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A Bibliometric Analysis of Food–Energy–Water Nexus: Progress and Prospects

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Abstract: Food, energy and water are important basic resources that affect the sustainable development of a region. The influence of food–energy–water (FEW) nexus on sustainable development has quickly become a frontier topic since the Sustainable Development Goals (SDGs) were put forward. However, the overall context and core issues of the FEW nexus contributions to SDGs are still unclear. Using co-citation analysis, this paper aims to map the knowledge domains of FEW nexus research, disentangles its evolutionary context, and analyzes the core issues in its research, especially the progress of using quantitative simulation models to study the FEW nexus. We found that (1) studies within the FEW nexus focused on these following topics: correlation mechanisms, influencing factors, resource footprints, and sustainability management policies; (2) frontier of FEW studies have evolved from silo-oriented perspective on single resource system to nexus-oriented perspective on multiple systems; (3) quantitative research on the FEW nexus was primarily based on spatiotemporal evolution analysis, input–output analysis and scenario analysis; (4) the resource relationship among different sectors was synergies and tradeoffs within a region. In general, current research still focuses on empirical data, mostly qualitative and semiquantitative analyses, and there is a lack of research that can systematically reflect the temporal and spatial contribution of the FEW nexus to multiple SDGs. We believe that future research should focus more on how FEW nexus can provide mechanistic tools for achieving sustainable development.

1. Introduction

Food, energy and water (FEW) are basic resources that affect the sustainable development of a region. They have mutual influence that is strongly interconnected [1,2] and appears in the Sustainable Development Goals (SDGs). Due to this strong interaction, the realization of SDGs related to food, energy and water becomes challenging [3–6]. The Sustainable Development Solutions Network (SDSN), an entity that assesses the SDG global progress, reported a shortage of FEW resources in different regions of the world [7]. Sub-Saharan Africa, for example, is facing difficulties to obtain adequate clean drinking water, food security, access to electricity, energy efficiency, and these challenges eradicate

extreme poverty [8]. Many environmental problems occur in Central Asia, particularly after 2015 [9]. China's SDG scores at the provincial level decreased in 2015 compared to the ones in 2000 [10]. With its existing agricultural system, India has difficulty in achieving food security in 2030 [11].

To understand how FEW have mutually interacted, both scholars and policymakers have gradually begun to study the interaction or nexus among them. Nexus is defined as the processes and results of interactions among multiple subjects. The nexus approach thus highlights the connections of different resources to promote efficient resources [12]. Based on the above definition, research in FEW nexus is therefore derived from the research that combines FEW securities. Indeed, most FEW nexus research takes resource security as their main goal [13,14].

Although numerous FEW nexus studies have been accumulated during the last three decades, with some new conceptual models launched [15,16], there is still not enough research about how these studies have evolved and how FEW nexus can promote the realization of SDGs. Therefore, there are four core questions studied in this paper: (1) What are the characteristics of knowledge studied by FEW nexus? (2) What are the issues to be solved in FEW nexus research? (3) What are the main research methods and tools used in FEW nexus studies? (4) How can FEW nexus systematically promote the realization of SDGs? According to its impact on regional sustainable development, nexus can be positive enhancement (synergies) or negative weakening (tradeoffs) [17–19]. In this paper, we use the "mapping knowledge domains" method to: (1) systematically summarize the context, important outcomes and frontier issues of FEW nexus research, and (2) analyze quantitative models associated with FEW nexus and their impact on regional sustainable development.

2. Methodology and Data

2.1. Method for Bibliometric Analysis

In recent years, the "mapping knowledge domains" has gradually become a core method in bibliometric analyses [20–24]. CiteSpace is considered the most widely used method because of its comprehensive co-citation ability. Basic scientific theories of CiteSpace include Kuhn's scientific development theory, scientific frontier theories, structural holes and Kleinberg's burst detection technology, optimal information foraging theory, and knowledge unit decomposition and reorganization theory [25,26].

In CiteSpace, there are three types of network analysis: (1) Co-authorship network analysis takes authors, institutions, and countries into consideration. It can be used to analyze the cooperation network of different scopes from small to large. (2) Co-occurrence network analysis takes terms, keywords, and categories into consideration. This analysis counts the number of a group of words appearing in the same group of documents to extract keywords representing the core of the research field. (3) Co-citation network analysis includes cited references, cited authors, and cited journals [25–28]. This paper adopts co-authorship, co-occurrence and co-citation network analysis, aiming to systematically review the characteristics of the knowledge of FEW nexus, the issues involved and the main methods adopted in existing research. We did (1) a co-authorship network analysis to show the cooperative relationship on authors, institutions, and countries; (2) a co-occurrence network analysis on Web of Science categories to identify research themes and associated terms; (3) a co-citation network analysis to extract the most influential papers. The parameters were set by (1) selecting one year for time slicing and applying it within each sliced time, (2) using cosine algorithm to calculate link strength, and (3) applying "top N = 50", LLR algorithm, pathfinder pruning algorithm, and minimum spanning tree pruning algorithm for clustering.

In the visualized graph, the size of the node indicates different counts, with larger nodes indicating higher counts. A node with a purple outer circle indicates high betweenness centrality, different colors of tree rings of the node indicate different times, and the connecting lines indicate the structural relationship between different nodes, with their thickness indicating the strength of the links. If the betweenness centrality is ≥0.1, it means that the node is a turning point connecting two different fields. The modularity Q value and silhouette values indicate the difference among every single cluster and

internal consistency within the cluster, respectively. If the modularity Q value (0–1) and silhouette value (0–1) are, respectively, greater than 0.3 and 0.5 after clustering, it indicates that the clustering is effective. A silhouette value bigger than 0.7 indicates the homogeneity of clustering is relatively high [27,28].

2.2. Data Collection

All scientific literature came from the Web of Science core collection. Since studies that were conducted between 1983 and 2003 were scattered and unsystematic, we selected studies that were conducted between 2003 and 2020. According to the scientific explanation of FEW nexus and the principle of recall and precision ratio [29–31], the retrieval strategy was set as TS = ("food energy water nexus" OR "food energy water synergies" "OR "food energy water tradeoffs"). The search types were article, review, and proceeding paper, the search language was English, and the search date was 20 June 2020. The source databases include Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index—Science (CPCI-S), Conference Proceedings Citation Index—Social Science and Humanities (CPCI-SSH). The number of retrieved literature was 1112, and after data deduplication, the final number of research literature considered was 1089 (Figure 1).
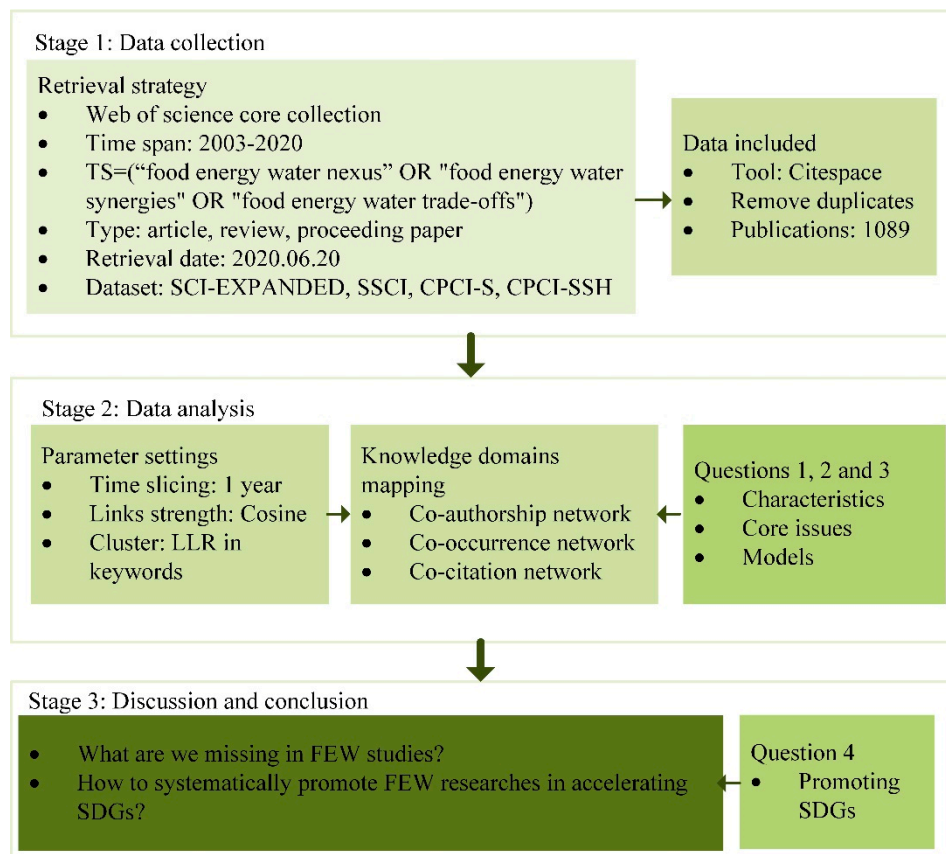

Figure 1. Research framework.

3. Results

3.1. Food–Energy–Water Nexus Literature Trends

Our results showed that literature in FEW nexus consisted of 862 articles (79.16%), 144 reviews (13.22%), and 83 proceeding papers (7.62%) (Figure 2A). The number of published articles that focus on FEW nexus has been increasing (Figure 2B). In 2003, there were only 4 related papers published,

but in 2019, there were 298 related papers in total. It should be noted that the literature in 2020 was incomplete due to mid-year retrieval time. Based on the average annual number of publications, we divided the FEW nexus research into three development phases: (1) the first phase (2003–2010) with the average annual number of publications 5; (2) the second phase (2011–2014) with the average annual number of publications 22; (3) the third phase (2015–2019) with the average annual number of publications 170 (Figure 2B).
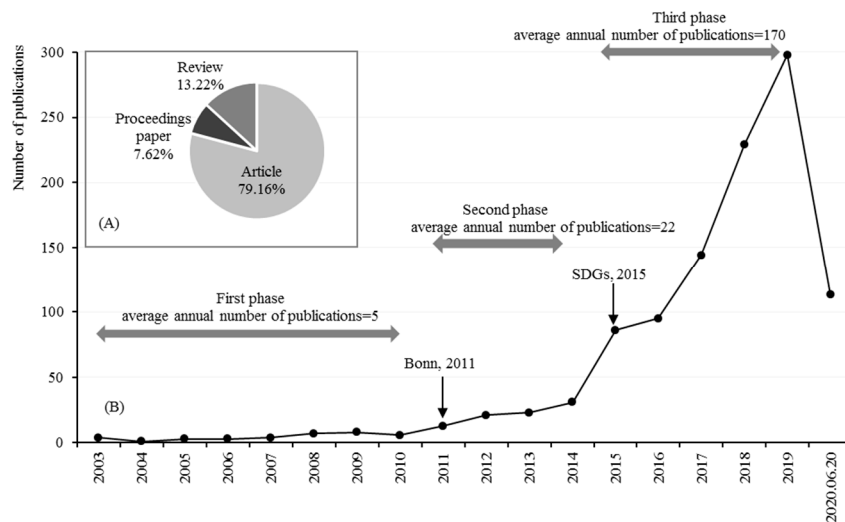

Figure 2. The trends in research of food–energy–water (FEW) nexus. (**A**) The type of published articles on FEW nexus; (**B**) The number of published articles on FEW nexus by year.

The FEW nexus research showed significant differences in different phases. In the first phase, the FEW nexus research was relatively scattered and not yet systematic. In 1983, the United Nations University initiated a project to study the correlation between food and energy, which became one of its long-term projects [32]. The World Bank was among the early adopters of this method by analyzing interrelationships between water, food, and trade in the 1990 s, followed by other research institutions and international organizations [33,34]. Finally, the nexus between food, energy and water was first proposed as a formal concept during the 2008 annual meeting of the World Economic Forum [35]. Papers that received the most citation in this first phase were the research on the tradeoff of resources required for reproduction by Bonneaud et al. [36] and the research on the relationship between biomass energy as a low-carbon energy source and climate change by Fargione et al. [37].

The second phase was marked by the Bonn conference in 2011. The Bonn conference pointed out that the nexus among FEW should be systematically applied to promote the development of a green economy [38]. The United Nations "Rio+20" conference emphasized the application of sustainable agricultural methods to obtain food security, sustainable energy and safe drinking water [39]. Research in this phase clearly took the FEW nexus as a specific research object. For example, Bazilian et al. [40] proposed the basic framework of quantitative simulation of FEW nexus from the perspective of resource security. Later, the FEW nexus research was gradually combined with sustainable development [41,42].

The third phase started with the proposition of SDGs in 2015. Since the SDGs were put forward, academic research and policy practices under the SDGs framework have increased rapidly. SDGs emphasize that sustainable development goals are one system and that social, economic and environmental goals interact with each other. This framework is consistent with the analysis of nexus among FEW. Since 2015, FEW research has been mainly carried out under the framework of SDGs [43–46]. Research in this phase was based on the research during the earlier phases, with a stronger connection to sustainable development such as sustainable livelihoods, sustainable governance, and some retrospective studies [47–50] (Figure 3).
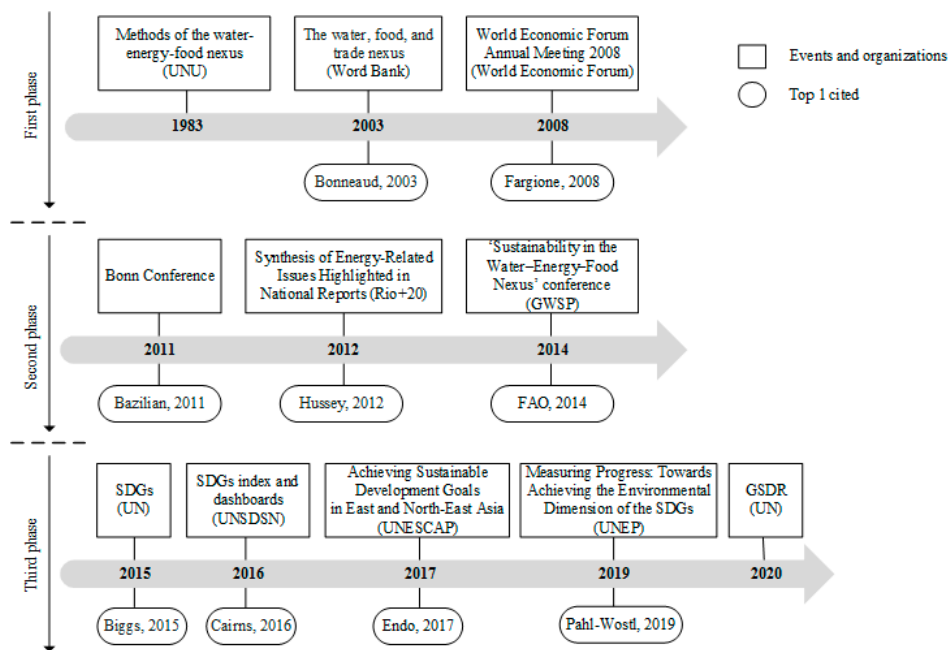
Figure 3. Timeline illustrating the development of food–energy–water nexus since it was launched.

Literature about FEW nexus was published in 336 different journals. The top 10 journals were those that focus on sustainable development, resources and environmental research, accounting for 32.69% of the total number of publications. Most of the FEW nexus articles were published in the "Journal of Cleaner Production" (Figure 4A). Based on the number of citations, 998 papers (91.64%) received less than 50 citations, 68 papers (6.25%) received between 50 and 100 citations, and only 23 papers (2.11%) received more than 100 citations (Figure 4B).
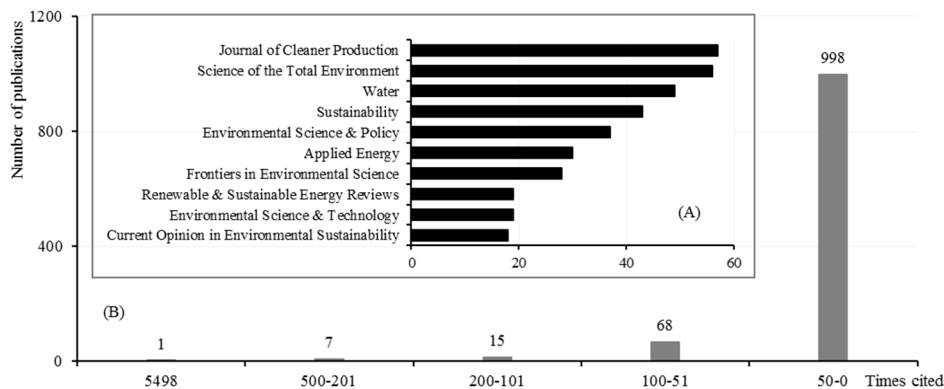

Figure 4. The times cited and the top 10 journals with publications on food–energy–water (FEW) nexus. (**A**) The top 10 journals of published articles on FEW nexus; (**B**) The number of citations on FEW nexus.

3.2. Who Studied the Food–Energy–Water Nexus?

In order to grasp the structure of scientific cooperation in the existing FEW nexus research (i.e., the spatial distribution of authors), we further analyzed the co-authorship network, institutions and countries. In this analysis, a node represents the number of published papers. Larger nodes indicate more papers associated with the authors, institutions and countries. The connecting line reflects cooperation strength. The thicker the connecting line, the closer the cooperation is.

Based on the results, most authors formed a fixed and repetitive cooperative group. However, the cooperative relationship between different author groups was weak since they were decentralized and isolated. Nodes of the same or similar color indicate a cooperative group. The larger the group,

the stronger and closer the cooperation is. However, the centrality of each group was so small that there was no representative author.

In terms of the number of articles, Al Ansari T (13) published the most articles in this field, followed by Ringler (11) and Mohtar (8). Furthermore, the scientific research cooperation network had strong partial cooperation. Taking the top 10 productive authors, for example, there were more authors who had their studies based on their respective research issues, forming separate cooperative subnetworks with more researchers involved. An exception was for Al Ansari T and Shah N, who were in the same cooperative subnetwork (Figure 5 and Table 1).

Figure 5. Co-authorship network of authors.

Table 1. The top 10 productive authors.

Author	Publication Number	Top 1 Cited in the Author's Publications
Al-Ansari, T.	13	Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems [51]
Ringler, C.	11	The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? [29]
Mohtar, R.H.	8	Complexity versus simplicity in water energy food nexus (WEF) assessment tools [52]
Huang, G.H.	7	Transfer of virtual water embodied in food: A new perspective [53]
Taniguchi, M.	7	Water, energy, and food security in the Asia Pacific region [54]
Chen, B.	6	Linkage analysis for the water–energy nexus of a city [55]
Shah, N.	6	Sustainable planning of the energy–water–food nexus using decision-making tools [56]
Martinez-Hernande,z E.	6	Understanding water–energy–food and ecosystem interactions using the nexus simulation tool NexSym [57]
Ponce-Ortega JM	6	Optimization of biofuels production via a water–energy–food nexus framework [58]
Rulli MC	6	The water–land–food nexus of first-generation biofuels [59]

The overall cooperation network of institutions was relatively scattered. Chinese Academy of Sciences (28, China), Texas A&M University (27, USA) and Beijing Normal University (26, China) published the most papers. Universities published a greater number of papers than research institutes (Figure 6).
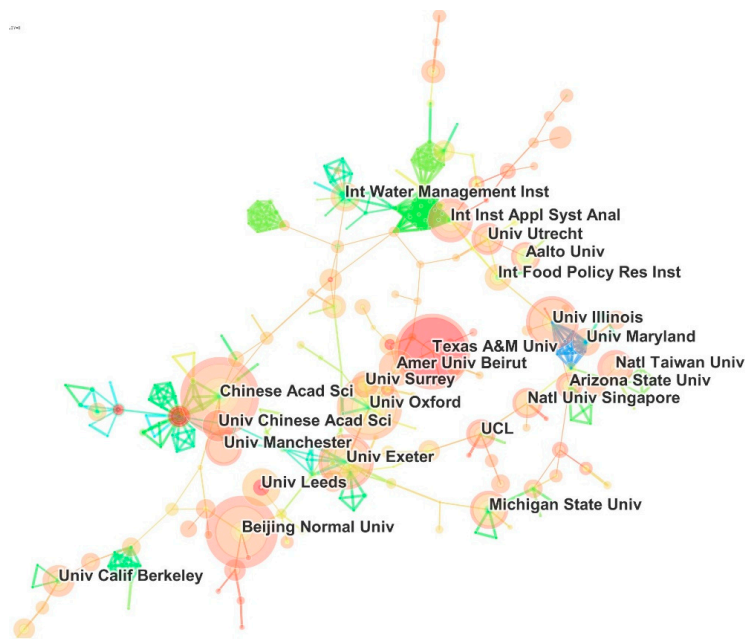
Figure 6. Co-authorship network of institutions.

Among all countries, the USA (403), England (215) and China (163) have the highest records of published papers and made outstanding contributions to this field. Countries with high betweenness centrality were Germany, Australia, England and Sweden, indicating that they had an important influence on researchers in other countries. The connecting lines show the co-authorship network among countries. In general, scientific cooperation was relatively scattered, which is a characteristic of partial cooperation (Figure 7).
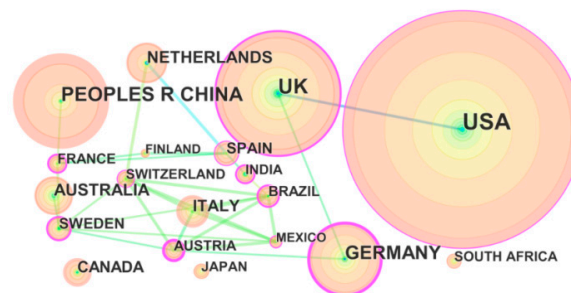
Figure 7. Co-authorship network of countries.

3.3. What Is the Specific Content of Food–Energy–Water Nexus?

3.3.1. Co-Occurrence Network of the Web of Science Categories

We used the co-occurrence network of the Web of Science categories to analyze research categories. Cluster identification number started from #0, the largest cluster size that contained most papers among all clusters. Our clustering result was significant and highly reliable, with Q = 0.6227, S = 0.9365 (Figure 8).

The research cluster themes included: sustainability, mitigation, policy integration, predictive regulation, indicators, osmotic potential, water footprint and knowledge base. The "#0 Sustainability" was the biggest cluster that reached the threshold in this research field. The mean of year in this cluster was 2012, and the clustering efficiency was 0.874. The clustering words were those related to "SDGS, water–food–energy nexus, energy–water nexus, irrigation energy efficiency, systems thinking, land use optimization". Dense connecting lines present a high clustering centrality and form a strongly close

research network. The "#3 predictive regulation" was the most efficient clustering with a silhouette value of 0.995. This refined cluster research on the internal elements of FEW, which promoted the optimal development of FEW systems. In general, with the continuous advancement of the relationship among FEW systems, new challenges constantly emerge (Table 2).
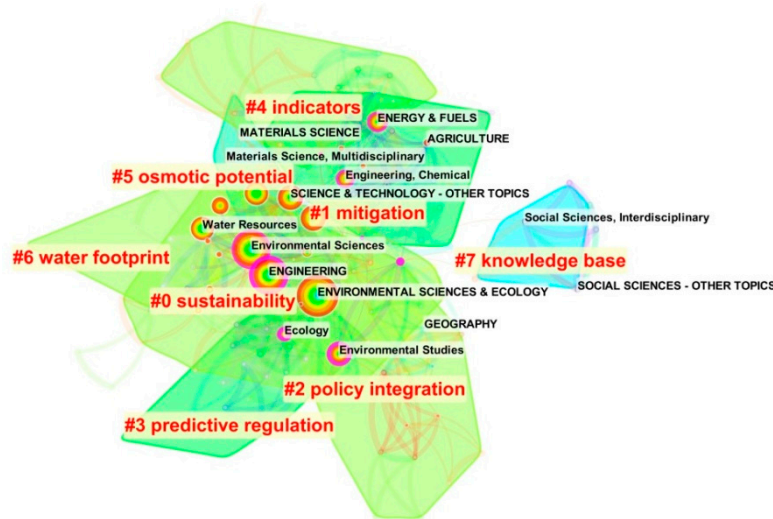

Figure 8. Co-occurrence network of the Web of Science categories.

Table 2. The clusters of the Web of Science categories of the network.

Cluster	Theme	Size	Silhouette	Mean (Year)	Top Terms
0	Sustainability	34	0.874	2012	SDGs; water–food–energy nexus; irrigation energy efficiency; systems thinking; land use optimization
1	Mitigation	30	0.821	2010	optimization; fuzzy analytic hierarchy process; biogeochemical technology cycles; resource recovery; techno-economics; ecological sustainable development
2	Policy integration	26	0.875	2015	policy; sustainability assessment; global governance; practice; environmental policies; resource management
3	Predictive regulation	23	0.995	2009	osmotic stress; homeostasis; water limitations; allostasis; tradeoff
4	Indicators	21	0.876	2015	food waste minimization; life cycle costing; biomass; multi-stage stochastic programming; circular economy
5	Osmotic potential	11	0.899	2012	land-use optimization; irrigation efficiency; osmotic stress; soil–water-waste nexus
6	Water footprint	11	0.911	2011	crop water requirement; water–energy–carbon nexus; virtual water; irrigation efficiency
7	Knowledge base	7	0.987	2013	crop-biomass coproduction; food–energy–water nexus; food waste; irrigation energy efficiency

3.3.2. Co-Occurrence Network of the Titles, Abstracts, and Keywords for the Terms

We conducted a co-occurrence network analysis for the use of terms in FEW nexus to further understand the specific issues involved. The "energy–food nexus" appeared most frequently (165), followed by "water energy" (143), "food energy" (82), "energy–water nexus" (76), "nexus approach" (75), "water–energy nexus" (52), "energy water" (41), "FEW nexus" (38), "food–energy nexus" (36) and "water food" (33). All these terms showed that FEW research remained on the three systems and nexus among them. The terms "climate change" (140), "ecosystem service" (57), "environmental impacts" (51) and "natural resources" (38) were based on the perspective of the natural ecological environment to explore the influence of the FEW nexus. Meanwhile, "sustainable development" (88) and "sustainable development goal" (56) were the guiding principles (Figure 9).

Figure 9. Co-occurrence network of terms.

Frontier studies in literature can be shown by burst detection analysis [25,60]. CiteSpace uses the algorithm proposed by Kleinberg in 2002 to conduct this analysis, which detects a rapid increase in the frequency of term used in a given time period (i.e., a turning point in a research field). Table 3 shows that 11 terms had burst from 2003 to 2020. All the three dimensions of FEW were covered in the list, and most terms were around the nexus or its systems. The earliest burst term was "energy security," which began in 2011 and ended in 2016. Since 2014, the environment was an emerging topic and research was conducted to understand how FEW influenced both climate and the economy. The number of the appearance of terms "energy consumption," "food nexus," and "energy–water system" increased in the past three years, which means that these terms could be representative of emerging trends in the field (Table 3).

Table 3. Terms with strongest citation bursts.

Term	Strength	Begin	End	2003–2020
energy security	5.4857	2011	2016	
food security	3.4495	2012	2014	
water food	4.1186	2013	2016	
energy-food security nexus	3.1331	2013	2015	
biofuel production	3.2198	2014	2015	
degrees c	3.8016	2014	2016	
economic development	2.9071	2015	2017	
critical role	3.2475	2016	2017	
energy consumption	3.2634	2016	2017	
food nexus	4.2059	2016	2017	
energy-water system	3.0011	2017	2018	

3.4. What Are the Main Quantitative Models Used in Food–Energy–Water Nexus?

We extracted research models by using the word "model" or "approach" and querying "node details" to find the papers where the term appeared. The models involved diverse fields, such as economy, management, and mathematics. Results showed that the research of FEW nexus was very inclusive, absorbing and integrating multidisciplinary and multidimensional knowledge. It also included the impact of FEW nexus on various research fields and from different perspectives such as temporal-spatial evolution characteristics, simulation modeling and prediction, and multi-departmental management policy optimization.

The research methods mainly included input–output analysis, life cycle assessment, target decision evaluation, and econometric model. Input–output analysis was widely used in the research of public policy

performance like environmental performance. It was also combined with production functions to carry out system evaluation to examine the relationship between capital, labor, energy, other inputs, and environmental output. For example, when examining the relationship between water and energy consumption and food production, we seek ways to reduce input while increasing the output [61–64]. Life cycle assessment calculates the correlation between different energy varieties and water consumption, agricultural production and carbon emissions by making a full life cycle list of agricultural production [65,66]. Target decision evaluation is usually used in conjunction with econometric models. By selecting representative indicators in each system, a comprehensive index is calculated to judge the correlation and degree of correlation between systems [67–71].

Simulation modeling and prediction were commonly in combination with scenario analysis and system dynamics analysis, revealing the mutual influences and development trends of multiple systems under future uncertain scenarios [72–75]. For example, the Integrated model for sustainable development goals (iSDG) is based on the basic idea of system dynamics. It divides the environmental, social, economic and governance factors that affect the sustainable development of a region into 30 interrelated analysis modules, distinguishes the endogenous and exogenous variables that affect the relationship of the system, and quantifies the feedback relationship between different departments. It is the complete model in all the studies [76]. There were also research models combining environmental cost–benefit analysis. According to model logic, they are divided into top-down, bottom-up, and mixed models. They calculate the cost–benefit of different resources to investigate the relationship among different systems [77,78]. There were also studies that have specifically developed system correlation models. For example, the WEF Nexus Tool can be used to analyze the correlation between water, energy and food systems and to assess the demand for resources in different scenarios. It is believed that changes in land use are highly sensitive to food production, followed by water and energy [79].

Multi-departmental management policy optimization research was mostly based on system modeling. At present, there are long-term multi-departmental planning systems such as computable general equilibrium (CGE), long-range energy alternatives planning (LEAP), water evaluation and planning model (WEAP), climate, land-use, energy and water systems (CLEWS). These models are used to quantitatively study the relationship between social-economic factors and resource utilization. Among the bottom-up model structures that can fully reveal the impact on the overall sustainable development of a region [80–85], the CLEWS approach has the most complete object analysis, including multiple modules, and its main goal is to optimize the resource utilization rate of an existing system and to evaluate energy and water supply of agricultural production under climate change conditions [85] (Table 4).

Table 4. The main quantitative models used in food–energy–water nexus.

Method	Model	Publication
Econometrics	Based on existing research or expert judgments	Fu et al. [45] Nerini et al. [86]
Target decision-making	Multicriteria comprehensive evaluation; econometric model	Weitz et al. [87] Huang et al. [71]
Input–output analysis	Input–output model; data envelopment analysis (DEA)	Munoz Castillo et al. [62] Sueyoshi et al. [64]
Life cycle assessment	Life cycle assessment (LCA)	Laurent et al. [66]
Econometric model	Global macro-econometric model	Brouwer et al. [88]
Simulation modeling prediction	Threshold 21; system dynamics model; Integrated model for sustainable development goals (iSDG); Bayesian networks; agent-based model	Collste et al. [76] Li et al. [72] Bakhshianlamouki et al. [73] Chai et al. [74] Abdel-Aal et al. [75]
Multi-system model	Computable general equilibrium (CGE); long-range energy alternatives planning (LEAP); water evaluation and planning model (WEAP); climate, land-use, energy and water systems (CLEWS); WEF Nexus Tool	Weitz et al. [80] Payet-Burin et al. [81] Zhang et al. [82] Philippidis et al. [83] Olawuyi [84] Welsch et al. [85] Daher and Mohtar [79]

3.5. What Are the Core Research Issues in Food–Energy–Water Nexus?

The co-citation network had a high modularity Q value (0.8034), and all clusters had a high silhouette value (>0.7). A node represents the number of times the paper has been cited, the connecting line represents the strength of co-citation, a color represents different clusters, and the color of the line represents the difference in the first co-citation time. The red color in the tree ring of a node indicates the frequency of citation has increased rapidly. The more burst nodes in a cluster, the more active a field is (i.e., an emerging research trend).

Our analysis showed that the clusters were closely connected with some overlaps. Overall, #0 and #5 concentrated on ecological and environmental issues; #2 and #3 concentrated on policy implementations while other clusters focused on FEW and the FEW nexus. Indicated by the mean of co-citation year of all clusters, the environment and policy research are core issues in FEW nexus research, which run continuously through the entire research network. Studies in these clusters have been conducted for about 10 years on average. Among them, "#5 environment" lasted the longest, while "#2 Policy coherence" and "#6 Water footprint" lasted for a relatively short time and had a hiatus of several years (Figure 10 and Table 5).
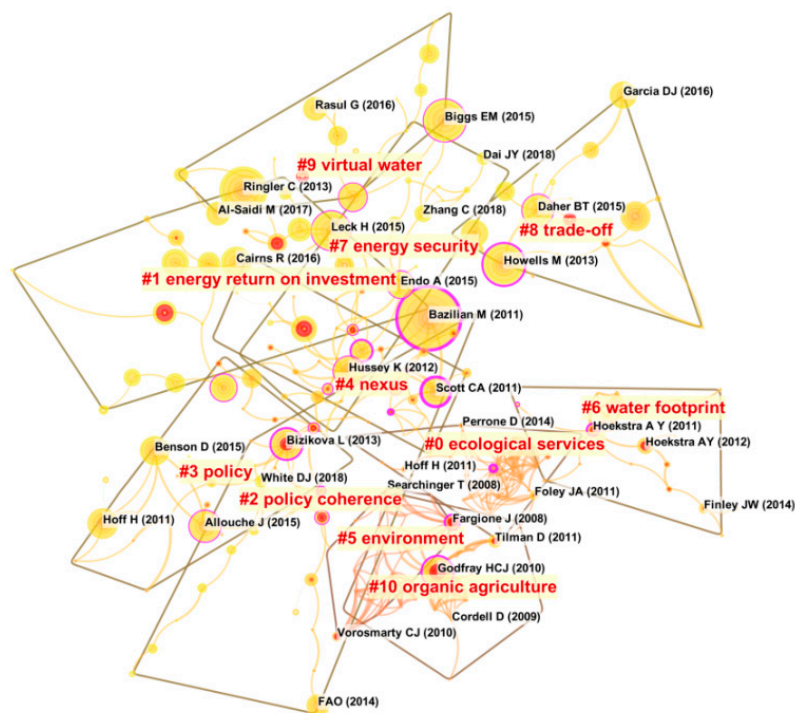

Figure 10. Co-citation analysis network of references.

"#0 Ecological services" had the largest cluster size, containing 264 papers. This cluster's silhouette value (0.738) was the lowest among all clusters. However, considering the cluster size and cluster homogeneity criteria, this cluster was effective. The mean of the citation year of this cluster was 2015. The terms included were FEW nexus, agriculture, resource security, synergy, and adaptation. Based on the research history of the highly cited literature in the #0 cluster each year, the research has undergone a transformation from water resource safety issues to water, energy, food and land nexus. The research object changed from a single system to multiple systems, and the research methods changed from conceptual frameworks to model simulations. Recently, reviews of literature increased gradually, and they highlight the research deficiencies in FEW nexus [29,42,47–50,89–91].

Table 5. The top clusters of the co-citation analysis network (size > 50).

Cluster	Theme	Size	Silhouette	Mean (Year)	Top Terms
0	Ecological services	264	0.738	2015	FEW nexus; agriculture; resource security; synergy; adaptation
1	Energy return on investment	126	0.843	2014	food energy water nexus; urban agriculture; urban metabolism; network analysis; virtual water
2	Policy coherence	105	0.886	2011	agrobiodiversity; energy and resource use in food consumption; agroecology; sustainable intensification; food security; environmental impacts
3	policy	84	0.903	2016	integrated assessment modeling; nexus; land-use change
4	nexus	84	0.874	2013	Hydrology; integrated assessment model; water demand; policy mix; modeling and optimization of multiple spatial and temporal scales; water–food–energy-ecosystem nexus; projection
5	environment	67	0.916	2010	renewable energy; biofuels; poverty reduction; optimal management
6	Water footprint	52	0.919	2013	hydropower; transboundary water–energy–food nexus; water security; water resources management

　　Judging from the important nodes of the co-citation analysis network, whether it is a node with high citation frequency or high betweenness centrality, the common theme was that these studies were carried out under a sustainable development framework. In the early stage, the conceptual framework was mostly used, while in the later stage, they gradually turned into the construction of comprehensive models.

　　There were 3 nodes with more than 100 citations, and each developed the FEW nexus in terms of research systems, research methods and research goals. The research system became more complete with the inclusion of land. The integrated modeling promoted quantitative simulation methods. Meanwhile, incorporating human well-being and sustainable livelihoods as a research goal made FEW studies more in line with the core ideas of SDGs. To be specific, Bazilian et al. [40] reviews the integrated models of FEW nexus in existing research from the perspective of resource security and propose future research direction (i.e., integration of policies that can reflect the interaction among food, energy and water). Ringler et al. [29] expand the nexus framework across water, energy, land and food from the perspective of improving resource utilization efficiency. He believes that differences in the nexus will affect human well-being and the environment, so research and governance on the water, energy, land and food nexus should continue to advance. Biggs et al. [47] takes livelihood as the core of sustainable use of natural resources and study the impacts of water, energy, food, and climate nexus on environmental livelihood security. The goal is to achieve a sustainable balance between resource supply and human demand.

　　Our results also suggested that high betweenness centrality nodes were scattered in each cluster. The prominent nodes were mostly large-scale studies carried out at the global or national level. Scott et al. [33] study the environmental coordination impact of water energy utilization in areas with different water and energy resources endowments in the United States. Godfray et al. [92] predict global food security challenges. The turning points of the integrated model were CLEWs and WEF Nexus Tool [79,93].

　　Based on burst detection analysis, papers that have received many citations can be analyzed to reflect the emerging trends in their specific research field [25,94]. In this study, the earliest reference citation burst began in 2010 [37]. Godfray et al. [92] had the strongest burst intensity, and therefore it was a research frontier at that time. From 2015 to 2020, there were increasing studies with high burst intensity as SDGs promoted the studies of FEW nexus. All papers still maintained the burst in 2020, which means that they would continue to serve as the basis for future research (Table 6).

Table 6. Top 10 references with strongest citation bursts.

Reference	Title	Strength	Begin	End	2003–2020
Fargione et al. [37]	Land clearing and the biofuel carbon debt	10.47	2010	2020	
Godfray et al. [92]	Food security: the challenge of feeding 9 billion people	11.08	2011	2020	
Rockstrom et al. [95]	A safe operating space for humanity	9.09	2013	2020	
Hellegers et al. [96]	Interactions between water, energy, food and environment: evolving perspectives and policy issues	7.17	2015	2020	
Bizikova et al. [97]	Climate change adaptation planning in agriculture: processes, experiences and lessons learned from early adapters	6.9	2015	2020	
Waughray et al.	Water security: The water-food-energy-climate nexus	5.92	2015	2020	
Gerbens-Leenes et al. [98]	Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030	5.91	2015	2020	
Hussey and Pittock [41]	The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future	5.61	2015	2020	
Gerbens-Leenes et al. [99]	The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply	5.49	2015	2020	
Orr et al. [100]	Dams on the Mekong River: Lost fish protein and the implications for land and water resources	5.46	2015	2020	

4. Discussion

4.1. Rethinking on Food–Energy–Water Nexus

The academic research on FEW nexus is closely integrated with international sustainable development practices. The characteristics of academic research results in different phases are consistent with the discussion topics of important international organizations and conferences related to sustainable development at different times (Figures 2 and 3). Our analyses of FEW nexus support that (1) Productive authors engaged in FEW nexus research (Table 1) are mostly from western countries, as we can see in the cooperation network on institutions (Figure 6) and countries (Figure 7). However, research cases (Table 1) are mostly concentrated in countries and regions of the Global South (e.g., Qatar, Ghana, China, and Sub-Saharan Africa) [29,51,53–56], and the spatial differences and separations between scholars and research cases are worthy of attention [101]; (2) The research topics mainly focus on ecosystem services, energy investment, policy consistency, environmental footprint, etc. (Figure 10 and Table 5), involving systematic research related to economy, society, resources, environment, and governance. Therefore, the core issues to be solved are how FEW systems interact with each other and how the interactions affect regional sustainable development; (3) The current main streams of research methods of FEW nexus are quantitative analyses (e.g., econometric model, input–output analysis, life cycle assessment, multi-system simulation) (Table 4).

There have already been many reviews specifically on FEW nexus. Although the perspectives and methods that they adopt are different from those in this paper, our views on the basic trends, core issues and methodology are consistent [52,82,102–104]: (1) FEW nexus, rather than a special conceptual tool, is a way of thinking that integrates and systematically promotes the sustainable management of multi-sectoral resources [15,16,101]; (2) FEW nexus research entails transdisciplinary knowledge, and directly related to multi-sectoral resources policies and management in practice. The most prominent case is the FEW nexus governances in a transboundary context [15,16,105], and the difficulty lies in how to integrate multi-sectoral policies and management to promote multi-stakeholder collaboration.

Our study reveals that the main aim of literature on FEW nexus is to investigate how multiple resource systems influence and interact with each other. FEW nexus studies come from resource security, which restricts regional development [17–19,38]. FEW nexus research involves a wide range of disciplines (Figure 8), and the research topics focus on the environmental impact assessment and the consistency of multi-sectoral resource policies. The core issue is sustainable development under the limitation of the total amount of regional resources.

4.2. Implications for Advancing Food–Energy–Water Nexus Study

The Bonn conference is a milestone in FEW nexus research. Since then, research results have increased year by year [101] and entered a period of rapid growth after SDGs were put forward. The reason is that SDGs are a systematic and integrative issue, and the "nexus" way of thinking has a positive effect on the implementation of SDGs. Judging from the top references with the strongest citation bursts, how SDGs promoted the studies of FEW nexus will still be a frontier issue in the future (Table 6).

This paper sorts out the development of the FEW nexus research and further understanding of its development under regional resources limitation is beneficial to SDGs implementation. Although it is beyond the scope of this paper, it can be seen from current research that more quantitative studies of the FEW nexus are still needed. First, such factors as population growth, urbanization, climate change, food security may lead to uncertainty in the interaction of regional food, energy, and water resources [2,42]. Second, how to achieve regional sustainable development under resource limitation, especially based on the scientific theory of planetary boundary, the realization of SDGs related to food, energy, and water resources has already faced huge challenges [106–109].

5. Conclusions and Outlook

5.1. What Are We Missing in FEW Studies?

In FEW studies, the key points of research evolved around sustainability, mitigation technology, resources security, ecosystems, agricultural sciences, and policy governance (Figure 10 and Table 5). Based on the co-occurrence network analysis, most research focused on the FEW nexus, climate change, ecosystem service, and sustainable development (Figure 9). Yet we observed the following deficiencies in current research on the nexus of FEW:

First, in terms of research objects, existing studies mostly start from a single field or sector and consider the other systems as exogenous variables. Therefore, they lack correlation analysis among multiple sectors (e.g., lacking comprehensive study on tradeoffs among agricultural expansion, agricultural water use, and deforestation [110]). Given the complex correlations among FEW, this, in turn, leads to research focusing on the identification of tradeoffs but not on minimizing the tradeoffs between multiple sectors in FEW nexus [111].

Second, in terms of research methods, most studies use qualitative or semiquantitative analysis (e.g., econometric models, target decision-making, literature evaluation, and expert evaluation) as the main methods (Section 3.4). Yet few studies simulate the correlation among multiple systems, including research on the complex mechanisms that explain the interaction among FEW nexus [112,113].

Third, in terms of research data, the existing research is mainly based on empirical analysis and statistical data from national statistics and international organizations [6,86,87]. Few spatiotemporal evolution data truly reflect the correlation process of a system [114].

Fourth, in terms of research scales, multiscale research is insufficient, including research on the sub-national scale. Since sub-national scale sustainable development management policies have more impacts on synergies and tradeoffs, lack of research on this aspect is not conducive to narrow the gap between theory and practice [115,116].

5.2. How to Systematically Promote FEW Research for SDGs?

We believe that the overall FEW nexus research is based on environmental issues and environmental policies. Many studies have shown that there are complex interactions (synergies and tradeoffs) in the sustainable use of food, energy, water, and land [30,117]. While resource security, efficiency, and sustainability and policy consistency are active research topics [29,111,118,119], the FEW nexus is also affected by economic growth, urbanization, climate change and other economic, social, resource and environmental factors [6,44]. This knowledge gap suggests that quantitative analysis of the synergies and tradeoffs of FEW nexus are necessary but challenging [45,46].

Research analysis shows that synergy is more prominent in the relationship between water and food. Crop production models show that there are differences between the planting area and crop yield under different rainfall conditions. At the same time, a reasonable food production layout can reduce environmental impacts like land degradation [120,121]. Effective land use can promote food production. Some studies show that for every 10% increase in agricultural irrigation, there is a potential for food production to increase by up to 47% [122,123]. In contrast, tradeoffs are more common in dry regions, where irrigation reduces the lake area and damage the fishery in that area. Although new energy in clean production has more advantages than fossil fuels, its production consumes more water and has a higher cost, which can lead to an increase in food prices [124–126]. Furthermore, there are differences between synergies and tradeoffs at different scales. The synergy is more obvious at large scales [127], while small-scale studies sometimes show tradeoffs between land-use changes and food production [128,129]. At present, the global agricultural sector (i.e., production and supply) consumes 70% of freshwater and 30% of energy resources. As the world population is predicted to reach 9 billion by 2050, the world's food supplies must also be increased by at least 60% [130]. Future research should consider the synergies and tradeoffs among different fields and scientific mechanisms, serve for policy formulation and management of resources at different scales, and coordinate policy consistency

between different sectors. Therefore, the FEW nexus is a fundamental development problem, limited by the regional boundary of resources.

In this paper, we use "mapping knowledge domains" to conduct a comprehensive review of existing research. We find that the co-authorship network in the existing research is not close and shows relatively strong cooperation only in some areas. Based on the current research situation, we discuss the shortcomings of existing research from the perspective of achieving SDGs. The essential scientific issue is to clarify the impact of regional resource constraints on sustainable development. The conceptual pressure–state–response model, which incorporates environmental sustainability into development decisions, can analyze the relationship between some factors like economic growth and environmental factors. Therefore, it may be a good explanatory framework for future research on the FEW nexus [131,132].

Overall, FEW resources must be treated as a whole system. We should consider not only the interactions within the system but also the impacts of external factors such as the economy, social and environment. Another thing that needs to be considered is that the FEW Nexus has multisubject, multi-sector, multi-region, and multiscale characteristics. In the future, it is necessary to study how to promote positive correlation in FEW Nexus to achieve multi-sectors' governance coordination, policy coherence and eventually SDGs.

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