Environmental Science and Pollution Research (2023) 30:121354–121369
https://doi.org/10.1007/s11356-023-29863-1

REVIEW ARTICLE

The water-energy-food nexus: a systematic bibliometric analysis

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Received: 6 March 2023 / Accepted: 9 September 2023 / Published online: 24 November 2023

Abstract

Adequate water, electricity, and food are essential for sustainable development. Regional conflicts intensified by global water, energy, and food shortages necessitate a rethinking of the security and interdependence of these resources. However, most earlier scholars concentrated on the subsystems of the water-energy-food nexus (WEF nexus), lacking holistic studies. Therefore, to understand the history and current state of research on the WEF nexus and predict future research directions, this study analyzed 1313 journal articles from the Web of Science database between 2007 and 2022 using the bibliometric analysis and Citespace software. The findings in this study indicate that (1) the progress of the WEF nexus research can be classified into three stages between 2007 and 2022: the early stage (2007–2010), the fast-developing stage (2011–2015), and the steady and in-depth stage (2016–2022). The WEF nexus has become a hot zone for academic research. (2) Map of the network of countries, institutions, and author collaborations implies tight academic collaboration among countries, institutions, and writers. (3) Climate change, integrated WEF nexus, sustainable development, and security are research hotspots in this field. Meanwhile, energy security, circular economy, and resource allocation are advanced subjects in this field. These key findings can provide managers and researchers with valuable information for decision-making.

Keywords Water-energy-food nexus · Sustainable development · Bibliometric analysis · Literature visualization · Knowledge mapping

Introduction

The viability of humankind is being challenged more than ever since the growth of human civilization has irreparably destroyed the Earth's ecology. Global sustainable development becomes a Utopian concept. In 2015, the UN Sustainable Development Summit unveiled the 2030 Agenda for Sustainable Development, outlining 17 sustainable development objectives to achieve clean, cheap, dependable, and sustainable energy for all by 2030 and a world without starvation. Despite this, the linkages between ecosystems and socioeconomic systems invariably bring about enormous challenges for society, particularly in light of the interconnections among food security, access to clean water, and energy supply becoming crucial to global sustainable development. According to UNFCC COP 27 (2022), 1.1 billion people still cannot get modern energy services (SE4All 2016), and 1 billion people lack access to clean drinking water globally. These people rely largely on agricultural production and operation for food and income (Stevens and Gallagher 2015). Therefore, it is necessary to reconsider the resources of water, energy, and food and their inseparable connections.

The demand for natural resources is rising with the global population and socioeconomic and environmental changes. Resources of water, energy, and food are necessary for sustaining socioeconomic growth and providing fundamental

Responsible Editor: Eyup Dogan

Highlights

- The WEF nexus has received increasing attention.
- The relationships of WEF nexus subsystems have been thoroughly investigated.
- The progress of WEF nexus research is evaluated using a distinctive framework of bibliometric analysis in this article.
- Future research challenges for the WEF nexus are identified in this paper, with climate change and carbon emissions as external factors.
- The findings in this study can provide a research perspective for managers and researchers.

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human requirements. They are inextricably intertwined (Yan et al. 2020; Bazilian et al. 2011; Waughray 2011; Shang et al. 2018). Water is used in irrigation for food production. Energy is necessary for water pumping, transporting, treating, gathering, and distributing, and it is also a necessary resource for extracting and processing fossil fuels and generating electricity (Liu et al. 2018). For these three resources, changes in any one can variously affect the others since water, energy, and food interact (Hellegers et al. 2008; El-Gafy 2017). Therefore, to promote the nexus of the three for human beings' sustainable future, it is of great significance to conduct comprehensive research on the water-energy-food (WEF) nexus and creating multi-resource strategies.

The nexus of water, energy, and food is a complicated problem that can be anticipated and solved with the help of nexus, which has attracted more and more attention from policymakers and researchers (Zhang et al. 2018). Nexus management has become one of the most challenging subjects in the world (Allouche et al. 2019). According to Brouwer et al. (2018), nexus management is no longer confined to a single resource but enables collaborations between sectors and sustainable development, thus achieving the high security and efficiency of numerous resources (Smajgl et al. 2016). Moreover, AI-Saidi and Elagib (2017) uncovered the motivation for generating nexus thinking and emphasized the significance of systematically analyzing the relationships among water, energy, and food. Aiming to effectively make trade-offs between sectors or collectives of interest, promote sustainable development in each sector, and maximize resource utilization, the WEF nexus facilitates the synergistic development and integrated management of water, energy, and food (Kurian 2017; Niu et al. 2021).

Extensive research on the WEF nexus has been done from various disciplines, methods, and modeling frameworks (Hachaichi & Egieya 2022). In spite of this, Albrecht et al. (2018) raised the necessity for a knowledge base of the WEF nexus approaches, illuminating the urgency of addressing the inherent complexity of the essential resource interactions in nexus approaches. Nevertheless, merely a small proportion of existing literature thoroughly analyzed the general strategies employed in nexus approaches (Keairns et al. 2016). For instance, Albrecht et al. (2018) considered that the studies on the interconnections of all three subsystems of the WEF nexus were rare and mostly focused on just two of them.

To fill in the gap in the perception of the WEF nexus, this study probed into the research trends of the WEF nexus from its connotation and investigated the interactions of its subsystems using the bibliometric approach. The main contributions of this study are as follows: (1) a thorough analysis and critical reflection of existing WEF nexus research for further development in relational evaluation techniques; (2) a bibliometric analysis of selected publications to identify applied methods and addressed problems by determining major academic journals; (3) an analysis of the challenges faced by WEF nexus research and future research directions.

Literature review

Water-energy nexus

Gleick (1994) was recognized as one of the early experts on the water-energy nexus in the USA. The World Energy Outlook released by International Energy acknowledged the significance of the water-energy nexus (Zhang et al. 2018; Ingram 2011). In the water-energy nexus, water is necessary at every stage of energy production, and the availability of water resources is crucial for producing and delivering both conventional and emerging energy sources (Cai et al. 2018). Energy is required to power water transport, irrigation, treatment, and distribution. According to studies, the energy industry is the world's second-largest water consumption (Hightower & Pierce 2008). Therefore, water and energy systems are complementary and interdependent (Wada et al. 2013).

However, for multiple reasons, such as global population expansion, industrialization, urbanization, and climate change, the worldwide demand for water and energy increases quickly (Chen & Chen 2016; Siciliano et al. 2017). Compared with 2015, the world's freshwater and energy consumption will grow by 50% in 2050. Moreover, it is anticipated that switching from biofuel production to water-intensive power plants will increase water demand for energy production by 85% by 2035. In contrast to 2010, global demand for primary energy is predicted to rise by 40% by 2035. In China, energy used for the transportation, treatment, and distribution of water resources has dramatically increased due to rapid economic growth and industrial expansion (Li et al. 2016). The supply limitation in the majority of the world places tremendous pressure on current water and energy infrastructure. Furthermore, environmental disasters brought on by unsustainable water and energy use are the greatest global concern (Waughray 2011). Therefore, conserving water and energy becomes one of the primary requirements for achieving worldwide sustainable development (Dai et al. 2018; Feng et al. 2012; Gu et al. 2016; Ramos et al. 2010).

The scientific and policy community has been paying more and more attention to the water-energy nexus (Dai et al. 2018). Zhou et al. (2016) examined the possible effects of energy policy on water use using a general multi-sectoral computable dynamic equilibrium model. Fang and Chen (2017) adopted the input–output analysis of ecological networks to investigate the energy-water nexus. Pacetti et al. (2015) examined the trade-offs between water and energy production by exploring water footprint and life-cycle assessment techniques. Ahmad et al. (2020) conducted a systematic examination and a thorough evaluation of the water-energy nexus from energy efficiency, spurring initiatives to reduce water and energy use and achieve the highest potential efficiency for urban water delivery systems.

Water-food nexus

Due to the uncertainty of future safe access to resources necessary for livelihoods, the water-food nexus has recently drawn the attention of scientists (Ahmadzadeh et al. 2016). Furthermore, the sustainable management of common pool resources, such as water and food, has become a substantial concern (Endo et al. 2017). The water-food nexus is conducive to achieving fair, balanced, and sustainable access to water and food resources and meeting the rising needs of the global population (Corona-López et al. 2021). Food and water resources work in harmony to guarantee a sustainable social environment for human existence. Water resources are required for the production, preparation, and consumption of food. The capacity to meet food demand depends on the availability of water resources (Zhang et al. 2018). Food processing, distribution, transaction, and consumption also rely on water resources besides food production (Molajou et al. 2021).

Agriculture is the largest user of water, accounting for around 70% of the world's freshwater consumption (Mohtar & Daher 2012). Besides, due to the increasing demand for food, it is predicted that from 2015 to 2050, the worldwide demand for food production may increase by 70%, while in developing countries, the rate will be up to almost 100% (Li et al. 2016). Moreover, a 10% rise in agricultural water demand is also anticipated by 2050 (Lee et al. 2017).

Energy-food nexus

Agriculture systems also contribute to the energy supply besides consuming energy. Energy is used for various tasks in the food system, such as running agricultural equipment and the preparing, processing, packing, and transporting of food (Ingram 2011). Energy is also applied to the manufacturing of fertilizer, an indispensable nutrient for crops (Garcia and You 2016). Energy inputs and utilization play an increasingly great role in the mechanization of the agriculture industry. Moreover, food crops connect food and energy as the primary raw material for the manufacturing of biofuels (D'Odorico et al. 2018).

Currently, nearly 30% of the world's energy is used for the production and distribution of food. Although primary agriculture just consumes a small portion of the world's energy, food processing and transportation take nearly 40% of the energy, greatly raising global energy consumption (Sims 2011). Additionally, the food-energy nexus can be an approach to climatic environment mitigation as worries about climate change increase (Namany & Al-Ansari 2021). Therefore, scientists in the world should focus on the existing energy-food nexus.

Water-energy-food nexus

An innovative idea for resource management called the WEF nexus has attracted significant attention around the world (Weitz et al. 2017). One of the development issues was identified as understanding the connections among water, energy, and food as early as the 2008 Davos Annual Conference (WEF, Ed., 2011). Concerns about the WEF nexus have generated many conversations about innovations in managing water, energy, and food resources since 2008 (Giupponi & Gain 2017). In 2011, the issued Global Risks Report (6th edition) regarded the "WEF Nexus" as one of the three primary risk groupings (World Economic Forum 2011). The same year, the "Water-food-Energy Security Bond Conference" in Bonn, Germany, foresaw threats to food, energy, and water security due to the rise in global population and economic development. It also stressed the complicated mutual connections among the securities of water, energy, and food supply and examined the interconnections of the systems of water, food, and energy. The official definition is a significant development in the study of nexus (Hoff 2011) . The Rio + 20 Summit in 2012 saw the rise of "nexus thinking," urging new approaches to handle interconnected water, energy, and food problems. The study on "Water-Food-Energy Nexus in the Asia–Pacific Area" was published by the United Nations Economic and Social Council for Asia and the Pacific in 2013 (Deng et al. 2017). Moreover, many worldwide academics expressed their opinions on the relationships among water, energy, and food. Hoff (2011) championed the idea of the overall synergy of sectors and put forth the framework of the WEF nexus research. According to Salem et al. (2022), the WEF nexus aims to optimize objectives and expectations by balancing social and natural resource development and tackling related issues in the context of sustainable development. Simpson and Jewitt (2019) regarded the connections among water, energy, and food as an efficient instrument for sustainable development.

Researchers have conducted extensive literature reviews to explore the interrelationships among water, energy, and food, as well as their integrated management and mutual impacts. Molajou et al. (2021) delved into the nexus of water, energy, and food from a comprehensive management perspective. Concurrently, Soleimanian et al. (2022) focused on addressing the application barriers within the water-energy-food (WEF) nexus, seeking optimal water simulation models to integrate into the nexus concept. On another front, Arthur et al. (2019) provided a detailed account of the current state of quantifying interdependencies among food, energy, and water in urban settings through the extraction and analysis of indicators. Borge-Diez et al. (2022), against the backdrop of sustainable development, addressed management issues within the water-energy-food nexus by reviewing methodologies, tools, and case studies, aiming to identify spaces for improvement and analyze existing gaps and challenges. Simultaneously, Opejin et al. (2020) assessed the trajectory and impact of food-energy-water (FEW) nexus literature through bibliometric analysis, aiming to delineate key themes and future research directions. Furthermore, Zhang et al. (2019) undertook a comprehensive review of the concepts and methods of the food-energy-water (FEW) nexus across various scales, aiming to establish a conceptual knowledge framework for scientific analysis and policy development related to the urban FEW nexus. These studies collectively offer crucial insights to facilitate a profound comprehension of the intricate interplay among food, energy, and water, enabling effective responses to their complex relationships.

In this context, scholars from around the world have investigated management techniques for the links among water, energy, and food using various analytical tools. Allan (2003) advocated "virtual water" to manage resource pressures and foster cross-sectoral cooperation for holistic governance. Salmoral and Yan (2018) investigated how water and energy were allocated in economic systems using virtual water and embedded energy theory. Al-Ansari et al. (2015) proposed an integrated WEF nexus life cycle evaluation method to assess the regional environmental situation and the condition of Qatar's water, energy, and food resources. Similarly, Mannan et al. (2018) investigated the inner links in the energy-water-food nexus using a life cycle assessment technique. Li et al. (2019) created an integrated and intuitive fuzzy multi-objective non-linear model to manage the scarce resources of water, food, and energy in agricultural systems. Medina-Santana et al. (2020) realized the optimum WEF nexus for agricultural communities using a multi-objective non-linear planning model. Yu et al. (2020) proposed a multilevel interval fuzzy confidence constrained planning (MIFCP) method for regional WEF nexus systems. Aviso et al. (2011) suggested a fuzzy input–output model for the optimization of supply chains while accounting for water footprints. Owen et al. (2018) introduced a multi-regional input–output approach to evaluate the influence of WEF nexus in supply chains. Al-Thani et al. (2020) built a linear optimization model for WEF nexus management and optimized the distribution of water and energy resources to maximize agricultural production. Figure 1 depicts the intricate relationships among water, energy, and food.

Data sources and research method

Data sources

To demonstrate the concept and application of the WEF nexus and verify that the data from the literature are complete and representative, this study searched the Web of Science core database using the following themes: "water-energy-food," "food-energy-water," "food-water-energy," "water-food-energy," "energy-water-food," and "energy-food-water" to obtain research data. An advanced search for WEF nexus yielded 1399 documents from January 2007 to December 2022. For analysis, the data in the Web of Science format were filtered first, and duplicated ones were removed. Ultimately, 1313 valid papers were obtained and used as the source data in this study.

Bibliographic analysis

CiteSpace is known as an effective visualization program for the map of scientific knowledge due to its extensive co-citation capability (Zhu et al. 2020). CiteSpace can represent the history, research frontiers, and changing trends of a specific study area in a more effective, intuitive, and multi-angle visualization way than other tools (Chen 2006). Consequently, it can prevent the influence of researchers' subjective judgment to obtain objective results to some extent. This study adopted CiteSpace to examine and evaluate the WEF nexus, thoroughly analyzing scientific research on this topic. Using CiteSpace's data conversion tool, the selected literature is sorted by publication date and transformed into a processable document data format. The quantitative analysis process of the WEF nexus is shown in Fig. 2.

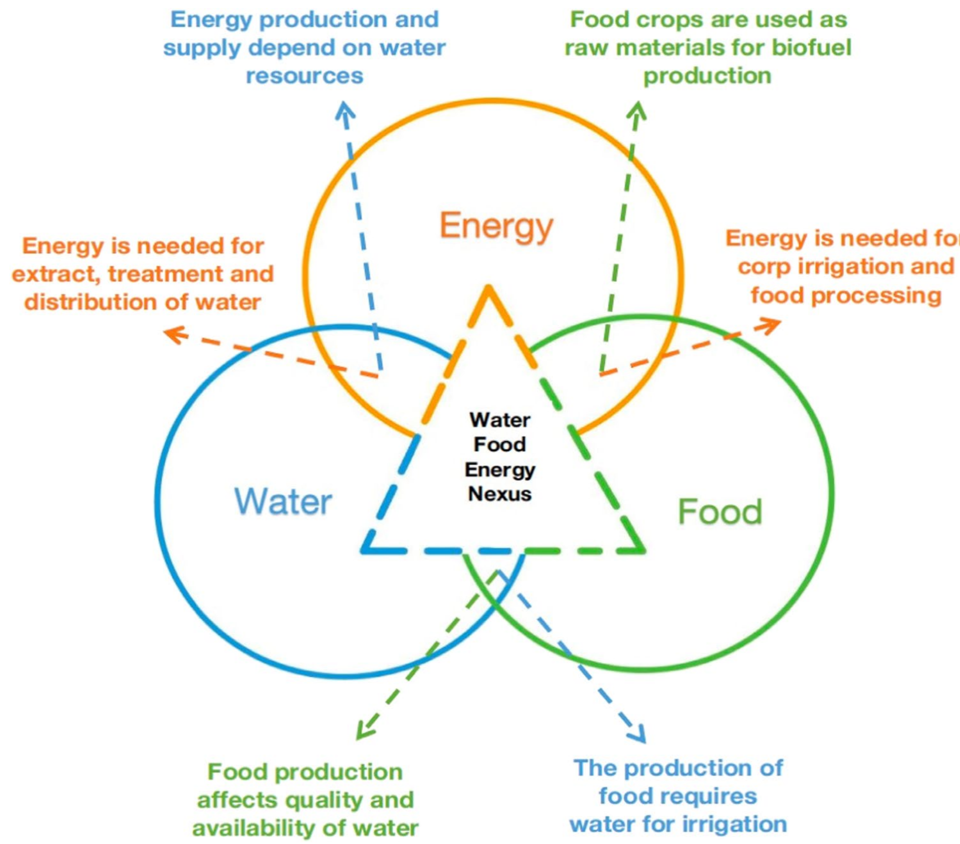
Results and discussion

Trend analysis of literature publication

Analysis of literature publication volume

The search reveals that 1313 papers screened for this study were published after 2007. The annual circulation of papers from 2007 to 2022 is depicted in Fig. 3. The search results indicate significant differences in the WEF nexus at different stages. Its literature volume changes broadly

Fig. 1 Map of the WEF nexus



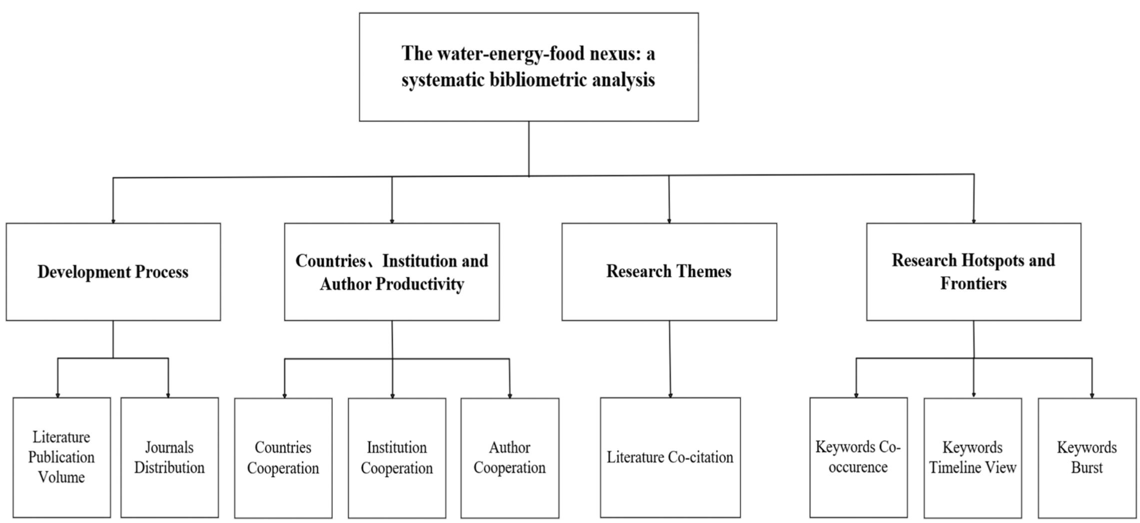


Fig. 2 Analysis process of WEF nexus

through three phases, newborn, rapid growth, and mature development.

First, during the newborn phase from 2007 to 2010, the number of publications is relatively small. The research on bonding relationships was in its infancy and mainly focused on the interconnection of the two subsystems in the WEF nexus. Therefore, research on the WEF nexus is scattered and yet to be systematized (Zhu et al. 2020). Second, the rapid growth phase started from 2011 to 2015, when there was an increase in the literature. The Bonn Conference in

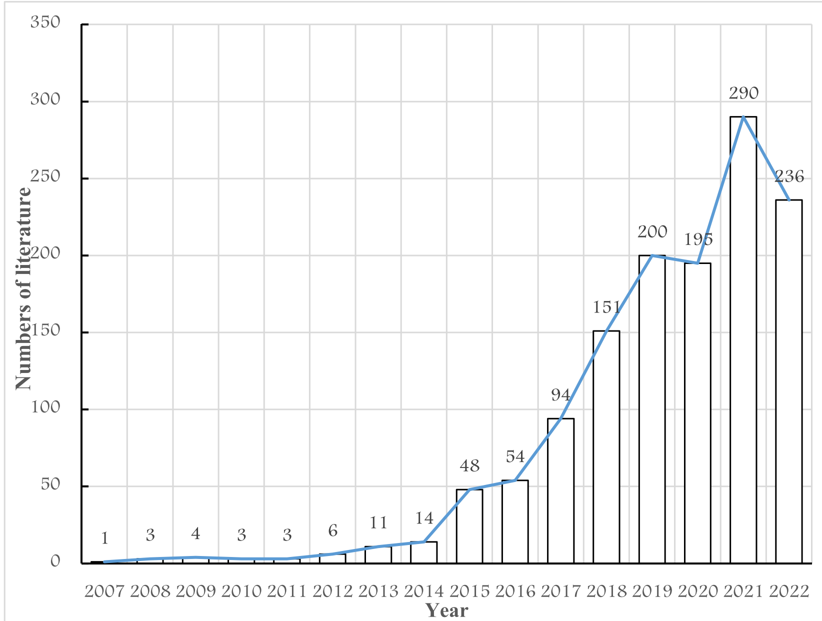


Fig. 3 Number of published literature on research on the WEF nexus, 2007–2022

2011 marks the pinnacle of the nexus study. Around 300 academic, commercial, and governmental institutions engaged in nexus research during this period (Endo et al. 2017). Moreover, at this time, the WEF nexus research was increasingly linked with sustainable development (Hussey & Pittock 2012). As a result, there are a substantial number of publications on the WEF nexus. Third, from 2016 to 2022 is the mature development phase. The total number of WEF nexus articles increased, reaching a peak of 290 in 2020. It suggests that the WEF nexus, a worldwide hot subject, is further expanded.

Key journal types

Figure 4 is the periodical co-citation network of the WEF nexus built by CiteSpace software. Nodes represent referenced journals. The bigger the node, the more citations. The co-citation frequency, centrality, and journal titles of the top ten journals in the WEF nexus field are shown in Table 1. Majority of the journals that publish literature in WEF nexus related areas are from environmental or high-impact publications. The top five periodicals featuring papers on the WEF nexus are the *Journal of Cleaner Production*, *Science of the Total Environment*, *Environmental Science & Policy*, *Energy Policy*, and *Applied Energy*. With 650 citations from 2007 to 2022, the *Journal of Cleaner Production* is one of the best publications in environmental research. The journal aims to share knowledge and research on concepts, tactics, and technology developments to promote social and regional sustainability. *Environmental Science and Policy*, the second most referenced journal, focuses on ecology and science and fosters multidisciplinary studies on environmental concerns. The total citations of leading international environmental publications of *Environmental Science & Policy*, *Energy Policy*, and *Applied Energy* are 593, 586, and 509, respectively. Overall, these publications have the maximum impact on water resources and environmental sciences. It implies that the WEF nexus is an excellent future topic for environmental professionals.

Network analysis of country, institution, and author cooperation

Analysis of country cooperation network

The findings of the research of countries represent the development level in this field of each country. Figure 5 depicts the visual analysis of CiteSpace to comprehend the global cooperative network of the WEF nexus. The number of published articles in a nation is represented by the size of the corresponding node. The lines connecting nodes represent international collaborations. The thickness of the connection between nodes indicates the partnership's strength. The importance of a nation on a map is reflected by its centrality. Table 2 shows the top ten nations sorted by the number of published publications. Figure 5 and Table 2 exhibit that the USA ranks top with 505 published articles, followed by China (282), the UK (202), Germany (125), and the Netherlands (87). The centralities of Germany (0.19), Italy (0.11), and Australia (0.12) exceed 0.1, suggesting that these three nations are more significant in the field of the WEF nexus. In general, the research on the relations of the WEF nexus is dominated by developed nations like those in Europe and the

Fig. 4 Journal co-citation network diagram

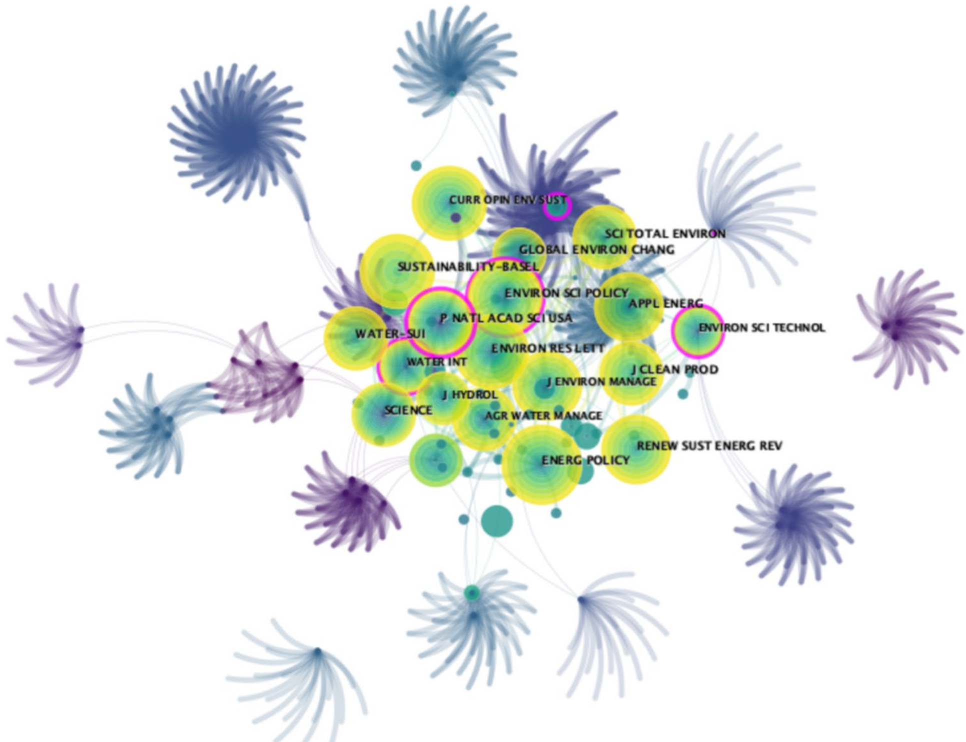


Table 1 Top 10 most productive research journals in WEF nexus field

Rank	Count	Centrality	Journal
1	650	0.05	*Journal of Cleaner Production*
2	634	0.03	*Science of the Total Environment*
3	593	0.06	*Environmental Science & Policy*
4	586	0.02	*Energy Policy*
5	509	0.02	*Applied Energy*
6	507	0.02	*Environment Research Letters*
7	482	0.01	*Renewable & Sustainable Energy Review*
8	456	0	*Sustainability*
9	442	0.02	*Science*
10	440	0.01	*Water*

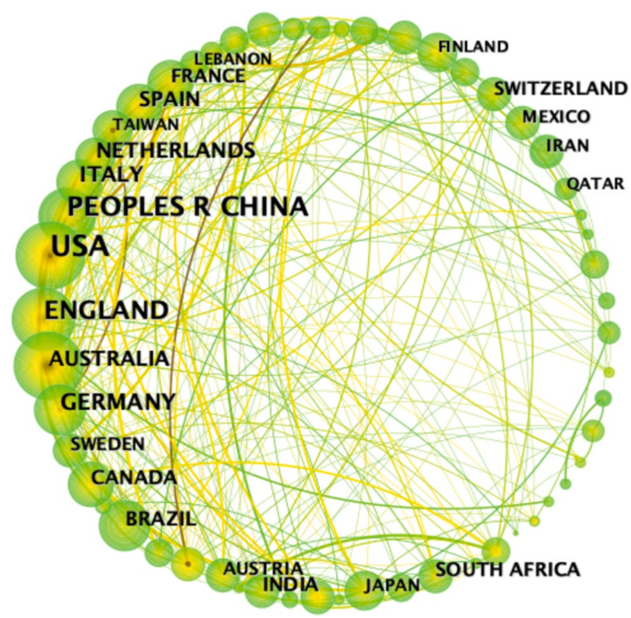


Fig. 5 Diagram of the country cooperation network

USA. In contrast, developing nations have less research capability. According to Gain et al. (2015), many developing countries are unaware of the connections among water, energy, and food, resulting in a dearth of studies on this subject.

Analysis of institutional cooperation network

A visual examination of research institutions displays the actual outcomes and collaborations of institutions in a subject. The number of articles published by each institution is reflected in the size of the corresponding node in the graph. The larger the node, the more articles are published by the institution. The lines connecting the nodes symbolize institutional collaborations. Figure 6 shows a great number of nodes and lines between institutions, indicating that many of the institutions in the

Table 2 Top 10 published research countries in WEF nexus field

Rank	Count	Centrality	Year	Country
1	505	0.05	2007	USA
2	282	0.04	2009	China
3	202	0.09	2012	England
4	125	0.19	2009	Germany
5	87	0.06	2014	The Netherlands
6	83	0.11	2014	Italy
7	76	0.12	2008	Australia
8	71	0.08	2014	Spain
9	64	0.01	2017	Brazil
10	56	0.08	2015	Canada

Table 3 Top 10 published research institutions in WEF nexus field

Rank	Count	Centrality	Year	Research institution
1	45	0.08	2015	Chinese Acad Sci
2	42	0.12	2016	Beijing Normal Univ
3	40	0.08	2018	Texas A&M Univ
4	28	0.04	2018	Hohai Univ
5	26	0.15	2012	Univ Oxford
6	25	0.19	2017	Univ Exeter
7	22	0.14	2014	Amer Univ Beirut
8	20	0.01	2009	Natl Taiwan Univ
9	20	0.02	2018	Univ Chinese Acad Sci
10	19	0.08	2014	UCL

chart work closely. Then, the data of the papers issued by each institution is analyzed. Table 3 shows the top ten research institutes in terms of the number of articles published in this discipline. The top five institutions of the WEF nexus research are the Chinese Academy of Sciences (46 papers), Beijing Normal University (42 papers), Texas A&M University (40 papers), Hohai University (28 papers), and Oxford University (26 papers). Furthermore, most organizations produced more than 20 articles, indicating that the WEF nexus has attracted the increasing interest of experts.

Analysis of author cooperation network

The co-citation network of authors in the discipline of nexus was built using CiteSpace, as illustrated in Fig. 7. Prominent authors in this research were compared and analyzed. The schematic diagram of the author co-citation network depicts the collaborations of authors for the WEF nexus and the depth of the relationship, providing researchers with a reference for collaboration in this research area. As shown in Table 4, the co-citations of all three authors, Hoff H, Bazilian M, and Fao, are 250 or more. In addition, Rasul G, Endo A, and Biggs EM are ranked fourth, fifth, and sixth with 228, 218, and 193 frequencies, respectively.

Analysis of literature co-citation

The literature with the same research topic and reference is regarded as co-citation literature, containing a great quantity of scientific knowledge in the scientific map. Co-citation literature can be used to efficiently conduct research on the WEF nexus. The larger the number of co-citation

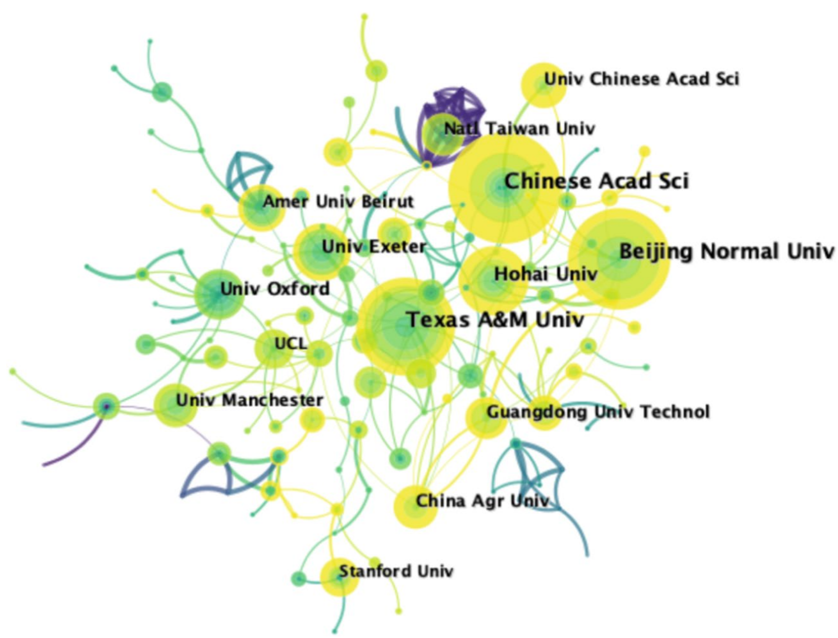


Fig. 6 Diagram of the institutional cooperation network

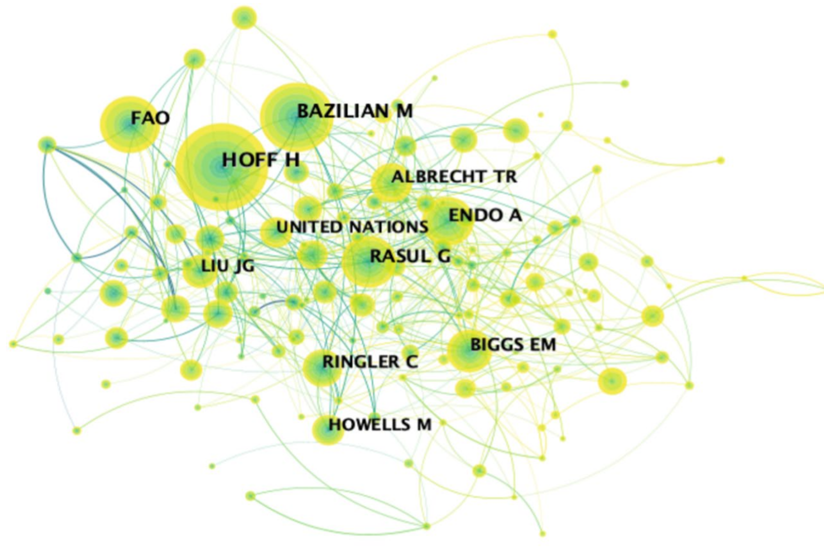


Fig. 7 Diagram of the author's co-citation network

Table 4 Author information table of the top 10 in WEF nexus field

Rank	Count	Author
1	390	Hoff H
2	307	Bazilian M
3	255	Fao
4	228	Rasul G
5	218	Endo A
6	193	Biggs EM
7	177	Albrecth TR
8	169	Ringler C
9	151	Liu JG
10	137	United Nations

literature, the closer the correlation between literature. Figure 8 is the network map of the co-citation literature. The authors cited the most times are Albrecht TR, Endo Ad, and Biggs EM, indicating that their articles have significant influences on the research field of the WEF nexus. Albrecht TR et al.'s paper in the 2018 *Environmental Research Letters*, which proposed a comprehensive framework and approach to promoting sustainable water, energy, and food management, is cited most frequently.

Analysis of hot research topics and frontiers

This section analyzes the keywords in the literature based on CiteSpace. It identifies research areas currently concentrated and predicts future hotspots, guiding scholars in their following research work.

Keyword co-occurrence analysis

The highlights of the research are summarized in the keywords. The frequencies of the keywords represent the

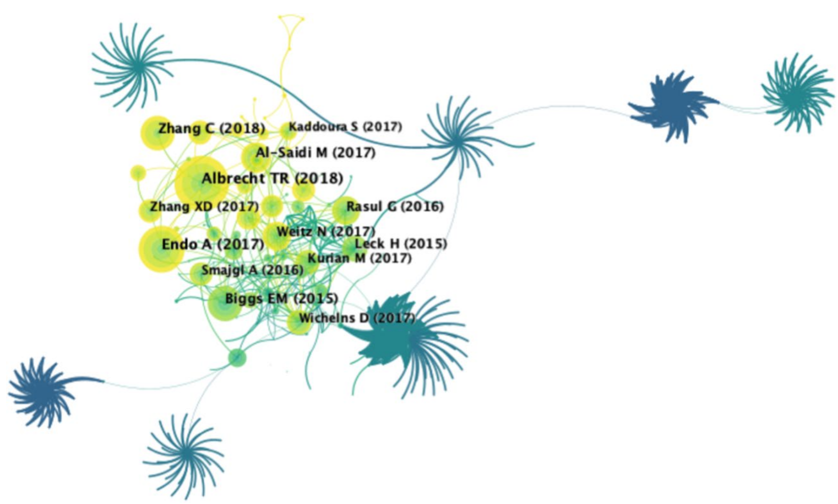


Fig. 8 Co-citation knowledge map of literature

research directions and hotspots in the field. The sizes of nodes in the graph denote the frequencies of keywords. The lines connecting these nodes exhibit how closely the keywords are related. Table 5 shows the distribution of terms searched for frequently, such as "nexus," "water-energy-food nexus," "food-energy-water nexus," and "sustainable development." Due to the strong connection between the WEF nexus and climate change, the word "climate change" is used the most frequently, with 259 citations. Water-energy-food nexus comes in second place, with 249 citations, followed by "the system," with 183 citations. The co-occurrence of topics and keywords that are closely related to WEF can be displayed in network graphs. Furthermore, the wider the circle on the graph, the greater the significance or influence of the research field on WEF. The frequency of each keyword is displayed in Fig. 9.

Keywords timeline view analysis

The clustering timeline analysis of keywords using CiteSpace further probed into the evolution of each cluster. The intensities of the supported associations of keywords between clusters can be reflected by the lines between clusters. Figure 10 illustrates that grouping yields obvious boundaries for the 11 cluster templates. The smaller the cluster number, the larger the cluster template. The largest one is cluster 0, and cluster 11 is the smallest. The chart shows that each cluster-tagged research area can sustain an ongoing in-depth study, and a large number of keywords with common usage emerge in each research area. Among them, clusters 5 (water-energy-food nexus), 9 (food-water-energy nexus), and 10 (energy-water-food nexus) are search phrases whose primary study materials are their keywords.

Table 5 Top 20 keywords with co-occurrence

Rank	Occurrences	Keyword	Rank	Occurrences	Keyword
1	259	Climate change	11	108	Food-energy-water nexus
2	249	Water-energy-food nexus	12	101	Policy
3	183	System	13	100	Resource
4	181	Management	14	95	Sustainability
5	151	Impact	15	87	Framework
6	147	Model	16	87	Land
7	142	Sustainable development	17	84	Consumption
8	136	Security	18	80	Governance
9	130	Nexus	19	77	Life cycle assessment
10	121	Perspective	20	76	Challenge

Fig. 9 Keyword co-occurrence network map

Results analysis of burst keywords

Keyword burst analysis can disclose research trends in the industry over the time frame of the study. Clusters containing more nodes in CiteSpace represent more active aspects or emerging trends in the research field. The timeline is depicted by the light blue line in the article, and the red line shows the emerging keywords from the literature on the nexus from 2007 to 2022. High-intensity keywords denote the cutting edges of studies at particular times. Figure 11 illustrates that the three keywords of the research on the nexus, "food security," "environment," and "freshwater," have been active for 7 years. Food security has the highest intensity. It implies that global academics have followed the field for the longest time. Researchers' concentration on system dynamics has increased since 2019 and will stay the same in future.

Conclusions

Research conclusions

Due to the rising demand for water, energy, and food, the WEF nexus is viewed as a multidisciplinary solution. This study employed bibliometric analysis to systematically and graphically outline the literature on the WEF nexus from 2007 to 2022, aiming to deeply comprehend the development process and research trends. Since 2011, the number of literature has risen steadily, peaking in 2015. Academic collaboration across countries and institutions has become a prominent topic. The USA is the most productive country in this field, followed by China and the UK. The Chinese Academy of Sciences has the most publications (46), followed by Beijing Normal University (42) and Texas A&M University (40). The journals with the most published literature include the *Journal of Cleaner Production* and the *Science of the Total Environment*. The research hotspots and trends are shown by the study of frequently referenced publications and keywords. Overall, the bibliometric analysis depicts a picture of WEF nexus literature and research orientations. These findings will be a useful reference for future studies.

Research limitations

Based on the Web of Science database, this study acquired and analyzed the literature on the WEF nexus to find hot areas and frontiers of research in this field, offering a

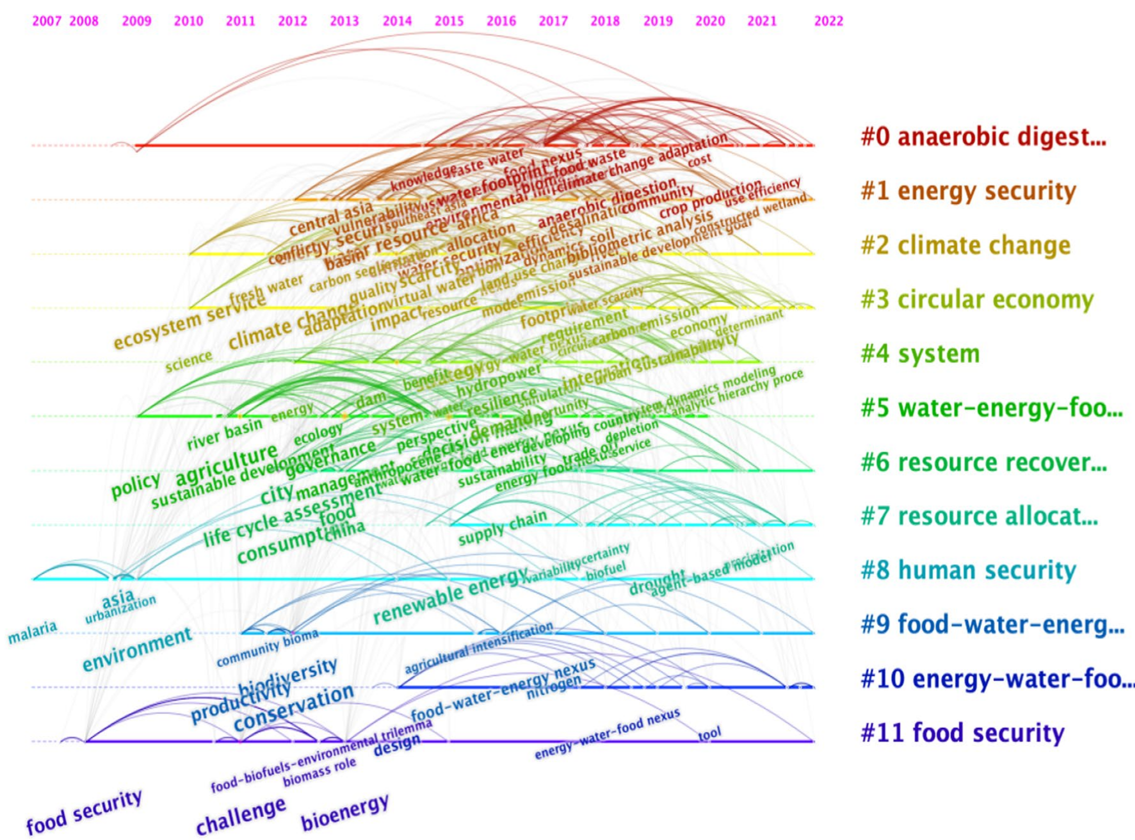


Fig. 10 Clustering timeline view map

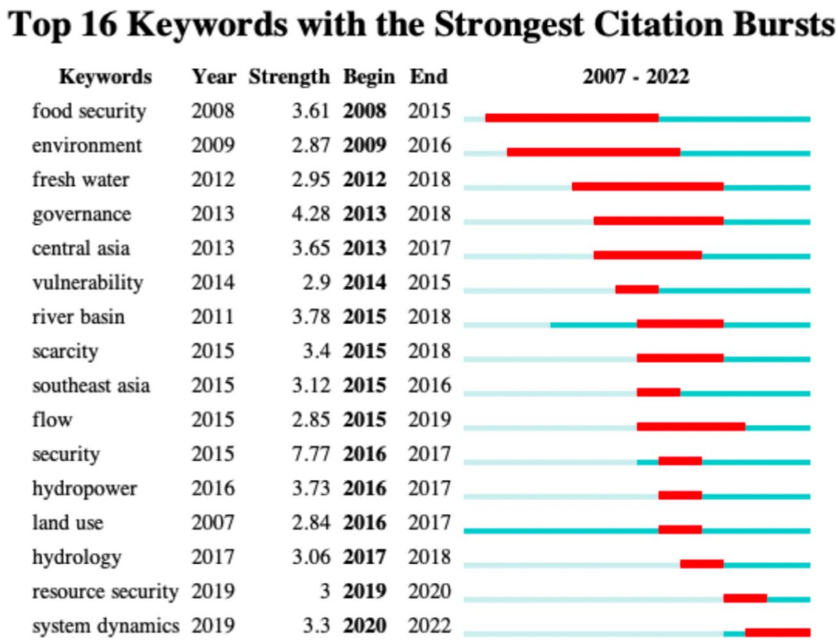


Fig. 11 Keywords with the strongest citation bursts in WEF nexus filed

reference for relevant researchers. Because of the limits of a single database and the time range, the literature may be insufficient, and the data analyzed may be biased. However, the research methods and the dependability of the results remain unchanged. Future studies can combine with other visualization software and databases to obtain more thorough analysis results.

Research implications and prospects

Studying the WEF nexus is essential for worldwide sustainable development and socioeconomic expansion. The pressing scientific concerns are how to effectively manage the three resources through trade-offs and enhance the efficiency of resource utilization. Therefore, the primary study directions in this topic include but are not limited to the following two features.

Climate change

As a vital concern for human beings and an immense obstacle to sustainable human growth, the effects of global climate change have elevated to the top of the agendas of governments and academic institutions during the past 10 years. The hazard and increased climatic unpredictability brought on by climate change are anticipated to persist as catastrophic climate change–related occurrences rise around the world (Yoon et al. 2022). The effects of climate change on the three sectors of water, energy, and food have gained global attention in studies (Han et al. 2022). Hoff (2011) identified these three industries as those that would be the most vulnerable to the effects of climate change. Food and energy production are subject to climate change, particularly unstable precipitation and catastrophic occurrences, such as droughts and floods (Zscheischler et al. 2020). The Intergovernmental Panel on Climate Change (IPCC) reported that 14 million people experienced severe drought and food shortages in 2016 (Zhang et al. 2021a). According to Tortorella et al. (2020), climate change has an influence on the availability of water resources, reducing the ability to produce energy and food. Similarly, Mimi and Jamous (2010) hypothesized that global warming would increase the agricultural need for water while decreasing rainfall, resulting in water shortages and detrimental impacts on food production. The demand for water, energy, and food will grow due to climate change and human pressures (Shrestha & Aryal 2011; Rockström et al. 2009). However, the production of the three sectors can decrease global greenhouse gas emissions and mitigate climate change (Howells et al. 2013). In contrast, economic growth and climate change hinder the sustainability of water, energy, and food (Bhaduri et al. 2015; Biggs et al. 2015). It highlights the vital need to make decisions on the rational utilization of resources in light of the pressure that climate change will put on water, energy, and food supplies (Holtermann & Nandalal 2015).

In managing the WEF nexus, climate change must be considered. Certain susceptible regions should take action to ensure water, food, and energy security under the effects of climate change (Holtermann & Nandalal 2015). The world community is concentrating on formulating new strategies for climate change and developments in water, energy, and food security (Rasul & Sharma 2016). The influence of climate change on WEF nexus interactions and the incorporation of the uncertainties it produces have been studied by international experts using a variety of quantitative planning methodologies and analytical tools. Han et al. (2022) assessed the influence of climate change and socioeconomic changes on water, energy, food, and other uncertainties by the meta-regression analysis. The most common approach for calculating how climate change will affect agricultural output and irrigation water is adopting crop models (Araya et al. 2015; Chenu et al. 2017). Yang et al. (2016) evaluated the complex effects of various climate change models on water, energy, and food in the Indus Basin using a hydro-agricultural economy model.

Carbon emissions

As one of humans' enormous challenges, global warming caused by greenhouse gas emissions threatens human life, prosperity, and security (Li et al. 2021). Resource usage and carbon emissions from agriculture turn into a critical problem in the setting of the increase in world population (Piao et al. 2010; Johnson et al. 2014). Two-thirds of the world's CO_2 pollution come from fossil sources (Mei et al. 2020). Additionally, energy consumption will increase CO_2 pollution (Martinez-Hernandez et al. 2017). Water resources are used in energy and food production (Wang et al. 2021), and energy is applied to irrigation and food production (Vora et al. 2017; Pellegrini and Fernández 2018), all of which aggravate carbon dioxide emissions. Moreover, crop growth is specifically impacted by atmospheric CO_2 concentrations (West & Marland 2002; She et al. 2017). Therefore, these four components of water, energy, food, and CO_2 emissions are intricately linked (Rulli et al. 2016; Walker et al. 2014; White et al. 2018; Ramaswami et al. 2017). In addition, scholars show increasing concern about the importance of water, energy, and carbon emissions to environmental initiatives (Wang et al. 2020). It is essential to explore the connections among water, energy, food, and carbon emissions.

The water-energy-food-carbon nexus (WEFC) exposes the interrelationships across several domains. It is commonly employed in integrated assessments to minimize the impact on resource consumption and environmental burdens (Sanders & Masri 2016). The Paris Agreement underlines the necessity of reducing greenhouse gas emissions and quickly addressing climate change and its effects, thus advancing sustainable development. Furthermore, worldwide scholars use various mathematical planning techniques and analytical tools to study carbon emissions and the WEF nexus. In the agricultural WFEC nexus, Zhang et al. (2021b) proposed a modified model to lower carbon emissions and produce adequate water and land management options. Miller-Robbie et al. (2017) employed the WEF nexus to account for greenhouse gas emissions using the technique of life cycle assessment. It is an urgent need for more research on optimization techniques for the water-food-energy-carbon nexus.

Author contribution Yangxi Lv: conceptualization, methodology, validation, writing — original draft, funding acquisition. Mingkang Yuan: data curation, supervision, writing — review and editing, funding acquisition. Xiaofeng Zhou: visualization, software, validation. Yuanmin Wang: data curation, editing and typesetting. Xiaobing Qu: software, validation.

Funding This work was supported by the Chengdu University of Technology Postgraduate Innovative Cultivation Program (Grant numbers [CDUT2022BJCX012]) and the Philosophy and Social Science Research Fund of Chengdu University of Technology (Grant numbers [ZDJS202204]).

Data Availability Data will be made available on the request.

Declarations

Ethics approval and consent to participate The experimental scheme was formulated by the water resources allocation guidelines of Dujiangyan Management Committee and obtained personal written informed consent.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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