obtained by the empirical wind-based models (Miao et al., 2022). However, there is large spatial heterogeneity in the estimations of the gas transfer velocity (Schilder et al., 2016). As a result, the estimation of the gas transfer velocity requires special attention (Wallin et al., 2011). Furthermore, different keywords with burst reflect the research characteristics of the different periods (Yu and Xu, 2017). From Figure 7, the burst duration of the research on "Three Gorges Reservoir" "surface" and "bubble" lasted until 2021, which showed that they have become new research topics in recent years. That is, research on the Three Gorges Reservoir, emissions from different interfaces of reservoirs and bubble-mediated gas exchange can be regarded as emerging trends.

4 Research challenges and future research priorities

In recent years, GHG-HR research has received worldwide attention, and obtained certain achievements, while there are also some limitations. It is of great significance to clarify the current research challenges and formulate the future research priorities to promote the further development of this field.

4.1 Application of remote sensing in GHG-HR research

At present, the monitoring methods of GHG emissions across a reservoir's water-air interface are mainly based on field measurements, such as the floating chamber method, the thin boundary equation method and the inverted funnel method, which requires high labor intensities, resulted in the limited samples and lack of regional continuous observation. It is clear that large-scale and long-term continuous observations are needed to better quantify GHG emissions from reservoirs (de Sousa Brandao et al., 2019). Remote sensing, as a feasible method for measuring spatiotemporal dynamics, provides the possibility for expansion of the spatiotemporal scale of monitoring data and fills data gaps in the global inland water carbon cycle.

First, remote sensing has the advantage of continuous observations. Therefore, the background data on GHG emissions can be obtained through remote sensing (Zhao et al., 2011). A growing scientific consensus worldwide agrees that assessment of the net GHG emissions from reservoirs is the basis for elucidating the GHG effects of reservoir construction and operation (Hu and Cheng, 2013; Li and Wang, 2022). The background values of the GHG emissions in the affected area before impoundment should be fully considered (Sun et al., 2020; Li and Wang, 2022). However, data on the pre-impoundment emissions are not easy to acquire (Li et al., 2017b). Due to the advantages of continuous observation of remote sensing, the background data on GHG emissions can be obtained through remote sensing (Zhao et al., 2011). However, there exist great challenges in the monitoring of GHG emissions from reservoirs (Wen et al., 2021).

Furthermore, remote sensing has the advantage of large-scale observations, and provides a basis for accurately obtaining the dynamics of GHG emissions from reservoirs. At present, the GHG emission dynamics of reservoirs are obtained through the fixed-point monitoring data and the spatial interpolation method. Although this method provides a reference for the dynamics of GHG emissions, it causes uncertainties due to ignoring the high spatiotemporal heterogeneities. As a result, it is of great urgency to improve measurements and spatiotemporal coverage (Pilla et al., 2022). When high spatiotemporal coverage data are available, a comprehensive and accurate estimate of GHG emissions from global reservoirs can be achieved (Ran et al., 2022). With the help of remote sensing, real-time remote sensing images are acquired, the relevant parameters can be inverted, and statistical models can be established to obtain the dynamics of GHG emissions from reservoirs. By means of remote sensing and *in-situ* observation data, Qi et al. (2020) obtained a long-term series map of CO_2 concentration in Lake Taihu, providing a new method for understanding the spatio-temporal dynamics of CO_2 concentration in the waters.

4.2 Carbon footprints of hydropower

Notably, the changes in the source-sink relationship of GHG emissions from reservoirs are not equivalent to the carbon emissions of hydropower energy (Sun et al., 2020). The carbon emissions of hydropower should be evaluated under the framework of the entire life cycle of the system, including the early stage, construction period, operation and maintenance period, dam demolition and river restoration stages of hydropower projects (Li et al., 2017a; Li et al., 2017b). The net emissions of reservoirs are just a part of the emissions in the operation and maintenance period. Assessment on the carbon footprints of hydropower is significant to objectively judge the clean property of hydropower. However, there are large uncertainties in the present research, for example, the GHG emissions from reservoir sediments during the dam decommissioning and river restoration period are still uncertain (Li et al., 2019). Therefore, in the future, it is necessary to conduct in-depth research on the carbon emissions for the life cycle assessment of hydropower plants to reduce the uncertainties. Besides, development of life cycle inventories of hydropower reservoirs can provide a scientific basis for the management of GHG-HR to actively respond to global climate change. Moreover, the future carbon management to reduce life cycle GHG emissions can be considered from the perspective of pre-impoundment clearance, which is an effective measure that can significantly reduce the potential emissions after reservoir impoundment (Li et al., 2017b).

4.3 Standardization research on measurement methods

The GHG emissions from reservoirs into the atmosphere are a dynamic biogeochemical process, which is affected by many factors. Therefore, long-term monitoring of GHG emissions from reservoirs is the most direct and effective means to conduct research on GHG-HR, but there are still several problems in GHG monitoring of reservoirs. Firstly, the GHG emission pathways of hydropower reservoirs cannot be fully and accurately monitored. Some pathways, such as downstream of the dam, degassing from spillways and turbines, are difficult to quantify (Hu and Cheng, 2013). Second, many episodic events, such as precipitations and floods, are ignored in the estimations of reservoir greenhouse gas emissions (Fearnside, 2002). Furthermore, GHG emissions from reservoirs into the atmosphere are biogeochemical processes involving multiple interfaces, including the water-air interface and soil-air interface (Zhang et al., 2020), while many studies have focused exclusively on the emissions across the water-air interface (Soued and Prairie, 2020), leading to underestimation of GHG emissions from global reservoirs (Deshmukh et al., 2018; Marce et al., 2019). Moreover, GHG emissions from inland waters are almost measured during daytime, the diel variability of GHG emissions is neglected, which will result in large uncertainties (Sieczko et al., 2020). Finally, the relevant monitoring data are point scale, resulting in a low resolution of monitoring data (Barros et al., 2011) and high uncertainty in related research.

As a result, the standardization research on the measurement methods of GHG emissions from reservoirs should be strengthened to reduce uncertainties (Yang and Tong, 2015), including *in situ* sampling and model simulation. As for *in situ* sampling, determining the rational sampling time, frequency and the minimum number of sampling points can greatly reduce research errors. It is also necessary to establish a method for assessing GHGs of multiple emission pathways from reservoirs (e.g., ebullition, degassing and emissions from downstream of the dam) to quantify their contributions. Meanwhile, GHG emissions from reservoir littoral zone contribute significantly to the total GHG emissions of a reservoir (Yang et al., 2012). Thus, sampling of different interfaces (water-air interface and soil-air interface) should be considered. When it comes into model simulation, a process-based model should be established to simulate the reservoir GHG dynamics responding to climate change and anthropogenic disturbance, providing a useful tool for quantifying GHG emissions from reservoirs.

4.4 Impact of anthropogenic activities on carbon dynamics

GHG emissions from reservoirs are a complicated process influenced by a series of biological, chemical and physical factors (Wang et al., 2017). In addition, human activities, such as agricultural activities, fertilization, urbanization and other nutrient sources, affect the production and consumption of GHGs by altering biogeochemical processes (Pilla et al., 2022). It was found that the concentrations of CO_2, CH_4, and N_2O in urban reservoirs affected by intense human activities were 3, 7, 10 times higher than those in reservoirs located in forest areas (Wang et al., 2017). The terrigenous inputs of C and N into reservoirs cause eutrophication and promote the growth of water bloom, which are environmental problems encountered by most inland water bodies. Research showed that eutrophication will increase methane emissions from reservoirs and lakes during the 21st century (Beaulieu et al., 2019), and the global social cost of methane emissions caused by lake eutrophication between 2015 and 2050 will be \$7.5–81 trillion (Downing et al., 2021). As a result, it is of great urgency to explore the impact of human activities on GHG emissions from reservoirs, especially under microscopic conditions. Improving the understanding the anthropogenic activities on carbon dynamics makes great sense for managing the problem of global GHG emissions.

4.5 Strengthening international cooperation and database construction

Due to limited data set and obvious lack of data on emission patterns for reservoirs (Zheng et al., 2011), it is a good attempt to increase international cooperation, database construction and sharing in the future. On the one hand, increasing international cooperation can not only effectively allocate scientific research resources, but also promote innovation and improvement in this field, which is conducive to strengthening the depth and breadth of the research in the future. On the other hand, future studies on freshwater GHG emission estimations will benefit from a more comprehensive global database integrating freshwater GHG measurements and related environmental information (Li et al., 2021a). With this database, it is helpful to the compilation of global GHG emission inventories, and process-based models can be more easily established.

5 Policy implications and recommendations

5.1 Influencing factors

The entry of GHG emissions from inland waters into the atmosphere is a dynamic biogeochemical process, which is affected by many factors (Yang and Tong, 2015). In the long-term context of facing global climate change and "carbon neutrality" target, understanding the influencing factors of GHG emissions from hydropower reservoirs provides a basis for mitigating GHG emissions during hydropower development.

The factors influencing GHG emissions from hydropower reservoirs can be divided into five categories:

(1) Climate conditions, such as: temperature, wind speed and precipitation. Water temperature has a great influence on the decomposition rate of organic matters (Lu et al., 2007; Barros et al., 2011; Zhao et al., 2013), activity intensity of microorganisms (Topp and Pattey, 1997), and gas solubility (Zhao et al., 2008). Besides, wind speed can change the gas transfer coefficient, influencing GHG fluxes at the water-air interface (Wanninkhof, 1992; Guerin and Abril, 2007). In addition, precipitation causes a large amount of organic matter to flow into reservoirs, increasing the degradation of organic matter and promoting the GHG emissions (Deemer et al., 2016).

(2) Water environmental factors, such as: pH, dissolved oxygen, organic matter and nutrients, *etc.* pH directly affects the dynamic balance and distribution of carbonate system in water, and controls the CO_2 concentration in water (Zhao et al., 2017). There is often a negative correlation between CO_2 exchange flux at water-air interface and pH (Zhao et al., 2011). The contents and distribution of dissolved oxygen (DO) in water determine the degradation pathways of organic matter in water, such as methanogenesis and methane oxidation, nitrification and denitrification (Yang et al., 2014). The emissions of CO_2 and CH_4 are related to the contents of easily decomposed organic matter submerged after reservoir impoundment (St. Louis et al., 2000). Zhang et al. (2022c) found that terrestrial organic carbon drives methane dynamics in cascade reservoirs in the upper reaches of the Yangtze River. Nutrient concentration can affect GHG fluxes at the water-air interface by affecting the primary productivity of aquatic plants and the metabolic process of aquatic organisms (Li et al., 2018).

(3) Characteristics of reservoirs and catchments, such as water depth, latitude, reservoir age, urbanization levels and land use types in the reservoirs' catchments. The release of methane is negatively correlated with the average water depth of the reservoir. The shallow water area in the reservoir releases more methane than the deep water area (Zheng et al., 2011). The release flux of GHG is closely related to the age of the reservoir, which is mainly related to the storage of organic carbon in the reservoir (St. Louis et al., 2000). Generally, young reservoirs are often considered as important methane emitters due to the decomposition of submerged organic carbon (Prairie et al., 2018). Carbon emissions from hydroelectric reservoirs linked to reservoir latitude, and GHG emissions from tropical reservoirs were higher than those in temperate and cold regions (Barros et al., 2011). Besides, land use types and urbanization levels in the reservoir catchment also affect the release of GHGs from the reservoir. Zhang et al. (2021a) found that the spatial variation of CO_2 flux in subtropical reservoirs along the southeast coast of China is related to urbanization and land use types, which affect the input of exogenous carbon.

(4) Hydrological conditions. Both drought and flood have an impact on GHG emissions (Jin et al., 2016; Kosten et al., 2018; Almeida et al., 2019a). Sediment drying stimulates bacterial growth and enzyme activity, thereby increasing CO_2 production and subsequent release (Almeida et al., 2019a). Shi et al. (2021) studied the impact of hydrological changes (continuous flooding, periodic flooding, and no flooding) on GHG emissions in the drawdown zone of Three Gorges reservoir. Results showed that hydrological conditions changes soil moisture, soil organic carbon, soil C/N ratio and functional genes of microorganisms, influencing the GHG emissions from riparian zone in the Three Gorges Reservoir area. In addition, the operation and management of the reservoir will also change the GHG emissions. Zhao et al. (2019) compared the GHG emissions from two tributaries of the Three Gorges reservoir under high water level and low water level. The results showed that the two tributaries released more CH_4 under low water level and more CO_2 under high water level.

(5) Biological conditions, such as vegetation cover and microorganisms. Almeida et al. (2019a) found that the CO_2 emissions in the drawdown zone of a Brazilian reservoir was related to the surrounding vegetation cover. CO_2 released by the exposed sediments near the grassland was lower than that of the adjacent forest land, consistent with the difference of organic matter between the adjacent grassland and forest land. Microbial activities play an important role in the carbon and nitrogen cycle. Shi et al. (2021) found that GHG emissions in the littoral zone were closely related to the abundance of microbial functional genes.

5.2 Policy implications

To enhance the clean property of hydropower, policymakers and managers can take the following aspects into consideration to mitigate the GHG emissions from hydropower reservoirs. First of all, the location of a reservoir is very important. St. Louis et al. (2000) pointed out that the reservoirs with low topographic relief produce more GHGs per kW hour than those built in canyons. The amount of organic carbon stored in soil with different geomorphic characteristics is different. If peatland is flooded, it can store a large amount of organic carbon, which can be gradually decomposed into GHGs and discharged into the atmosphere for a long time. Therefore, the GHGs released by reservoirs inundated with peat land will be more than those built on forest highlands and canyons with thin soil layer or no peat sediments (St. Louis et al., 2000). Secondly, cleaning activities (removing vegetation cover and fertile topsoil) before reservoir impoundment should be carried out, which can not only prevent the deterioration of water quality after impoundment, but also reduce the release of GHGs (Chen et al., 2011; Yang et al., 2014). Furthermore, a minor change in the dam design can significantly reduce the carbon footprints of the reservoir, such as elevating the water withdrawal depth, which can be taken into account in reservoir construction (Soued and Prairie, 2020). Besides, eutrophication is an important driving factor for methane emissions from lentic water bodies. Research showed that enhanced eutrophication of lakes and reservoirs will significantly increase CH_4 emissions from these systems (+30%–90%) in the next century (Beaulieu et al., 2019). Notably, the damage of GHG emissions caused by eutrophication is great in economic costs (Downing et al., 2021). As a result, more attention should be paid to improving watershed management to reduce the eutrophication sources (Hu and Cheng, 2013; Deemer et al., 2016), which is not only necessary to mitigate water quality deterioration, harmful algal blooms and fish deaths, but also to weaken the role of reservoirs as GHG factories (Hu and Cheng, 2013; de Sousa Brandao et al., 2019; Zhang et al., 2022a), and is beneficial for global economic implications (Downing et al., 2021). What's more, in China's reservoirs, the growth of phytoplankton and the production of planktonic bacteria are often limited by phosphorus, and priority control of phosphorus input is required to manage GHG emissions from hydropower reservoirs. Finally, research showed that the operation modes of the reservoir have a great impact on the methane ebullition fluxes (Fernandez et al., 2020), so it is important for policymakers to find a compromise between power generation and GHG emissions from hydropower reservoirs.

6 Conclusion

Scientometric analysis on GHG emissions from hydropower reservoirs was conducted in this paper. The publication data showed strong growth trend in researchers' outputs from 1993 to 2021, which indicated that this field gradually attracted global researchers' concern, especially over the last decade. China was the most productive country, followed by Brazil, Canada, the United States and France. Besides, the Chinese Academy of Science was the most productive and influential institution. Research on GHG emissions from hydropower reservoirs is interdisciplinary, and "Environmental Sciences and Ecology" and "Environmental Sciences" were the most active disciplines. "Greenhouse gas emissions from reservoir water Surfaces: A new global synthesis" published by Deemer et al. (2016) in *Bioscience* was a citation hotspot in the database, demonstrating that this publication laid a solid foundation for the development of this field. The research hotspots in this field mainly focused on CO_2, CH_4, N_2O emissions, and their temporal and spatial variations. The frontiers included research on the Three Gorges Reservoir, bubble-mediated gas exchange, GHG emissions from different interfaces of reservoirs and gas transfer velocity. Among them, according to the burst periods of keywords, the first three research are emerging trends in the research field.

Although great progress has been made in the field, there were still some research challenges. Future research should focus on strengthening the application of remote sensing to make up for the deficiency of traditional *in-situ* monitoring. It is of great necessity to enhance life cycle assessment on carbon emissions from hydropower for clarifying the clean property of hydropower, especially GHG emissions from reservoir sediments in the dam decommission and river restoration period. The standardization research on measurement methods for GHG emissions from reservoirs should be strengthened to reduce uncertainties, including *in situ* sampling and model simulation. In addition, the anthropogenic impacts on GHG emissions from hydropower reservoirs should be further studied to explore reservoir carbon cycle mechanisms in the changing environment. What's more, strengthening international cooperation and database construction is conducive to the depth and breadth of research in this field and the compilation of global GHG emission inventories. Finally, several mitigation measures are proposed to provide useful insight into the management and control of GHG emissions, including dam site selection and design, cleaning activities before reservoir impoundment, reservoir operation modes and eutrophication management, especially phosphorus control.

Author contributions

YA: Methodology, Formal analysis, Writing-Original draft preparation; TH, CD, DH, and YG: Writing-Review and Editing; HC: Conceptualization and Supervision.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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