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Evolution of water–energy–food–climate study: current status and future prospects

Yuanchun Zhou*, Bin Wei, Ran Zhang and Hui Li
Green Economy Development Institute, School of Economics, Nanjing University of Finance and Economics, Nanjing 210023, China
*Corresponding author. E-mail: zhouych11@163.com

YZ, 0000-0001-6646-9352

ABSTRACT

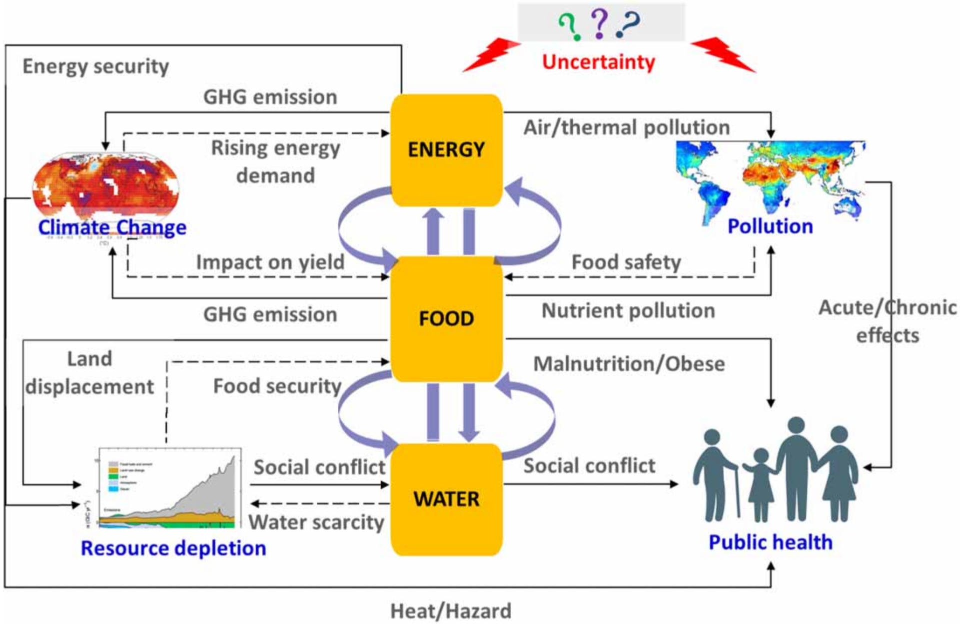
The relationship between changing climate and the three sectors of water, energy and food is increasingly drawing attention today while all of them are vital for sustainable development. This paper undertakes a bibliometric analysis of 1,959 published articles from 2010 to 2020 to provide a knowledge base of current nexus studies. The main research power, knowledge domains, evolution trends and frontier hotspots are analyzed. The main conclusions are as follows: (1) The USA, China and England contributed most in this field. *Applied Energy* published most articles. (2) The knowledge domains of nexus studies mainly focus on the combination of qualitative and quantitative methods to analyze the mutual consumption of resources, the impact of environmental changes on resources, policy formulation and implementation and so on. Besides direct interlink evaluation, other synergistic impacts should also be considered from the macro and microscale. (3) The evolution trend in this field has changed from the conceptual framework to management policy, risk security and optimal management: from knowing to taking actions. (4) The current hot points of this field are climate change and uncertainty. This study presents an in-depth analysis of water, energy, food and climate nexus research to inform more potential studies in this field.

Key words: bibliometrics, nexus study, sustainable development, uncertainty, water–energy–food–climate

HIGHLIGHTS

- Nexus needs to be considered in a global and systematic way.
- Optimal resource management, policy formulation and implementation are the main topics.
- Climate change and uncertainty are the major issues concerned by nexus.
- Other synergistic impacts should also be considered in the nexus study.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water, energy and food are all facing severe challenges today, but their availability is essential to the sustainable development of humankind (FAO *et al.* 2019). Unfortunately, extreme weather caused by climate change has exacerbated the scarcity problem in some areas, whereas the melting of glaciers has led to a rise in sea levels and a reduction in the area of inhabitable land (WWAP 2019). One of the causes of the above crisis is the consumption of fossil fuels. On the one hand, the production and consumption of fossil fuels will reduce the stock of and pollute water resources (Jin *et al.* 2019). On the other hand, the use of fossil fuels will emit a large amount of greenhouse gases and aggravate climate change. In the long run, a vicious circle will emerge. Due to the influence of water resources and climate, the food output of the agricultural sector will certainly not be able to meet the demand of the rapidly increasing population (Yildiz 2019). According to World Economic Forum's assessment, the top-five long-term risks in terms of likelihood are all climate-related, such as water crises and extreme weather (World Economic Forum 2019). Therefore, it is really urgent to address climate change and ensure the security of the water, energy and food sectors. In this context, a better understanding of the complex relationship between water, energy, food and climate was emphasized which can support the new contemporary paradigm 'nexus approach' for natural resources management (Hoff *et al.* 2019; Hogeboom *et al.* 2021).

The nexus between water and energy has been studied for a long time. For example, Malik (2002) studied the nature of the interaction between water and energy in India in earlier times. In the following years, increasing numbers of people began to pay attention to the complexity and extensiveness of the water–energy relationship, and the scale of research also showed a trend of diversification (Kahrl & Roland-Holst 2008; Eichelberger 2010; Keskinen *et al.* 2015). In the 21st century, the explosive growth of the population has not only increased the pressure on supply of water and energy but also increased the demand for food (Kansoh *et al.* 2020; Tsanov *et al.* 2020). The Bonn 2011 Nexus Conference brought the study of the water–energy–food nexus to a new stage. A large number of studies have begun to explore the concept and framework of the water–energy–food nexus (Leung Pah Hang *et al.* 2017; Zeng *et al.* 2017), as well as the optimal management and policy effects among the three sectors in different areas (Lucia *et al.* 2016; Artioli *et al.* 2017; de Andrade Guerra *et al.* 2021). In recent years, as greenhouse gases emitted by human activities aggravate climate change, more various natural disasters and public health events were observed (Burgan & Aksoy 2018; Mercado Burciaga *et al.* 2019). Increasing numbers of scholars have noted that climate change will have a knock-on impact on the water, energy and food sectors (Mpandeli *et al.* 2018; Memarzadeh *et al.* 2019; Sridharan *et al.* 2019). Currently, the research on the 'water–energy–food–climate nexus' has become one of the most popular topics and a large number of studies have been carried out.

Several articles have reviewed the nexus study from different aspects, different scales and different phases to show the developments and trends, but more work is still needed. For instance, some of the studies had small sample sizes and strong subjectivity in the screening process (Hamiche *et al.* 2016; Mpandeli *et al.* 2018; de Andrade Guerra *et al.* 2021); the research content has been limited, and only the research methods or models have been summarized (Mannan *et al.* 2018; Zhang *et al.* 2018; Urbinatt *et al.* 2020); the research object has also been limited to some content and the retrieval time is obsolete (Chen *et al.* 2019a; Hameed *et al.* 2019). Hence, some questions still need to be answered, such as: Which countries and institutions are more active in this field? What are the categories characteristics of research in this field? What is the knowledge base, research hotspots, cutting-edge topics and how did they evolve over time? Answering these questions will contribute to a comprehensive understanding of the development course and current status of climate–water–energy–food nexus study, which can provide valuable guidance for future research.

For traditional review, methods are difficult to quantitatively analyze and visually demonstrate data of large samples, bibliometric analysis allows scientific statistical and content analysis of literature data from a large sample and an intuitive display of it using visualization techniques. It was also used for a comprehensive review in different fields, such as medicine application (Yang *et al.* 2019), shared bicycles (Si *et al.* 2019), green energy and environmental technologies (HaoTan *et al.* 2021), but less used in the nexus study, especially for the 'water–energy–food–climate' nexus study (Opejin *et al.* 2020; Fan *et al.* 2021). Therefore, a bibliometric analysis is conducted in this study to gain a comprehensive understanding of key themes and future research directions, including 'water–energy', 'water–energy–food' and 'water–energy–food–climate'.

The rest of the paper is organized as follows (see Figure 1): Section 2 will elaborate the research methods, data collection as well as the processing process; Section 3 will present the results of bibliometric analysis, a detailed analysis of journals, countries, categories as well as keywords is visualized; based on the clustering results, Section 4 develops a discussion based on the results of the literature analysis; finally, conclusions and suggestions for future directions are provided in Section 5.

2. DATA SOURCE AND METHODS

2.1. Data source

Web of Science (WoS) is one of the main databases for obtaining global academic information, which covers nearly 9,000 of the most famous high-impact research journals (Zhao 2017). In light of the extensiveness and influence of the WoS database, many scholars use it as a data source in bibliometric analysis, such as Si *et al.* (2019), who analyzed the development of

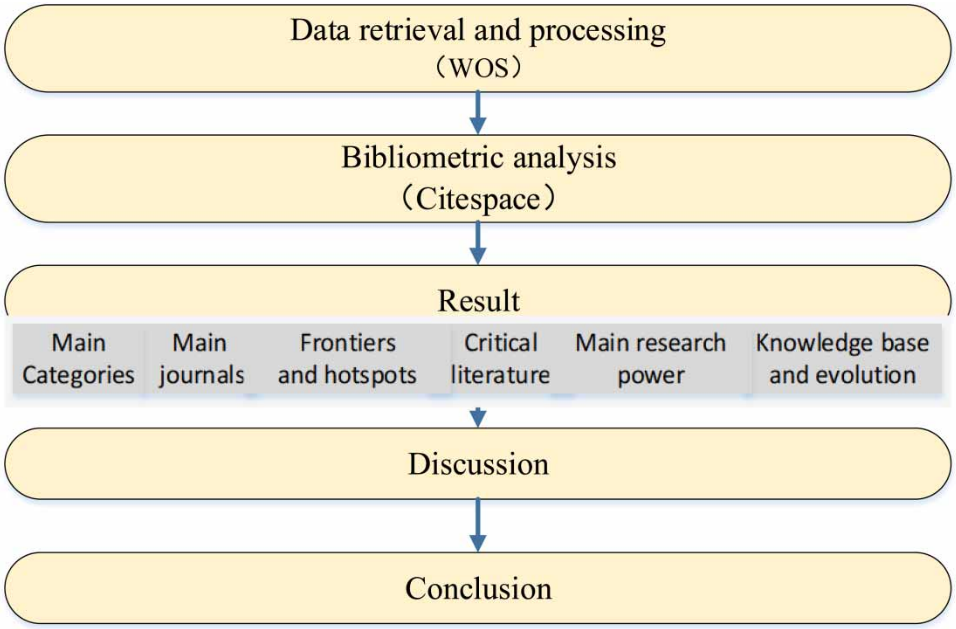


Figure 1 | Research flowchart of this study.

shared bicycles; Li *et al.* (2020), who undertook a visual analysis of global green buildings; and Huang *et al.* (2020), who depicted the theme of forest carbon sinks. All of the literature data in this paper come from the core data set from Web of Science.

Through the advanced retrieval function of WoS, this paper uses TS = ('water–energy nexus' OR 'energy–water–food nexus' OR 'water–energy–food–climate nexus') as the keyword in the core data set and sets the time range from 1985 to 2020. A total of 1,985 articles are retrieved, and a total of 1,959 valid literature data are obtained as data source for this study, after manually excluding irrelevant papers, conferences, news and announcements.

2.2. Research methods

2.2.1. Bibliometrics

Bibliometric analysis is a visualization method based on text data. By extracting the fields of author, country, keywords and references, it can systematically analyze the cooperative relationships, topics and hotspots in the field of knowledge (Chen 2004, 2012; Chen *et al.* 2009). Currently, much software has been developed to assist bibliometric analysis, like VOSviewer, BibExcel, Ucinet and so on. However, VOSviewer mainly focuses on the visualization of bibliometrics and cannot construct any kind of co-occurrence matrix (van Eck & Waltman 2010), whereas Ucinet and BibExcel can build a variety of co-occurrence matrices, but they do not provide sufficient visualization tools, and the operation steps are complex (Yang *et al.* 2019). In comparison, CiteSpace can provide more precise analytic functions we need and is easy to operate (Cobo *et al.* 2011). Therefore, CiteSpace V was used in this study to visually analyze the content of the related research that we collected from WoS.

2.2.2. Betweenness centrality

Betweenness centrality (BC) is an index measuring the importance of nodes in the network, which is often used in the co-citation network to find some important literature. This literature usually has a high BC (equal to or greater than 0.1) and includes the key hubs connecting two different fields (Chen *et al.* 2009). The calculation formula was introduced by Freeman in 1977, and the details are as follows:

$$BC_i = \sum_{s \neq i \neq j} \frac{n_{st}^i}{g_{st}}$$

In this formula, g_{st} is the number of shortest paths from node s to node t, and n_{st}^i is the number of shortest paths through node i among the g_{st} shortest paths from node s to node t (Freeman 1977, 1978).

3. RESULTS

3.1. Descriptive analysis

As shown in the lower left corner of Figure 2, the retrieved literature only began to appear after 2002. From 2002 to 2010, the growth rate was slow, and the field was in its infancy. After 2010, the number of documents began to increase significantly, especially in 2014–2015 and 2017–2019, and the growth rates reached 116 and 135%, respectively, and still showed an upward trend. To ensure the continuity and focus of the research, 1,950 articles from 2010 to 2020 are selected for follow-up bibliometric analysis.

3.2. Published journals

Based on WoS, the selected 1,950 articles were published in 321 journals. The top 16 journals, publishing more than 1% of the papers, are listed in Table 1, whereas the total number of articles published in these 16 journals accounted for 43.44% of the 1,950 articles. *Applied Energy* ranked first with a total of 101 articles in this field, followed by the *Journal of Cleaner Production* (78), *Water* (60), *Science of The Total Environment* (50) and *Sustainability* (48). The top five journals account for 23.14% of the total. In addition, from the disciplines involved in the journal, it can be found that the nexus research is mainly focused on the discipline of 'energy and environment', and it can be refined to the related policies, management, technology, sustainable development and other aspects.

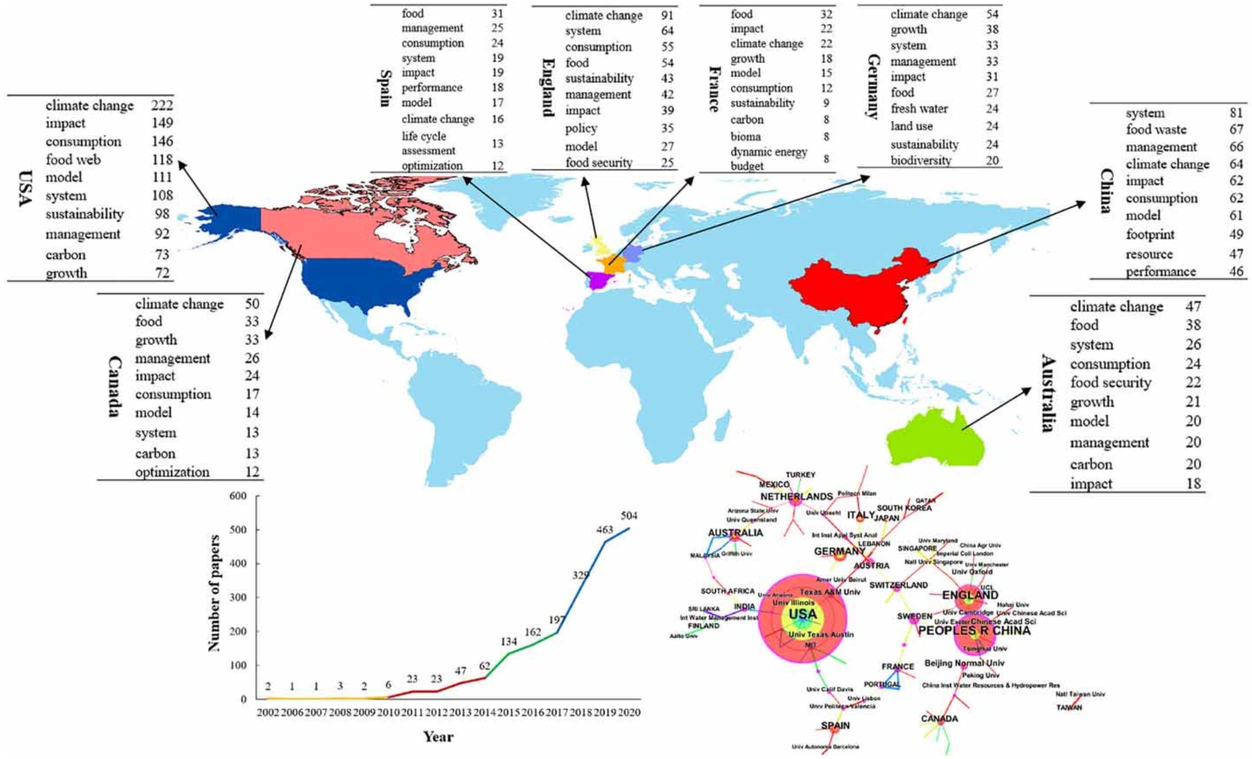


Figure 2 | Annual number of articles, national–institutional cooperation and main keywords of countries.

3.3. Categories analysis

Table 2 lists the top ten categories for the output of articles in this field, which are divided into three stages according to the trend of publication. First, in terms of the whole timeline, *Environmental Sciences & Ecology* (15.1%), *Environmental*

Table 1 | Major journals in the field of nexus research (2010–2020)

No.	Journal Name	Number	%
1	*Applied Energy*	101	6.94
2	*Journal of Cleaner Production*	78	5.36
3	*Water*	60	4.12
4	*Science of The Total Environment*	50	3.43
5	*Sustainability*	48	3.29
6	*Environmental Research Letters*	46	3.16
7	*Energy*	35	2.40
8	*Energy Policy*	35	2.40
9	*International Journal of Water Resources Development*	28	1.92
10	*Environmental Science Policy*	27	1.85
11	*Environmental Science Technology*	27	1.85
12	*Frontiers in Environmental Science*	23	1.58
13	*Resources Conservation and Recycling*	23	1.58
14	*Energy Conversion and Management*	19	1.30
15	*Water International*	17	1.16
16	*Journal of Environmental Management*	16	1.10

Table 2 | Major categories in the field of nexus research (2010–2020)

Categories	BC	2010–2013	2014–2016	2017–2020	Total
Environmental Sciences & Ecology	0.75	49	143	455	647
Environmental Sciences	0.75	41	125	407	573
Engineering	0.47	39	130	321	490
Water Resources	0.11	33	108	174	315
Energy & Fuels	0.21	17	69	201	287
Science & Technology – Other Topics	0.11	6	53	187	246
Green & Sustainable Science & Technology	0.16	5	44	174	223
Engineering, Environmental	0.67	17	50	154	221
Engineering, Chemical	0.06	8	37	128	173
Environmental Studies	0.93	17	41	107	165

Sciences (13.4%) and *Engineering* (11.2%) are the top three categories, accounting for 39.7% of the total. The last seven are in order: *Water Resources* (7.4%); *Energy & Fuels* (6.7%); *Science & Technology-Other Topics* (5.8%); *Green & Sustainable Science & Technology* (5.2%); *Engineering, Environmental* (5.2%); *Engineering, Chemical* (4.1%) and *Environmental Studies* (3.9%). Second, for each period, the number of articles in the top ten categories has increased significantly over the past decade, especially in the third period. Thus, research in this field has gradually shown the phenomenon of interdisciplinarity, and the growth momentum of some mixed categories (*Green & Sustainable Science & Technology*) has exceeded that of a single category (*Environmental Studies*).

Category co-occurrence is a visual analysis of the cross-relationships between categories. By building a network, the phenomenon of cross-penetration between them can be outlined. The network has a total of 70 nodes and 121 links, and the main part of it was selected to display.

As seen from Figure 3, the two branches under *Environmental Sciences & Ecology* form a cross network. The first branch, *Environmental Studies*, is mainly cross-linked with *Economics, Business & Economics*, *Energy & Fuels, Agronomy*, *Thermodynamics* and so on. The second branch is *Environmental Sciences*, which is directly related to *Meteorology & Atmospheric Sciences and Engineering, Environmental*. Those indirectly related to it are mainly *Geosciences*, *Multidisciplinary*, *Geology*, *Green & Sustainable Science & Technology* and so on. The results of the above picture reflect that it requires the joint efforts of multidisciplinary people to address climate change and resolve the crisis of water, energy and food.

3.4. Countries' and institutions' cooperation

Cooperation networks between countries and institutions can reflect the distribution of research power in this field. The lower right corner of Figure 2 shows the cooperative contribution network of countries and institutions in this field. There are 132 nodes and 155 links in the network. The size of the nodes represents the number of articles published by countries or institutions, and links between nodes represent the cooperative relationships between countries and institutions. As seen in the figure, countries that have contributed most to this field in the past decade are the USA (542 articles, 39.3%), China (247, 17.9%), England (181, 13.1%), Germany (96, 7.0%) and Spain (76, 5.5%).

At the same time, many institutions have made great achievements in the field of nexus research (see Table 3), such as Beijing Normal University (40), Texas A&M University (30), Chinese Academy of Sciences (29), the University of Illinois (26), the University of Texas at Austin (24), Oxford University (23), Massachusetts Institute of Technology (20), Peking University (18), Tsinghua University (18) and the University of Cambridge (17). Of these ten institutions, four are in the USA, four are in China and two are in England.

Finally, based on the upper part of Figure 2, high-frequency keywords studied by countries in this field are similar. Most of them are 'climate change, consumption, food, impact, policy, management, system, model, carbon' and so on.

3.5. Co-citation analysis of literature

Literature co-citation refers to the phenomenon that two references are cited by the same document (Small 1973). Based on key nodes in the literature co-citation network, the important literature and knowledge bases in a certain research field can be

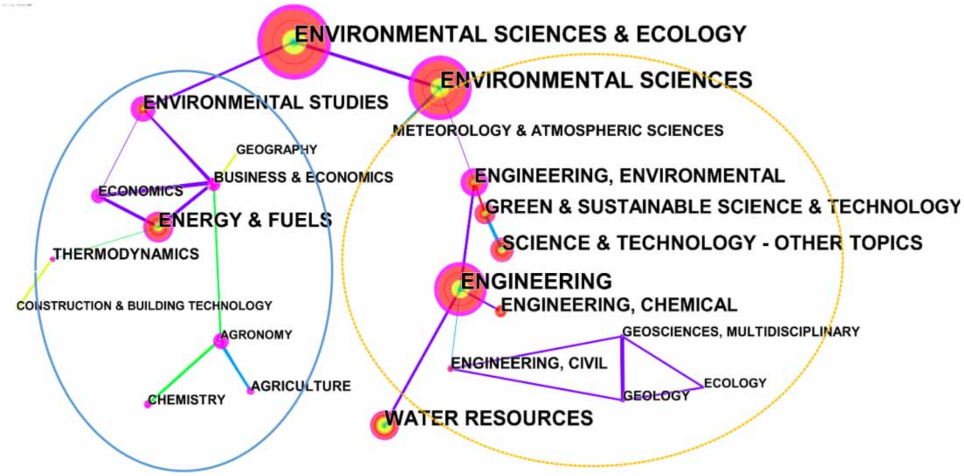


Figure 3 | Categories co-occurrence network (2010–2020).

Table 3 | Major countries and institutions in the field of nexus research (2010–2020)

Frequency	**BC**	**Year**	**Country**	**Frequency**	**BC**	**Year**	**Institution**
542	0.52	2010	USA	40	0.23	2016	Beijing Normal University
247	0.77	2012	People's R China	30	0.23	2018	Texas A&M University
181	0.38	2012	England	29	0.03	2016	Chinese Academy of Sciences
96	0.05	2014	Germany	26	0	2016	University of Illinois
76	0.08	2012	Spain	24	0	2011	University of Texas at Austin
75	0.27	2011	Australia	23	0.04	2014	Oxford University
72	0.44	2015	Netherlands	20	0.43	2013	Massachusetts Institute of Technology
69	0.05	2013	Italy	18	0.03	2013	Peking University
53	0.16	2014	Canada	18	0	2013	Tsinghua University
38	0.48	2016	Austria	17	0	2015	University of Cambridge

learned. Figure 4 shows the total cited network of 1,950 articles selected in this paper, with a total of 277 nodes and 744 links. Each node acts for a cited document, and the link between nodes stands for the co-citation relationship. The link color corresponds to color of time slice, indicating the reference relationship at different times. In addition, the larger the number of nodes in the graph is, the greater the cited frequency of the literature, showing that it is well recognized in this field. When the cited frequency is larger, the higher the BC is (equal to or greater than 0.1); thus, the node is an important hub of the network, and its corresponding literature is also of great significance (Chen *et al.* 2012).

Based on the statistical results of CiteSpace, Table 4 lists the ten most cited articles. These studies laid part of the knowledge basis of the nexus research. A total of 1,950 references were analyzed by the cited network. Bazilian *et al.* (2011) had the highest citation frequency. This paper introduced a systematic framework model to analyze the complex relationship among 'water, energy and food'. This article was published in 2011, just in the initial stage of the surge of achievements in this field. Siddiqi & Anadon (2011) was the second most frequently cited, and it analyzed the water intensity of energy production and the energy consumption intensity in the water price chain of countries in the Middle East and North Africa. Different from Siddiqi & Anadon (2011), Scott *et al.* (2011) further elaborated that the relationship between water and energy exists not only in a single region or country, and they pointed out that, when formulating policies and establishing management mechanisms, it is more important to consider cross-regional resource coupling.

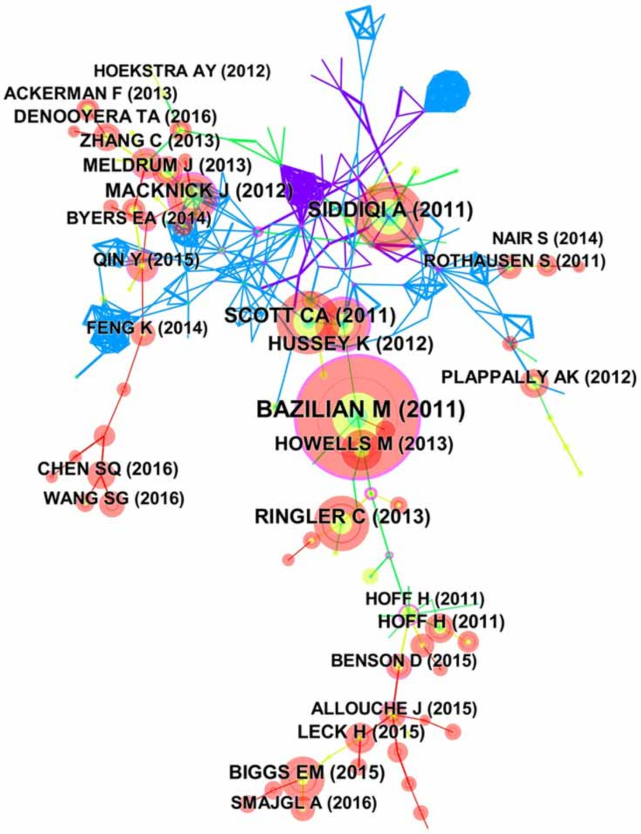


Figure 4 | Literature co-citation network (2010–2020).

Table 4 | 10 Articles with the highest numbers of citations in the field of nexus study

Author & Year	Title	Journal	BC	Frequency
Bazilian *et al.* (2011)	Considering the energy, water and food nexus: Towards an integrated modeling approach	*Energy Policy*	0.48	208
Siddiqi & Anadon (2011)	The water–energy nexus in Middle East and North Africa	*Energy Policy*	0.1	124
Scott *et al.* (2011)	Policy and institutional dimensions of the water–energy nexus	*Energy Policy*	0.03	113
Ringler *et al.* (2013)	The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency?	*Current Opinion in Environmental Sustainability*	0.04	99
Hussey & Pittock (2012)	The energy–water nexus: managing the links between energy and water for a sustainable future	*Ecology and Society*	0.49	89
Macknick *et al.* (2012)	Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature	*Environmental Research Letters*	0.26	83
Biggs *et al.* (2015)	Sustainable development and the water–energy–food nexus: A perspective on livelihoods	*Environmental Science & Policy*	0.04	77
Howells *et al.* (2013)	Integrated analysis of climate change, land-use, energy and water strategies	*Nature Climate Change*	0.03	75
Leck *et al.* (2015)	Tracing the water–energy–food nexus: description, theory and practice	*Geography Compass*	0.08	55
Meldrum *et al.* (2013)	Life cycle water use for electricity generation: a review and harmonization of literature estimates	*Environmental Research Letters*	0	55

The above three articles introduced the connotation of the 'water–energy nexus', which extends to related policy making and resource management, so it is cited more frequently. The other seven articles focus on the gradual expansion of the nexus on the basis of 'water–energy', such as 'water–energy–food' (Biggs *et al.* 2015), 'water–energy–land–food' (Ringler *et al.* 2013) and 'water–energy–land–climate' (Howells *et al.* 2013), and they explore the impact of these nexuses on sustainable development. All of the above articles emphasize the need to evaluate these nexuses with globalization and systematic thinking, and they believe that nexus study plays a key role in the sustainable development of human beings.

It is worth noting that, among the ten highly cited studies, four have a BC equal to or greater than 0.1. Among them, Bazilian *et al.* (2011) and Hussey & Pittock (2012) reached 0.48 and 0.49, respectively. As seen from the picture, they are all in the center of dense connections, which also shows that they are important hubs of the network, while Chinese scholars have fewer highly cited papers, although they are the second-largest research body in this field.

3.6. Keyword analysis

Keywords are the core generalizations of an article, and co-occurrence analysis can examine the research topics in this field. As shown in Figure 5, there are 110 keywords in the cloud map. The larger that the font of the keywords is, the more times they appear. In the picture, affected by the search words, 'nexus' has the highest frequency. 'Consumption' indicates that 'nexus' includes the quantitative relationship between mutual utilization and the consumption of resources. For example, Zhang & Anadon (2013) used the multiregional input–output model to analyze life-cycle water consumption and its environmental impact on energy production in China. Wang & Chen (2016) integrated the input–output table and ecological network to study the interwoven connections of energy consumption and water use for urban agglomerations.

In addition, through high-frequency keywords such as 'climate change', 'energy', 'impact' and 'water', it can be seen that this 'nexus' also includes the implicit relationship of resources with social economy, technology and natural environment. That is, the use of energy and water or the relationship between them will have a certain impact on socioeconomic, technology and climate changes. For example, Wang *et al.* (2012) used survey data from villages in 11 provinces to estimate the amount of greenhouse gas emitted by China when pumping groundwater for irrigated agricultural production, and they pointed out that it is possible to improve irrigation techniques to save water, improve energy efficiency and ultimately improve the climate and environment. Finally, 'system', 'management' and 'policy' could indicate the need for a complete system or a higher level of policy formulation in the management of the 'nexus' (Siddiqi *et al.* 2013; Rasul & Sharma 2015; DeNooyer *et al.* 2016).

The keyword co-occurrence network can represent knowledge domains; after adding the time factor on this basis, the changes in keywords with time can be seen. Figure 6 shows the keyword time zone map with a frequency greater than 5

Figure 5 | Cloud map of keywords in the field of nexus research (2010–2020).

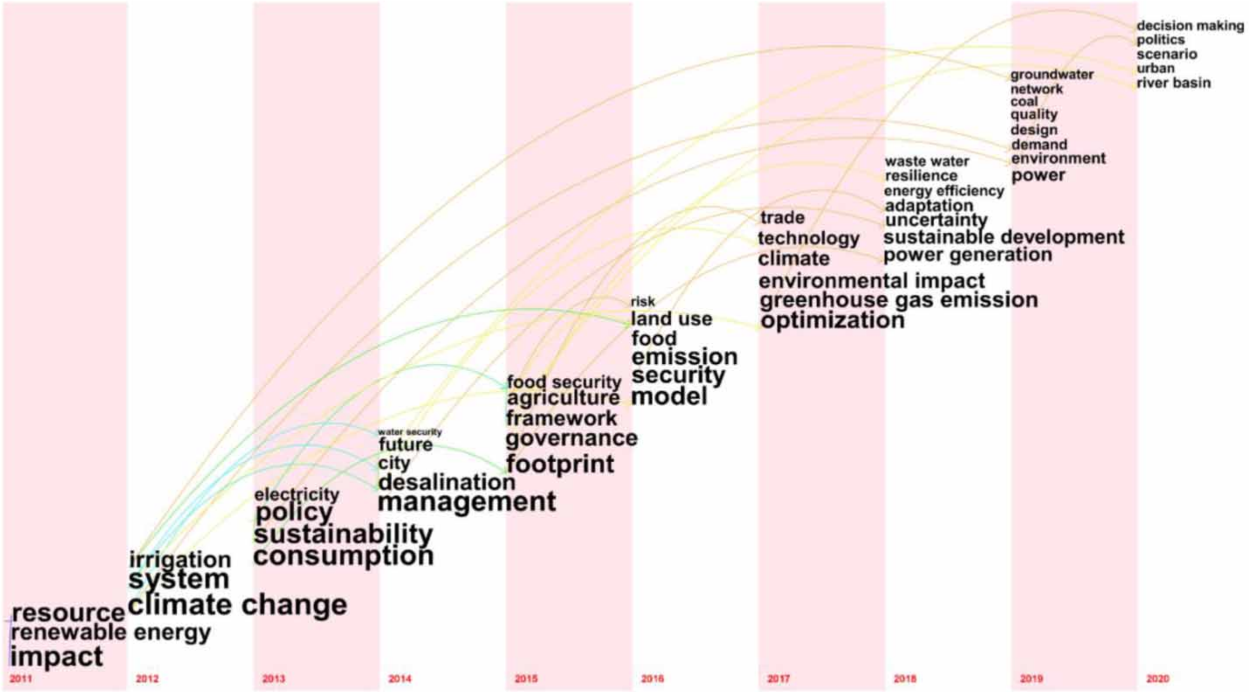


Figure 6 | Keyword time zone map in nexus research field (2010–2020).

from 2010 to 2020. Each keyword in the picture is arranged in each time bar according to the time when it first appeared, showing the evolution trends of keywords and the inheritance relationship between them. As shown in the figure, the fonts of keywords that appeared between 2010 and 2014 were significantly larger than those in other years, denoting that these keywords were more studied then. As time goes by, the number of keywords also gradually increases, especially from 2018 to 2020, indicating that the research in this field has received extensive attention in recent years, and the research content has been expanded and enriched.

It must be explained that, due to there being less literature in 2010 and the frequency of keywords in the literature being less than 5, there are no keywords in Figure 6 in 2010. The keywords that appeared from 2011 to 2013 are: 'impact', 'renewable energy', 'climate change', 'system', 'consumption', 'policy' and so on, mainly focusing on the changes of nexus research and external influences. New keywords emerged from 2014 to 2016, including 'management', 'governance', 'framework', 'model', 'security', 'footprint', 'food', 'risk' and so on. Security and risk of resources and food attracted more attention. Additionally, quantitative analysis and corresponding management research have been conducted. With the continuous increase in the population, the overuse of resources and the change of climate in recent years, research in this field has tended to optimize the use of resources ('optimization', 'trade', 'adaption') and pay more attention to the environment ('environmental impact', 'greenhouse gas emission', 'uncertainty', 'resilience', etc.). In addition, technological progress can improve the efficiency of the use of resources, which is one of the necessary conditions for sustainable development, so it has received sufficient attention in recent years ('technology', 'sustainable development', 'waste water', 'energy efficiency', etc.). In summary, Figure 6 roughly presents the research progress in this field.

3.7. Keyword cluster analysis

Although the above analyzes the main research content and evolution trends of the nexus research through keyword co-occurrence and time zone maps, there are no clear descriptions of the topic context in this field. Keyword cluster analysis can help to solve this problem (Wilks 2011). Based on keyword co-occurrence networks, it gathers closely related keywords together into a relatively small group and then analyzes and identifies the topics, contents and internal relationships of a certain research field.

In this study, the keywords of 1,950 cited papers are clustered by the CiteSpace V cluster function, and 9 cluster modules with clear boundaries are obtained. As shown in Figure 7, according to the built-in algorithm of the software, the smaller the

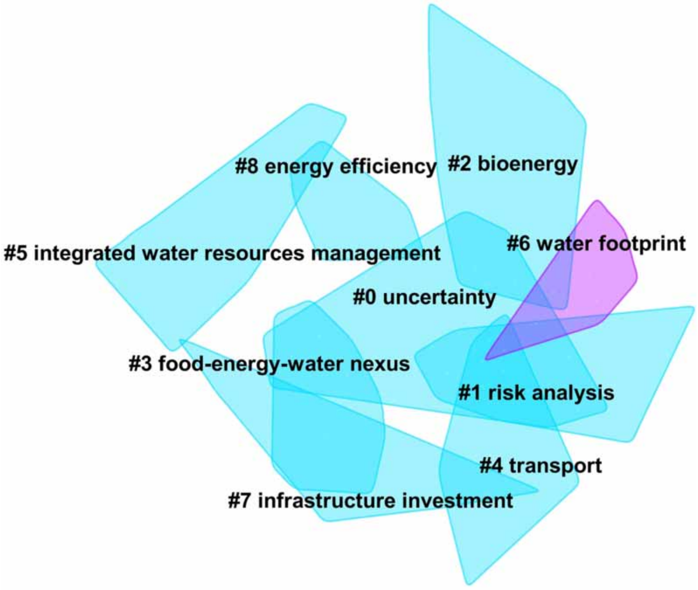


Figure 7 | Cluster analysis in nexus research fields (2010–2020).

cluster number is, the larger the cluster module is. The largest cluster is #0, and the smallest cluster is #8. In addition, the Modularity $Q = 0.7317$ (>0.3) in the clustering parameters indicates that the clustering structure is significant. Mean silhouette value is used to measure the homogeneity of the network. When it is greater than 0.5, it can be concluded that the internal homogeneity of the cluster is better. Here, $S = 0.9133$, indicating that the clustering result has high reliability (Chen *et al.* 2010).

Table 5 arranges the details of the cluster according to the cluster number from small to large. The silhouette value of each cluster is greater than 0.8, indicating that there is a strong relationship between the keywords within each cluster. Among them, the two largest clusters (#0 uncertainty and #1 risk analysis) represent the study of risk problems under many uncertain factors. Their main labels are future, elasticity, climate change adaptation and so on. In addition, cluster #3 (water–energy–food nexus) is one of the search words, and its main keywords are the main research content of it.

The purpose of the nexus is to comprehensively manage resources, to achieve the rational allocation of them and to reduce the pressure on the use of resources to achieve sustainable development (Hussey & Pittock 2012; Biggs *et al.* 2015). Clustering #2 (bioenergy), #4 (transport), #5 (integrated water resources management) and #7 (infrastructure investment) shows that

Table 5 | Keyword cluster details in the field of nexus research

No.	Cluster labels	Size	Silhouette	Cluster content
#0	uncertainty	16	0.872	future, resilience, irrigation
#1	risk analysis	14	0.896	perspective, climate change adaptation, transformative research
#2	bioenergy	13	0.921	sensitivity analysis, global warming potential, eco-efficiency analysis
#3	food–energy–water nexus	13	0.905	scarcity, scenario, life-cycle assessment
#4	transport	13	0.885	reuse, dietary patterns, water heating, water–energy nexus
#5	integrated water resources management	11	0.936	energy security, water security, groundwater, food–water–energy nexus
#6	water footprint	11	0.981	sustainable urban system, energy supply, input–output model, decision-making
#7	infrastructure investment	10	0.923	water program, Mediterranean Spain, common agricultural policy
#8	energy efficiency	9	0.899	renewable energy, water–energy nexus

academia has undertaken corresponding research for the above purposes. For example, Gheewala *et al.* (2011) pointed out that the future development of bioenergy should consider the use of freshwater to solve trade-off questions between climate change and water. Plappally & Lienhard (2012) assessed the relationship between the cost of treating water through specific treatment schemes and the amount of water, pointing out that, compared with sewage treatment and traditional water treatment and supply, the cost of transporting water by vehicles is enormous.

In addition, clusters #6 (water footprint) and #8 (energy efficiency) reflect the methods in nexus research and other related contents. According to their main keywords, 'sustainable urban system', 'energy supply', 'input–output analysis', 'renewable energy' and so on, it can be seen those quantitative methods play an important role in nexus research. For example, Zhang & Anadon (2014) quantified the scale and structure of China's provincial virtual water trade and consumption-based water footprint using a multiregional input–output model.

3.8. Keyword bursts analysis

Keyword bursts refer to the sharp increases in the frequency of keywords in a certain time range. The sudden occurrence of keywords indicates that the subject of a certain study has been or is attracting the attention of researchers. Therefore, burst analysis can be used to detect emerging research hotspots and trends.

Table 6 lists the keywords that emerged from 2016 to 2020, mainly as follows: 'Design, food, resilience, environment, recovery, biodiversity, input–output analysis, irrigation, cycle, carbon dioxide emissions and uncertainty'. Thus, it can be seen that, in recent years, the focus of research in this field has been to analyze the relationships among water, energy, food and climate and their impact on ecological environment through qualitative methods, such as conceptual model framework design, and quantitative methods, such as input–output analysis. The frontier of the research is to analyze the impact of changes in the climate and environment on human society under uncertain conditions and to manage the risks of climate change in the three sectors through the integrated management of nexus chains.

4. DISCUSSION

The nexus chain has been studied for a long time, and as the content of the nexus is gradually expanding after years of development, more components are incorporated (see Figure 8). Due to changing climate, complex human activities, regional relations and other uncertainties, the current research has some limitations; most of the research objects are only related to part of the nexus chain. It could be useful to provide an overall description of the development trends and content of nexus research. Therefore, the following are further discussed based on the results of the bibliometric analysis above.

4.1. Developing trends

According to the results of the above keyword time zone map, the evolution trend of nexus study into three stages can roughly be divided. From 2010 to 2013, the impact of external environmental changes and the conceptual framework of the nexus

Table 6 | Frontier hot words in recent 5 years

Keywords	**Strength**	**Begin**	**End**	**Burst duration**
Design	4.2238	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Food	3.3185	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Resilience	3.8003	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Environment	3.6803	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Recovery	3.2567	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Biodiversity	3.8003	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Input–output analysis	3.8003	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Cycle	3.8003	2016	2017	🟦🟦🟦🟦🟦🟦🟥🟥🟦🟦
Irrigation	3.1679	2016	2016	🟦🟦🟦🟦🟦🟦🟥🟦🟦🟦
CO_2 emission	3.4819	2018	2020	🟦🟦🟦🟦🟦🟦🟦🟦🟥🟥
Uncertainty	3.8004	2018	2020	🟦🟦🟦🟦🟦🟦🟦🟦🟥🟥

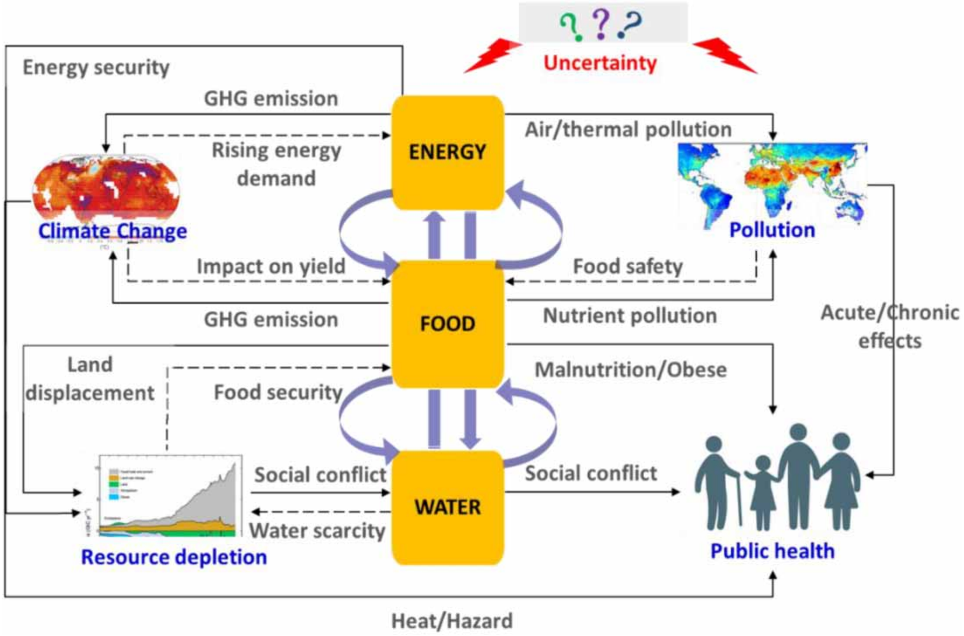


Figure 8 | Principal components of nexus framework.

chain obtained more attention. In the second stage, from 2014 to 2016, the focus shifted to water, energy and food security and risk issues. The main research of the third stage (2017–2020) deepened the theme of the first and second stages, responding to changes in the climate through the optimization of the use of resources. The trend may be illustrating people's 'from knowing to doing' process of WEF nexus. People have gradually recognized the importance and urgency of collaborative management; hence, more scientific studies were conducted to explore the physical linkage between water, energy and food. Then, based on the foundation, more management solutions were figured out and evaluated for security and risk issues.

From the relevant studies, the research scale begins to change from macro to micro, and there is increasing regional and basin analysis, rendering the content of nexus research richer and more accurate. In addition, advanced technology can alleviate the pressure on the water, energy and food sectors. For example, Richards *et al.* (2017) found the potential of a decentralized photovoltaic-driven membrane filtration system in providing drinking water, which can reduce energy consumption and alleviate the pressure of energy use. Research focuses also have changed gradually with more understanding about nexuses. For example, our study shows that 'climate change' appears frequently in the recent literature, whereas other studies show different results (Endo *et al.* 2015).

4.2. Knowledge domains

Obviously, in the part of the keyword cluster analysis, the results show a number of cross-cluster modules, but this classification cannot well reflect the knowledge field of association research. Combined with the cluster results and high-frequency keywords, this section undertakes a further division of the knowledge domains of nexus research.

4.2.1. Water–energy nexus

Clusters #4 (transport), #5 (integrated water resources management), #6 (water footprint) and #8 (energy efficiency) are common in the water–energy nexus, mainly showing the main research contents. ① Through water footprint, input–output analysis and other methods to quantify the mutual use of resources. For example, Chu *et al.* (2019) used a bottom-up method to quantitatively analyze water for energy and energy for water demand at the provincial level in China, and found the interdependence of resources among provinces from the point of view of the nexus; unlike some scholars who analyzed the water needed to produce energy from the perspective of production, Okadera *et al.* (2015) used the top-down input–output model to consider whether there is water to produce energy from the perspective of consumption, and they evaluated the water footprint of the energy supply in Liaoning Province. ② Combining scenario and model analysis to explore the water–energy relationship in power systems and energy efficiency in the process of transportation, as well as the treatment of pollution and related acute/chronic public health effects. For example, Ackerman & Fisher (2013) established four scenarios within the range of carbon prices and water prices (unconstrained, limited carbon prices, limited water prices, limited carbon prices and water prices), and they analyzed the water–energy nexus in the long-term planning of American electric power. ③ Exploring the impact of relevant policies on resource management and resource security. Alkon *et al.* (2019) used Pakistan as a case study to evaluate the impact of China's One Belt and One Road initiative on future energy production, water security and sustainability in Asia.

4.2.2. Water–energy–food nexus

The water–energy nexus does not exist alone in the social system; it is also closely linked to other sectors of the social system, especially the food sector. Since The Bonn 2011 Nexus Conference put forward the 'water–energy–food nexus', this nexus chain has also been widely examined by scholars worldwide. Combined with cluster content, clusters #2 (bioenergy), #3 (water–energy–food nexus) and #7 (infrastructure investment) are common in this relationship.

First, from the perspective of the research content, the focus of scholars' attention is mainly focused on two aspects. ① To explore the concept or framework of the 'water–energy–food association' in the context of resource scarcity and safety, Kattelus *et al.* (2014) concluded that the exploitation of natural resources in Myanmar affected the country's water, energy and food security, which should be balanced by the method of the 'water–energy–food nexus'; Jobbins *et al.* (2015) cited three cases of drip irrigation in Morocco to consider the relationship among water, energy and food from a bottom-up perspective. ② Optimize the allocation and management of resources by means of infrastructure investment and the development of bioenergy. For example, Artioli *et al.* (2017) believed that the urban infrastructure network supports the resource system and related management system, and the implementation of the 'water–energy–food nexus' through the smart city method can better balance the allocation of resources; Mirzabaev *et al.* (2015) reviewed the trade-off and synergy of bioenergy in the relationship among water, energy and food security, and they considered that the application of the nexus perspective to bioenergy analysis could result in a win-win situation.

Second, from the perspective of research methods or tools, the data can be divided into two categories: qualitative and quantitative. Qualitative research mainly includes case scenarios and framework construction, such as Kılkış & Kılkış (2017) and Leung Pah Hang *et al.* (2017). Quantitative analysis occurs mainly through tobit regression analysis (Chen *et al.* 2019b), network model construction (Vora *et al.* 2017), life-cycle analysis (Al-Ansari *et al.* 2015) and general equilibrium models (Ge *et al.* 2014) to quantify the relationship among 'water–energy–food'.

4.2.3. Water–energy–food–climate nexus

Clusters #0 (uncertainty) and #1 (risk analysis) are the two largest. With the world population increasing, demand from human society for water resources, energy and food is increasing inevitably. With increasing uncertainty (Sun *et al.* 2020; Yu *et al.* 2020), the water, energy and food sectors are all facing unprecedented risk problems. Climate change is one of the main problems. IPCC's special report indicates that IPCC (2018) risks across energy, food, and water sectors could overlap spatially and temporally, creating new while exacerbating current hazards, exposures and vulnerabilities. This view was further emphasized in IPCC's 6th Assessment Report (IPCC 2021). Many scholars have introduced climate factors into the nexus chain when studying the relationship among water, energy and food and then analyzed the water–energy–food–climate nexus. Combined with the existing studies, the current research is mainly focused on the analysis of the relationship between climate and the three sectors by evaluating the impact of climate change on water, energy and food. For example, Herrera-Estrada *et al.* (2018) used a multiple linear regression model to analyze the positive relationship between drought and the amount of energy used by the power sector in the United States, indicating that the use of a large amount of fossil energy would not be conducive to climate change mitigation. Berardy & Chester (2017) constructed a dynamic simulation model to assess the potential effects of rising temperatures and energy and water supply disruptions on crop irrigation demand, farm energy use and yields. Yang *et al.* (2016) used a hydroagricultural economic model to assess the multifaceted impact of a series of climate change scenarios on water, energy and food in the Indus Basin.

Generally, the above classification summarizes the main current situation of nexus research and deepens our understanding of the knowledge content of it. In this study, it is found that there is a cross-phenomenon in the content of nexus research, showing that, regardless of how the related content is expanded, it is necessary to balance the use of these resources with an integrated system framework. Compared with the reviews of Endo *et al.* (2015) and Chen *et al.* (2019a), this paper adds new

Table 7 | Comparison between this article and other similar reviews

References	Sample size	Time	Method	Main contents
Mannan *et al.* (2018)	79	2008–2017	Inductive summary	The different applications of life-cycle assessment method in energy–water–food nexus analysis were summarized.
Zhang *et al.* (2018)	161	2002–2018	Inductive summary	The concepts, research problems and research methods in the field of water–energy–food were reviewed.
Hamiche *et al.* (2016)	13	1996–2005	Inductive summary	The relationship between water and electricity was reviewed.
Albrecht *et al.* (2018)	245	2010–2017	Inductive summary	The research methods of water–energy–food were reviewed.
Chen *et al.* (2019)	380	2010–2017	Bibliometric analysis	The research contents and current situation of water–energy–food were reviewed.
Opejin *et al.* (2020)	257	2011–2018	Bibliometric analysis	The research contents of water–energy–food were reviewed.
Fan *et al.* (2021)	3077	1988–2019	Bibliometric analysis	The research contents of water–energy–food were reviewed.
This study	1959	2010–2020	Bibliometric analysis	The research content of water–energy–food–climate are comprehensively analyzed.

evidence supporting the content of nexus studies. At the same time, the main research countries, journals, and categories and important literature in nexus research are analyzed accordingly.

4.3. Comparative analysis

To better present the contribution of this study, Table 7 lists some WEF nexus review studies. These studies improved people's understandings of the WEF nexus study. However, it can be found that the bibliometric approach was less used to explore the nexus study, which can provide more detailed and comprehensive information compared to the inductive method. Compared to other studies, the sample size of this study was greatly increased, and a more comprehensive coverage of the ocular research content in the field was obtained. Time coverage was also updated accordingly, which is more indicative of changes in cutting-edge topics. For the review scale, climate change was barely included in the existing review articles, such as Fan *et al.* (2021) and Opejin *et al.* (2020), while it is a main element of nexus study today. Hence, this study provides a more comprehensive and updated analysis of the nexus study, which can inform potential research in the future.

5. CONCLUSION

Based on the bibliometric analysis, this paper reviewed the current situation of nexus research over the past decade. There have been many research achievements in the field of nexus study. After 2010, the research began to increase significantly, especially in 2014–2015 and 2017–2019, and it still showed an upward trend. *Applied Energy, Journal of Cleaner Production* and *Water* are the most influential journals. For countries and institutions, the United States, China and the United Kingdom are leaders in this field and are the homes of the institutions with the largest number of articles. Beijing Normal University, Texas A&M University, Chinese Academy of Sciences, the University of Illinois and the University of Texas at Austin are the institutions with the largest numbers of articles. The categories involved in this field have also shifted from the early environment, science and technology, and ecology to multicategories, including economy, agriculture, geography, etc. Ten highly cited studies jointly emphasize the need to evaluate these relationships with globalization and systematic thinking, and they report that nexus research plays a key role in the sustainable development of human beings. Combined with qualitative and quantitative methods, the content involves the mutual consumption of resources, the impact of environmental changes on resources, policy formulation and implementation and so on. The results of the keyword time zone map show that the research in this field can be divided into three periods: 2010–2013, focusing on the impact of external environmental changes and the conceptual framework of the nexus; 2014–2016, focusing on water, energy and food security and risks; and 2017–2020, based on the refinement of the themes of the first and second stages, focusing on the optimization of resource use under climate and environmental changes. Through keyword burst analysis, it can be seen that, in recent years, the hotspots of research in this field have analyzed the internal relationship and impact of water–energy–food–climate–ecological environment using qualitative and quantitative methods. The frontier of the research is to analyze the impact of climate change on human society under uncertain conditions, especially the change in climate, and to manage the risks of climate change regarding the water, energy and food sectors through the integrated management of nexus.

In summary, this paper undertakes a comprehensive analysis of the research situation in the field of nexus studies. The research power, knowledge bases, knowledge evolution, hotspots and frontiers in this field were expounded, providing valuable information for relevant researchers and participants. However, the research data of this paper are limited to the core data set of WoS, so it inevitably ignores some important studies from other databases. In addition, the literature itself has a certain lag, so there might be a certain lag based on the results of bibliometric research. Therefore, future research could provide a more comprehensive and accurate supplement to the current analysis by expanding the database or selecting other methods.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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