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# Trends in the Water–Energy–Food Nexus Research

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**Abstract:** This paper aims to analyze the scientific evolution and research trends concerning the water–energy–food (WEF) nexus, as well as its development within scientific databases. To achieve this, a bibliometric analysis has been conducted using publications sourced from Scopus and Web of science databases. This study examined key aspects such as primary journals, prominent authors, affiliated institutions, countries of origin, subject areas, and notable keywords. Furthermore, there is a dedicated section that delves into research and innovation gaps within publications related to the WEF nexus. Results reveal that research on the WEF nexus has experienced exponential growth over the past decade, with the majority of publications emerging between 2017 and 2023. The United States leads in this field, with engineering and environmental science being the predominant research categories, with Spain and Italy being the prominent countries in Europe. The WEF nexus concept in the agriculture sector is notably underdeveloped, particularly in its ties with the Sustainable Development Goals and the science–policy–society interface. The study stresses the importance of integrating health considerations into the WEF Nexus to understand the interconnections and their implications on public health, thereby enriching the Nexus approach with a critical dimension of human well-being. This situation underscores the urgent need to create a nexus community that bridges science and practice, and to incorporate this specialized discipline into university curricula.

**Keywords:** water–energy–food nexus; bibliometric analysis; gaps; topic modeling



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## 1. Introduction

The world is currently grappling with a pressing challenge in resource management, as the demands for water, energy, and food continue to escalate. This complex issue is exacerbated by factors such as population growth, urbanization, climate change, and environmental degradation. In order to address this multifaceted problem, the concept of the water–energy–food (henceforward, WEF) nexus has emerged as a potential solution. The WEF nexus recognizes the interconnectedness and interdependencies between water, energy, and food systems, as well as the vital role of ecosystems in sustaining them. By adopting a holistic approach, the WEF nexus aims to promote integrated resource management, enhance resource efficiency, and foster sustainable development. It encourages policymakers, scientists, and stakeholders to collaborate across sectors and disciplines, to identify synergies and trade-offs, and to develop innovative strategies that optimize resource allocation Embracing the WEF nexus not only ensures the long-term availability and accessibility of vital resources but also contributes to mitigating environmental impacts and enhancing resilience in the face of future challenges.

The WEF nexus gained particular prominence after the 2011 Bonn Conference, subsequent to the 2008 World Economic Forum Annual Meeting held in Davos (Switzerland). Following the Bonn Conference, the ecosystem has been incorporated into the triad of water–energy–food components. This concept was followed on by several organizations, including the United Nations Economic Commission for Europe (UNECE), the Food and Agriculture Organization (FAO), the World Economic Forum (2011), and the Join Research Center. WEF builds on the Integrated Water Resources Management (IWRM) principles, but differs from IWRM by not explicitly focusing on water, taking food security and energy security on board as well.

Due to the intricate interconnections between the WEF systems and their external resource and ecological surroundings, the sustainability triangle has expanded to encompass additional dimensions. These dimensions include water–energy–land–food [1], water–energy–climate–food [2], and ecosystem–water–food–energy [3]. This broader conceptualization aims to foster a comprehensive understanding of the opportunities, challenges, and trade-offs inherent in sustainability transitions within a more holistic system context.

Active collaboration among government agencies, the private sector, academia, and civil society is imperative for the successful implementation of the WEF nexus approach [4]. While the literature on the WEF nexus has grown, gaps persist in applying nexus frameworks to formulate policy recommendations [5]. Several recent review papers have employed various methodologies to pinpoint research gaps within the WEF nexus. This article aims to provide comprehensive insights into the decade-long evolution (2011–2023) of the nexus concept and framework, with a focus on identifying research gaps. The study addresses the principal research gaps that have influenced the evolution of the nexus concept through the exploration of three key questions: (i) Examining existing research on the WEF nexus; (ii) analyzing the progression of WEF nexus topics over the past twelve years; and (iii) identifying promising approaches and emerging research gaps within the WEF nexus literature.

## 2. Materials and Methods

This study employed a comprehensive methodology, integrating both a literature review and a bibliometric analysis. The methodology unfolded in three distinct steps:

- Database selection, processing, and merging (Step 1): This step involved a meticulous process of selecting, processing, and merging databases to establish a robust foundation for the study.
- Bibliometric analysis (Step 2): Delving into a thorough bibliometric analysis, this step aimed to extract valuable insights and patterns from the literature.
- Article selection (Step 3): Articles were selected utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, ensuring a methodologically sound and comprehensive approach.

### *2.1. Step 1: Databse Selection, Processing, and Merging*

Publications spanning the period of 2011–2023 were sourced from the Scopus and Web of Science databases. The database search specifically focused on articles featuring "Water-energy-food" in both the title and abstract.

Following the extraction of the file using specified keywords from both databases (Scopus records identified 900 articles, WOS records identified 601 articles), the information was filtered to eliminate duplications and rectify any errors. Subsequently, the database was consolidated into a single Excel file, resulting in a comprehensive compilation of 1278 articles.

### *2.2. Step 2: Bibliometric Analysis*

The data were analyzed using bibliometric software (VOSviewer, Version 1.6.20), enabling the identification of various subfields. These subgroups encompassed developmental trends, citation analysis, keyword co-occurrence analysis, collaboration analysis, and thematic analysis. The visualization of subgroup outputs and the generation of

networks, including authors, countries, keywords, and journals, were carried out using VOSviewer ([6,7]). A topic modeling analysis was conducted on the 1278 articles, utilizing the supervised latent Dirichlet allocation (sLDA) method.

### *2.3. Step 3: Article Selection*

This study adhered to established guidelines for conducting meta-analysis [8] Publications were chosen based on two criteria:

Criteria 1: Publications containing the most relevant keywords (Water–Energy–Food Nexus) were acquired from the co-occurrence analysis of authors' keywords. Out of the 1278 article, 468 were excluded.
Criteria 2: The documents were refined based on a citation range of 0–550, with a focus on selecting those with the highest number of citations number of citations (>50), accounting for approximately 7% of the entire database. A total of 86 articles were scrutinized to identify research gaps.

## 3. Results

### *3.1. Trends in Research on WEF Nexus*

Figure 1 depicts the evolution of scientific articles from 2012 to 2023. Over the past 12 years, the number of articles has experienced significant growth, increasing from 7 in 2014 to 253 in 2021. A substantial proportion, approximately 87% of the articles, were published between 2018 and 2023.

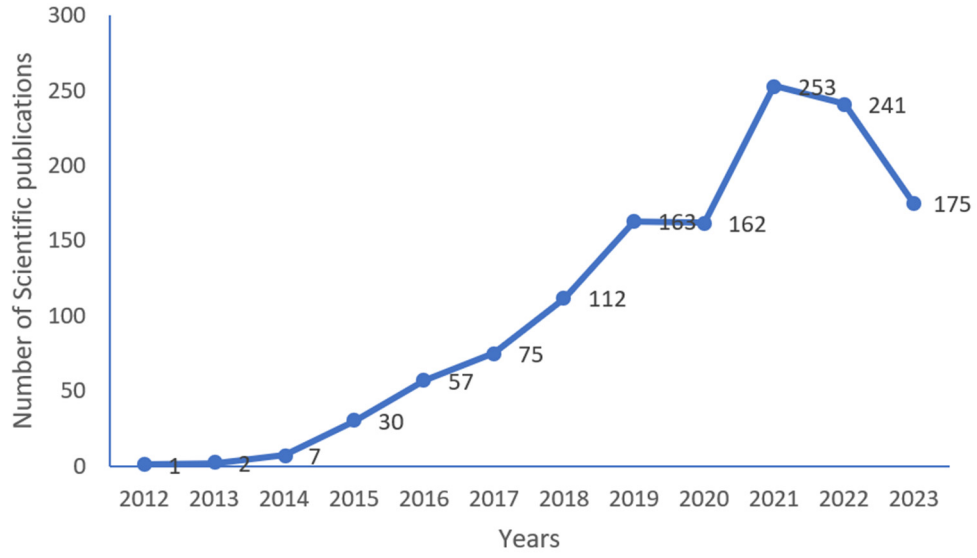


**Figure 1.** Distribution of annual scientific publications on WEF nexus research.

### *3.2. Prominent Scientific Journals for WEF Nexus Research Publications*

Figure 2 illustrates that the fields most represented in top publishing journals encompass sustainability, water resource management, environmental science, and cleaner production techniques.

The most cited journals are those where most of the articles are published; in particular *Environment Science and Policy*, *Water*, *Environmental Research Letters*, *Sustainability* and *Journal of Clear Production* (Table 1). The results are consistent with those obtained by Correa Porcel et al. [9]

**Table 1.** Number of total citations per journal.

| Journals | Total Citations |
|---|---|
| *Environmental Science and Policy* | 1974 |
| *Water* (Switzerland) | 1413 |
| *Science of the Total Environment* | 1343 |
| *Journal of Cleaner Production* | 1189 |
| *Environmental Research Letters* | 1187 |
| *Sustainability* (Switzerland) | 983 |
| *Frontiers in Environmental Science* | 691 |
| *Sustainability* | 228 |
| *Land* | 97 |

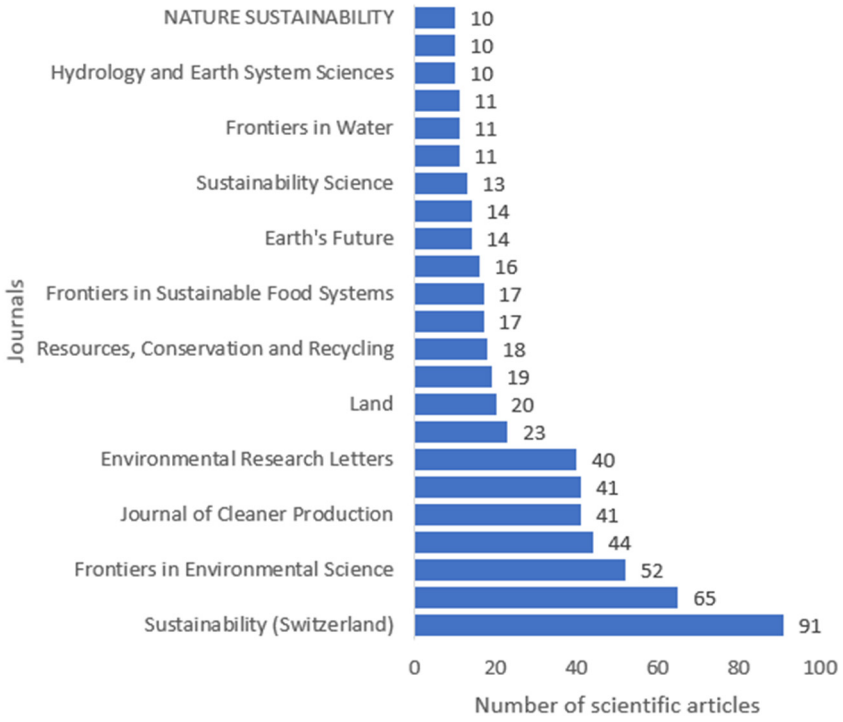


**Figure 2.** Number of scientific publications by journal.

### *3.3. Network Analysis*

The number of articles published in each country were considered, giving a clearer picture of the relative influence of each nation (Figure 3). The United States ranks first with 220 articles, followed by China with 125 articles. The UK occupies third place with 93 articles. Fourth and the fifth places are for Germany and Brazil with 57 and 31 articles, respectively. The top three countries (USA, China, and UK) represent one third of the total number of articles. These trends confirm the results obtained by Wang et al. [10].

The relationship between the different countries can be observed (Figure 4). The clusters group those nations with a minimum of five published articles on this topic.

In the map produced, the size of each node is proportional to the number of articles published by a respective country. The connecting lines between these nodes represent collaborative links between countries, with the thickness of these lines varying to reflect the degree of collaboration. Additionally, the map features colored clusters, which visually depict the primary groups involved in collaborative efforts.

Distinct groups of countries emerge, delineating identifiable clusters. The first, represented by the blue cluster, is led by the USA. The second cluster (green) is spearheaded by the UK and includes Italy, the Netherlands, Spain, Portugal, and Canada. The third cluster (red) encompasses Germany, China, India, and Egypt. Switzerland stands out, leading a separate group (purple cluster) that also includes Denmark, Norway, and the Czech

Republic. This clustering aligns with findings by [9]. Notably, in contrast to the "islands" effect observed in other disciplines where cross-authorships may not be prevalent, Figure 4 illustrates a global trend of cross-authorship.

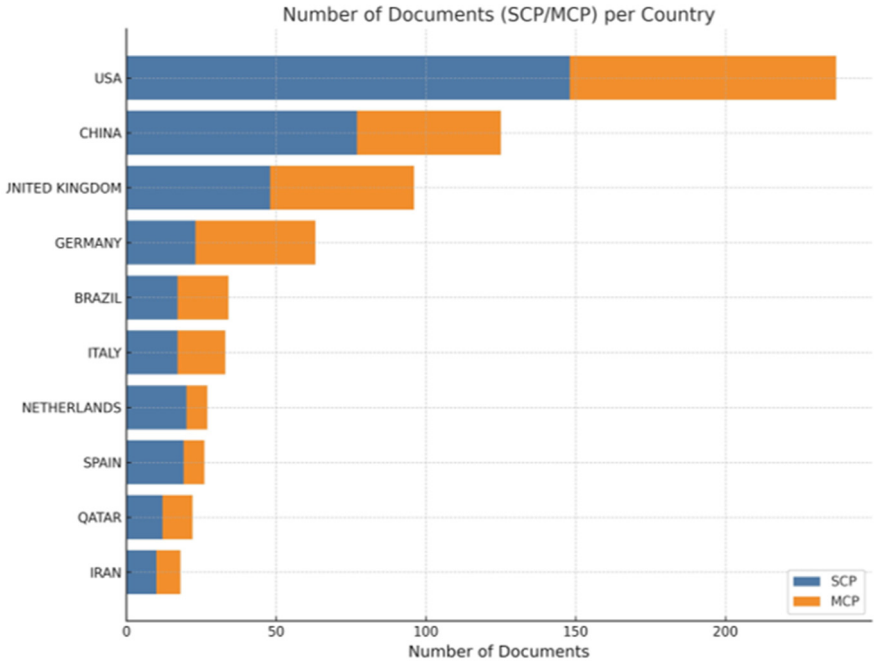


**Figure 3.** Countries with the most publications (SCP: single country publications, MSP: multiple country publications).

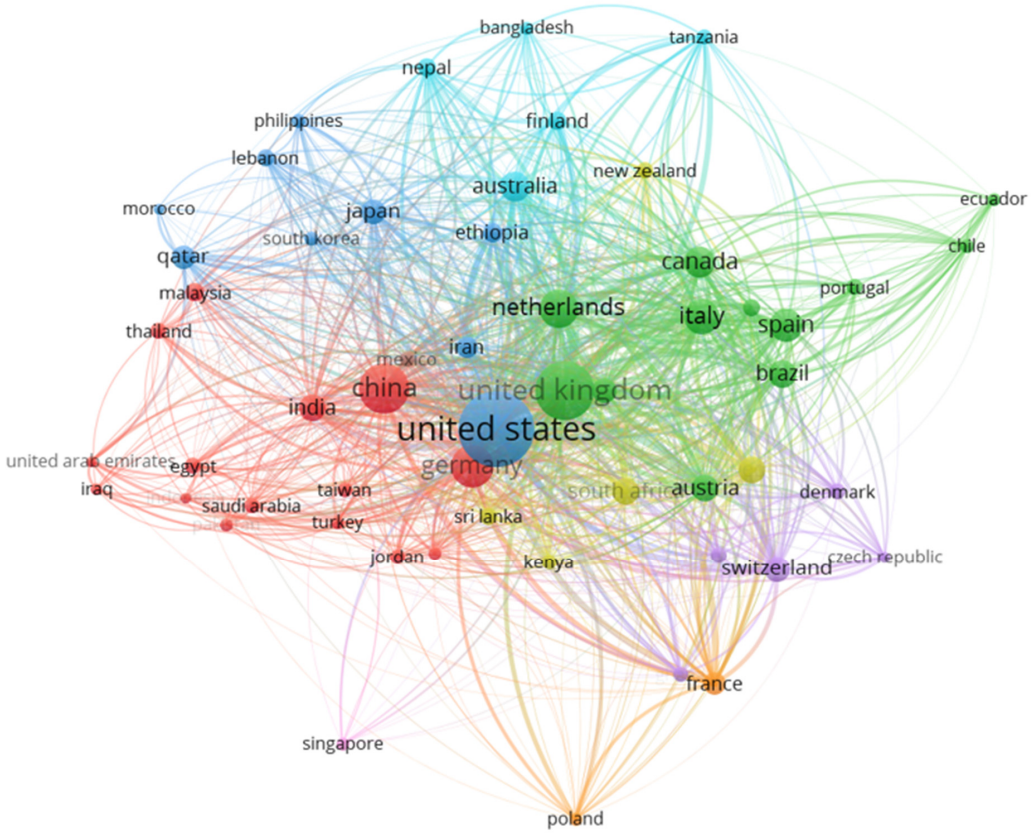


**Figure 4.** Co-authorship relations between countries.

A keyword-based mapping was constructed to identify the number of articles per country and the topics addressed within each country (Figure 5). In the United States, WEF nexus studies are more focused on food systems, water management, and energy, while in other countries like the UK, research is more concentrated on climate change, water management, and food production.


**Figure 5.** Country distribution of publications and research focus areas based on keywords.

### *3.4. Most Relevant Authors*

Considering the interdisciplinary nature of WEF nexus research and its results, the significance of authors is evaluated not just by the sheer number of their publications, but also through their local productivity. This is determined by tracking citations within the analyzed database, indicating instances where an author's work has been referenced by others in the same dataset. An analysis of these publications, as depicted in Figure 6, reveals a diverse distribution of author rankings, which varies both geographically and across various disciplines. Tareq-Al Ansari (h-index = 44) is the most productive author in terms of publications, with a technical research interest in energy systems and energy-water-food nexus aimed to address food insecurity, mainly focusing on the Middle East. In second place, Makoto Taniguchi (h-index = 56), with a background of hydrology and land–ocean interaction studies, addressed methods of the WEF nexus in addition to the inclusion of groundwater systems. His scale of work varied between global applications and studies between Japan and USA. Yaoping Wang (h-index = 13), with a research interest in ecohydrology, climate change, and water resources, contributed to different applications of the nexus on the urban scale in terms of water security, optimization methods, and soil studies. Claudia Ringler (h-index = 79), Yoshihide Wada (h-index = 96), and Rabi Mohtar (h-index = 40) share the same number of publications in fourth place, with research interest focusing on agriculture and development, hydrology and system science, and WEF security relationship with policies, respectively. As a result, preliminary findings suggest that the research conducted on the WEF nexus is distributed throughout a range of scientific fields and geographic areas, indicating the need for more evaluation of the authors' interactions.

On a first level, this is represented by the local citation results (Figure 7). These results help identify both H. Hoff and J. Liu as the most cited sources, despite not being the most productive recently. This highlights the ongoing importance of the initial WEF nexus concept proposed by Hoff, while recent researchers aim for a methodological and case-based development.

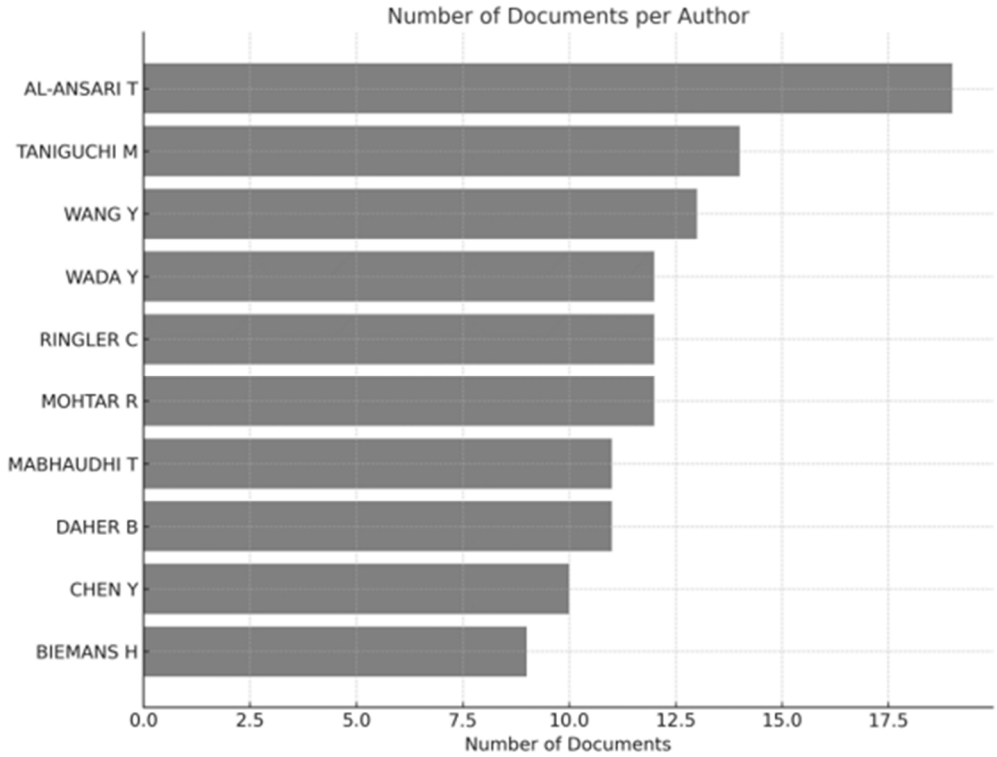


**Figure 6.** Most productive authors in terms of number of publications.

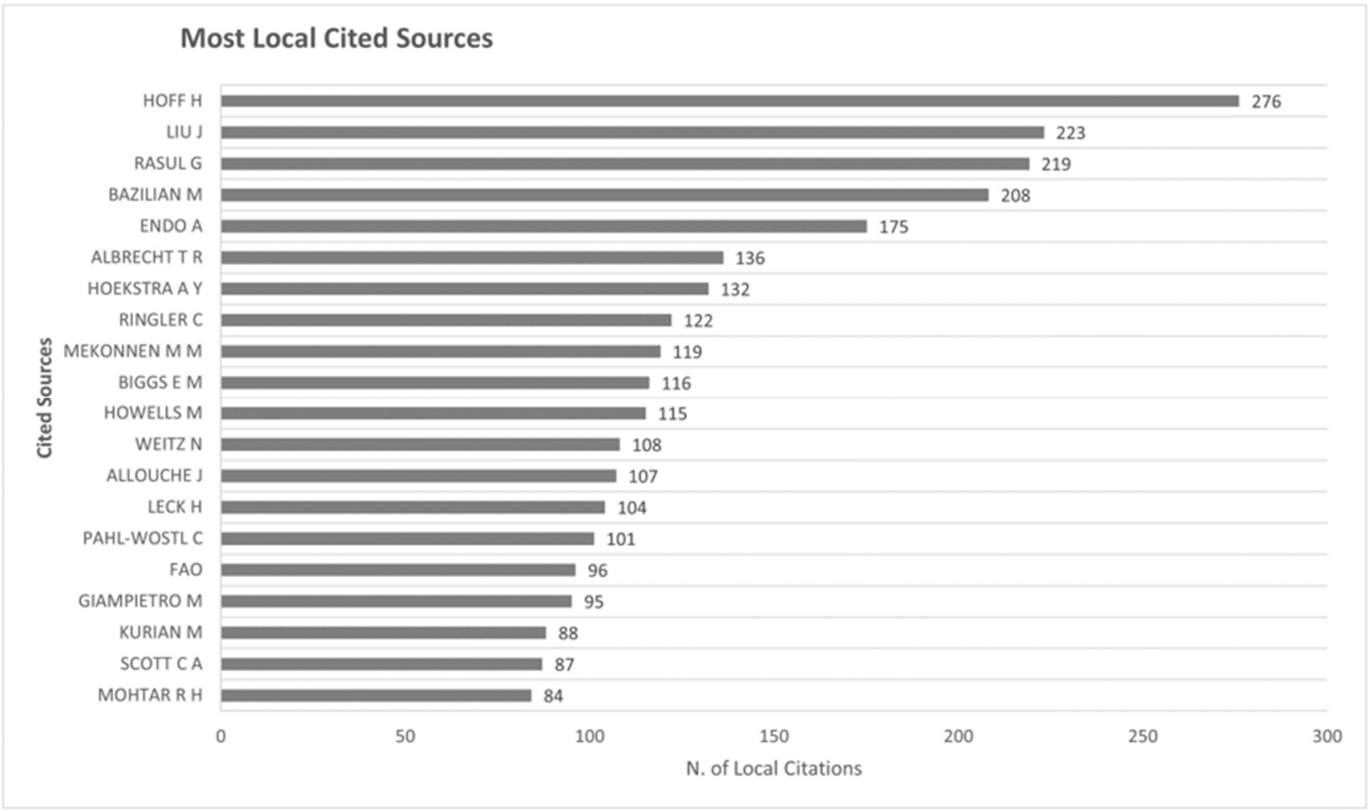


**Figure 7.** Most cited sources.

Another interesting aspect is presented in the fractionalized author's frequency distribution, where we refer to the distribution of the number of publications by individual

authors in the dataset. The fractionalized index of the top 10 writers is found to be greater than 1, indicating a noteworthy level of collaboration among these authors. In addition, it is possible to infer the contribution of several researchers like Mario Giampietro, and Alan Randall (Figure 8).

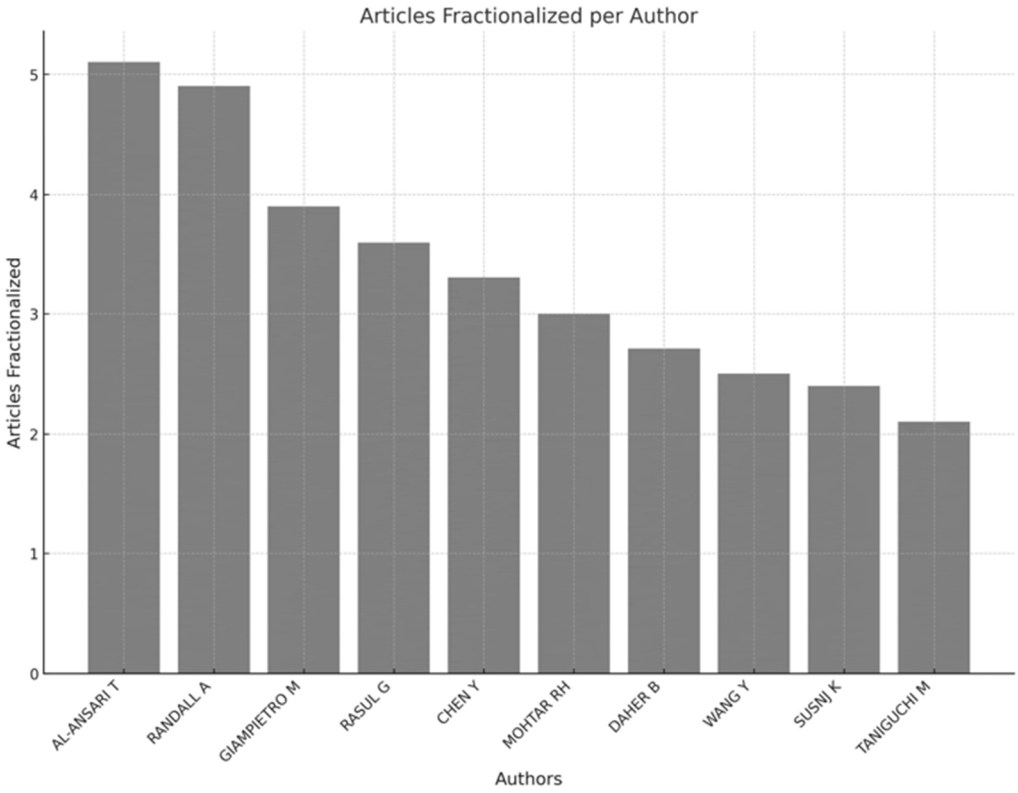


**Figure 8.** Articles fractionalized. For example, if a paper has four authors, each author would be credited with 0.25 of a paper. An equal contribution is assumed between the authors.

### *3.5. Co-Citation Analysis*

Co-citation analysis, introduced by [6], is a widely employed tool in the literature to reveal knowledge communities [11], research fronts [12], and invisible colleges [13]. Figure 9 illustrates four distinct clusters—green, red, yellow, and blue—representing references that share a common intellectual foundation but belong to different subfields. Each cluster offers insight into the evolution of the intellectual base of the WEF nexus, showcasing successive research across various sub-periods and subfields.

In an effort to explore the relationships between the writers in greater detail, Figure 9 illustrates these connections visually. A minimum of five publications by the author were chosen. The map illustrates how the most prolific writers on the WEF nexus are split up into four groups, all of which are affiliated with the same institutional entities. In a similar vein, cross-authorships across national and institutional borders are illustrated.

### *3.6. Co-Occurrence Network of Author Keywords*

The term "WEF Nexus" appeared most frequently (142), followed by "sustainability" (106), nexus approach (97), "Climate Change" (94), "Food-water-energy Nexus" (67), "sustainable development" (63), "water" (57), "energy" (51), "food" (44), SDG (41), and "ecosystems services" (37) (Figure 10). It is worth noting that "WEF Nexus" remains the strongest identifier for this discipline, followed by "Climate", "Nexus", and "Sustainability". Nexus identifiers are also disciplinary focus of "Water", "Energy", and "Food". "Sustainable Development Goals" is another effective designation. This shows that the SDGs are the ultimate nexus, and there appears to be an increasing tendency toward this as well.

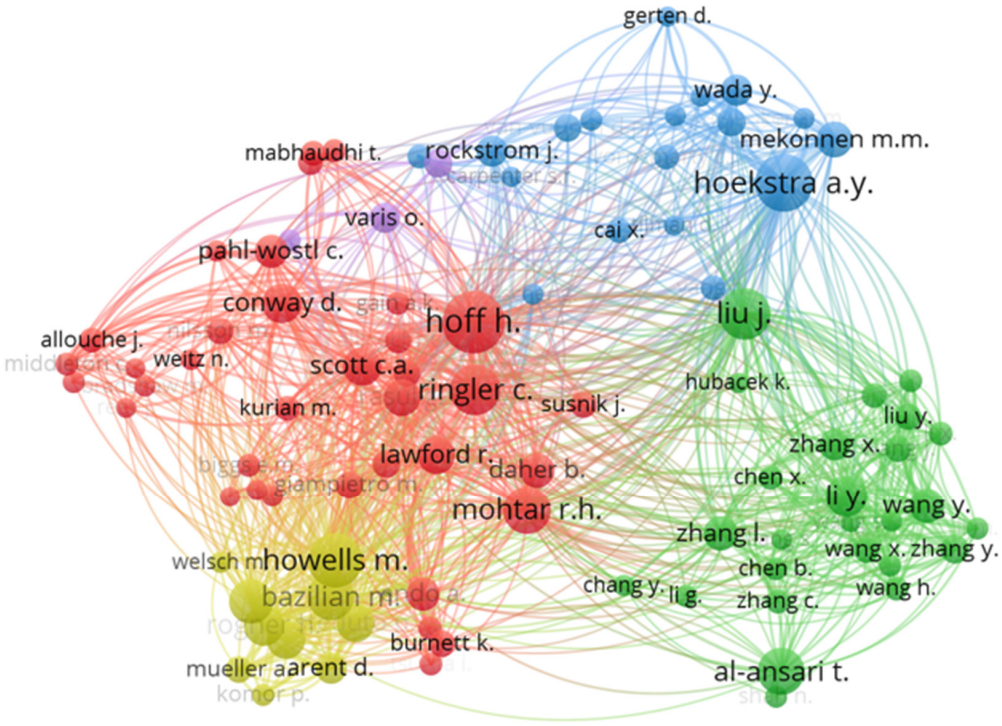


**Figure 9.** Co-authorship relations between WEF nexus authors.

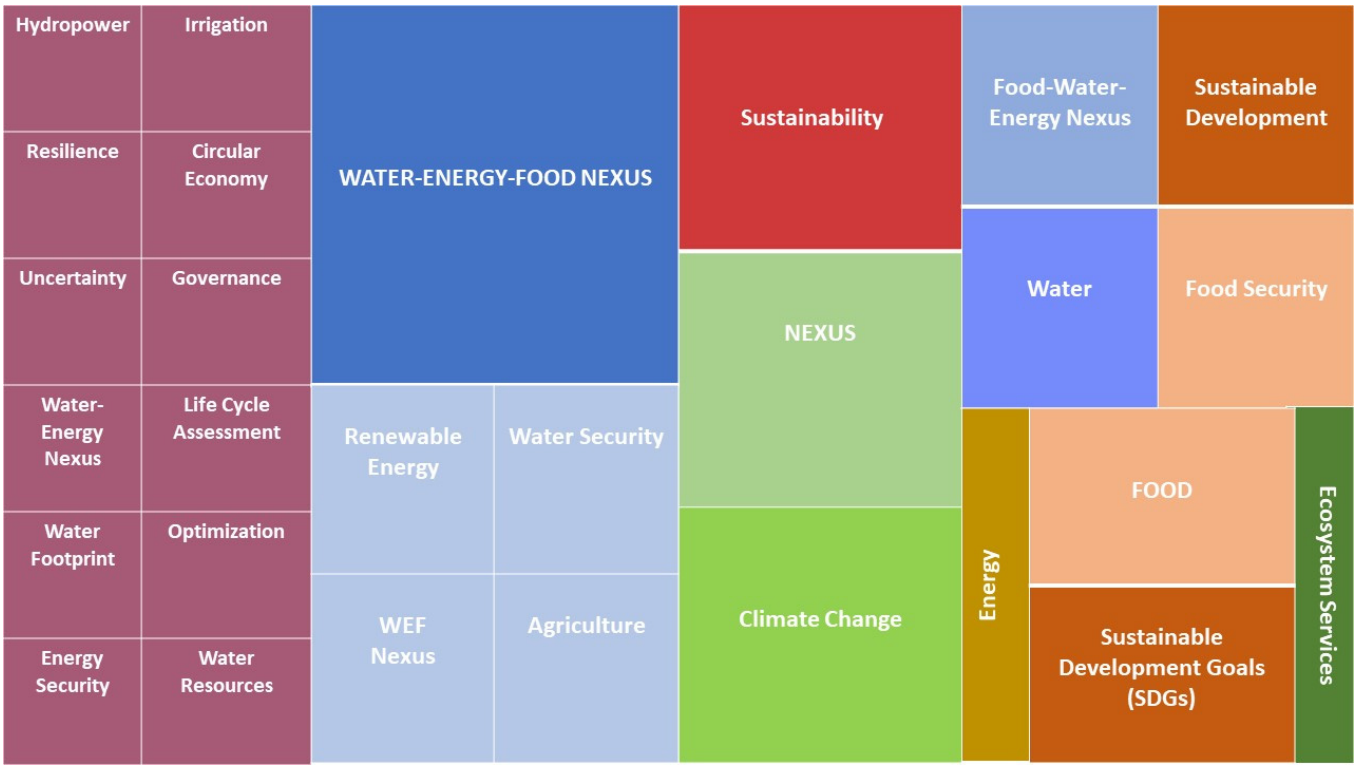


**Figure 10.** Most frequent topic words.

The heatmap of the most relevant keyword reveals the predominance of the use of nexus terminology with focus on fields of irrigation, food production, hydropower, and general sustainability. The recent inclusion of ecosystem services in the keywords, and hence the scientific production, provides the first evidence of a transition from WEF to WEFE nexus studies.

As previously highlighted, several facets of the nexus research make a detailed analysis on methodologies impractical and irrelevant, if a prior thematic analysis is not performed where the bigger picture of themes and ideas are captured. Hence, the thematic analysis aims to identify four categories of themes: basic, emerging, driving, and highly developed and isolated [14]. Looking at the emerging themes (Figure 11), socio-ecological systems are frequently represented within the nexus by terms like "humans", "environmental impact", and " sustainable development". The latter term, despite being the initial goal of nexus scholarship, has only recently gained explicit mentioning in the studies. This analysis is further expanded to show conceptual maps of sub-terms relevant to each cluster under each topic. Systems sciences and socio-ecological sciences are integrated into these topics. A clear dominance of the water–energy nexus is still noted. We note here the strong presence of "Energy", as it is represented in several entries including, "Energy", "Hydrogen Production", "Energy Food Nexus", and "Biochar". It is expected that the word "Tradeoff" is more represented as a lot of the nexus activities are all related to trade-offs.

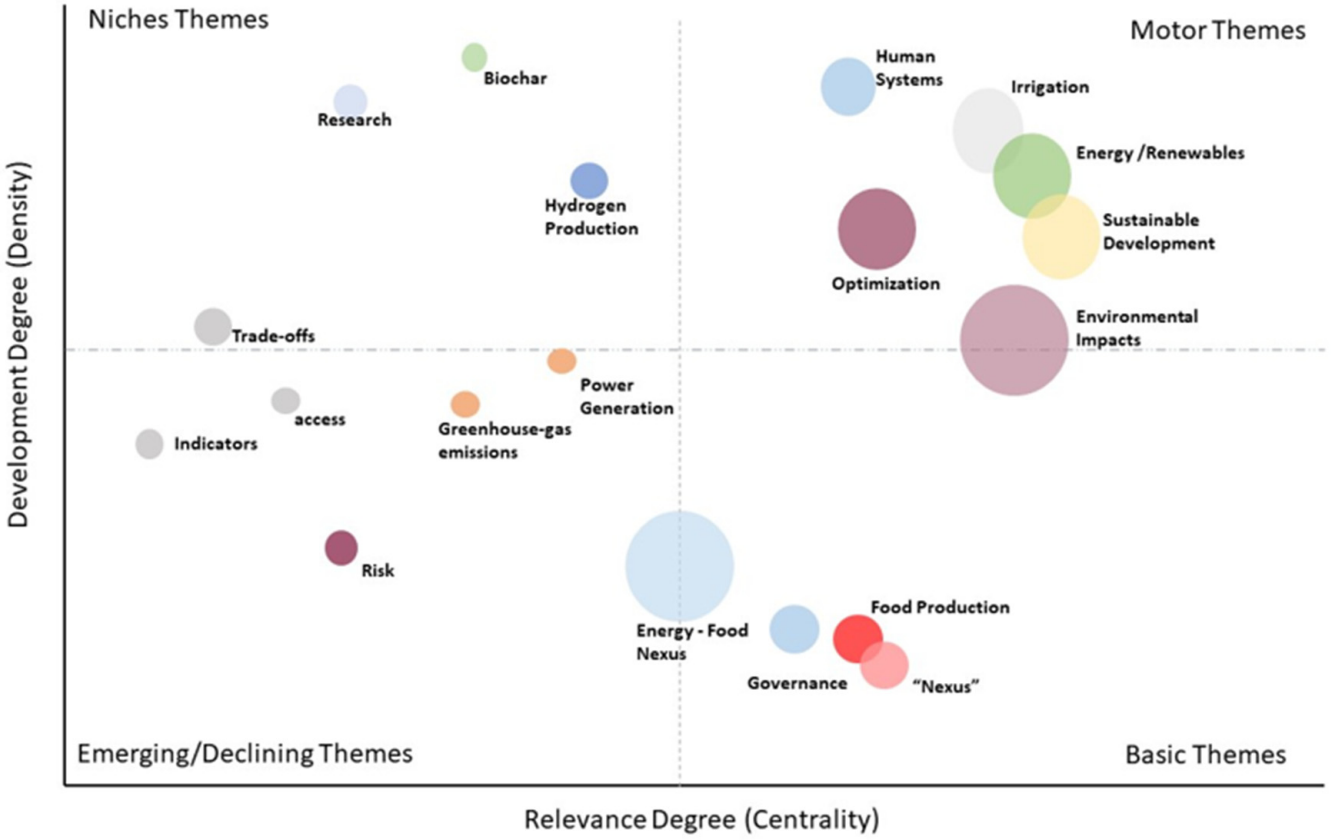


**Figure 11.** Thematic map representing the main themes of the nexus research used in keywords.

### *3.7. Analysis of Scientific Knowledge Production*

A dynamic topic modelling approach was adopted to investigate the evolution of nexus themes [15]. Given rapid development of nexus application and approaches, the Jaccard similarity was identified for several periods. Hence, for each topic and each period, a measure of how identical the themes are is given. Figure 12 shows the resulting diagram of the identified topics. Such representation contributes to the identification of the scientific knowledge production of the WEF nexus.

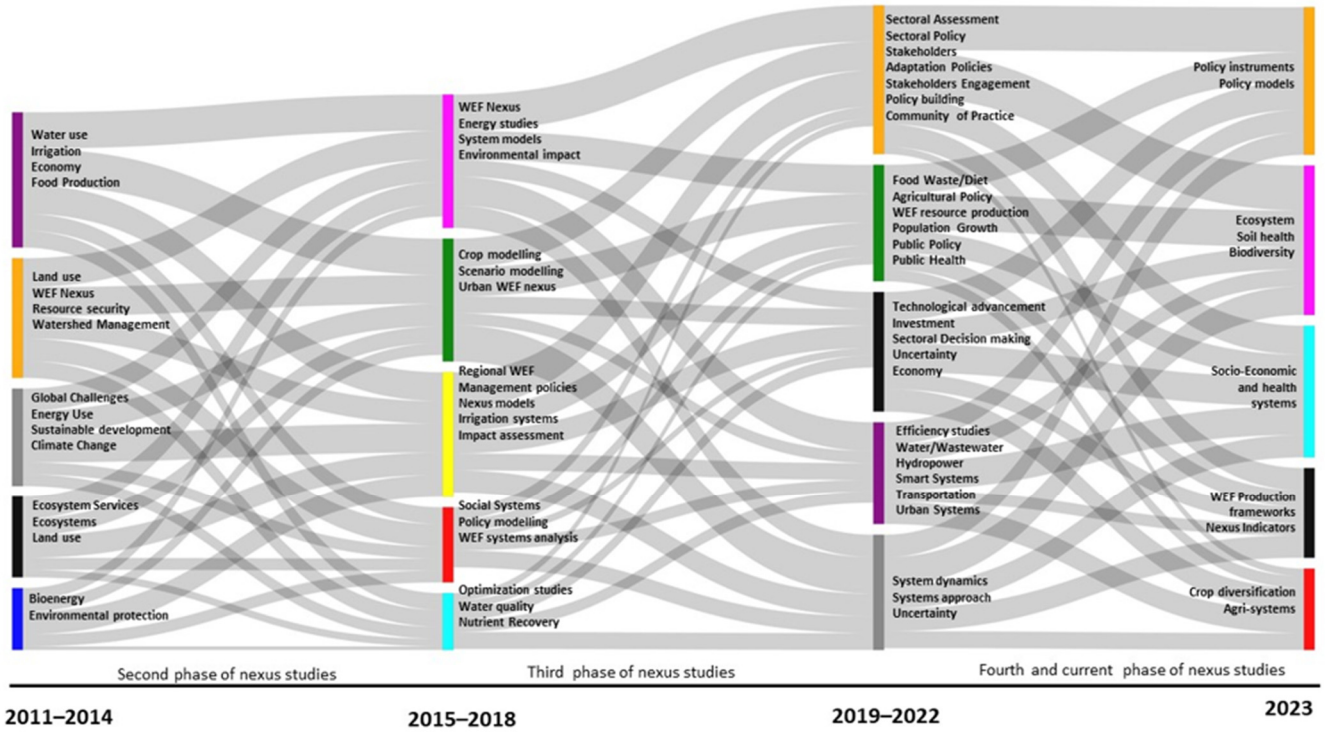


**Figure 12.** Evolution of WEF nexus topics up until 2023 based on the analyzed documents.

The WEF nexus research showed significant differences in different phases:

First phase (until 2010): In the initial phase, research on the nexus was fragmented and lacked a systematic approach. In 1983, the United Nations University launched a project aimed at investigating the interrelationship between food and energy, marking the inception of a long-term endeavor in this field. The formal conceptualization of the nexus between food, energy, and water was initially introduced at the annual meeting of the World Economic Forum in 2008 [16]

Second phase (2011–2014): The Bonn Conference in 2011 underscored the critical need for a systematic approach to harnessing the interplay between water, energy, and food to propel the growth of the green economy [17]. Subsequently, at the UN Conference on Sustainable Development in Rio de Janeiro in 2012, the agricultural dimension was introduced within the nexus framework [18]. These developments marked the emergence of the WEF nexus as a distinct focal point for research. Bazilian et al. [19] conducted pioneering work, employing quantitative simulations to explore the interconnections within the nexus, particularly in the context of resource security. Hussey and Pittock [20] directly integrated the WEF nexus concept into the realm of sustainable development. In 2014, the ecosystem services and their upstream–downstream linkages, particularly in the region's transboundary river basins, are an integral part of the nexus [21].

Third Phase (2015–2018): The year 2015 marked the inception of the Sustainable Development Goals (SDGs). These goals garnered immediate approval and enthusiasm from both the academic and policymaking communities. The SDGs represent a holistic framework where economic, environmental, and social objectives intricately intertwine, forming a coherent nexus closely aligned with the nexus, which subsequently emerged as the primary focus of research [22]. During this phase, the sustainable development concept was integrated with the existing body of research, encompassing areas like sustainable governance, livelihoods, and retrospective analyses [23].

Modeling techniques significantly evolved during this period, encompassing various approaches like simulation tools, integrated models for resource interlinkage assessment, and dynamic models.

Fourth period (2019–now): Over the most recent period, various key topics have gained prominence, including governance, ecosystems, sustainable development, resource management, and policy- and decision-making. Some studies characterize the nexus as a governance concept that aims to integrate resource management and sectors through policies and regulations to enhance sustainability and improve resource allocation [24]. The nexus approach fosters policy integration and coherence by identifying optimal policy combinations and governance structures across nexus sectors [25]. It recognizes the importance of integration and interdependence among diverse sectors as a crucial step in ensuring resource security in the global context of rising and competing demands [26].

A recent publication by the World Water Council [27] (WWC, 2023) provided an opportunity for expanding the Integrated Water Resources Management to food, energy, health, and education.

The fourth period is marked by developing nexus food indices that serve as vital tools in providing policymakers and stakeholders with essential information to develop integrated and sustainable strategies. Simpson et al. [28] developed a country-level index that has been calculated for 181 nations using open databases. Following an assessment of 87 water-, energy-, and food-related indicators, 21 were selected to constitute the WEF nexus index. Recently, Hua et al. [29] constructed an integrative analytical framework and synergy indicators to assess the synergy of water use for energy and food production through symbiosis theory. Entrena-Barberohis et al. [30] proposed a novel methodology for calculating a WEF nexus index combining the GHG emissions, water demand, energy requirements, and productivity performance of dairy farms.

## 4. Discussion

Most nexus research has focused mainly on the water–energy–food and the water–energy coupling. In Europe, especially in Italy and Spain, studies have largely concentrated on energy production within the water and energy pillars, as highlighted by Rezaei Kalvani and Celio [31]. On the other hand, North American research predominantly explores the food–energy–water nexus, a concept frequently discussed in that region and initiating from the food pillar.

The current fourth period exhibited numerous projects backed by both national and international funding. PRIMA initiated its first WEF nexus calls in 2019, emphasizing the importance of socioeconomic factors in addition to biophysical resources. PRIMA's focus has been on making the WEF nexus operational to facilitate a transition to a green economy and help achieve the Sustainable Development Goals. From 2019 to 2023, PRIMA allocated a total of EUR 34.18 million to fund 12 projects. To promote the adoption of nexus solutions, PRIMA supported a four-year project to establish a Community of Practices. This community brings together a diverse group including practitioners, scientists, policymakers, members of civil society, media professionals, entrepreneurs, innovators, and investors. The Nexus Community of Practice (NCoP) is centered around demonstration sites to exchange knowledge, develop capacities, and implement best practices, science-based policies, and innovative solutions.

The Union for the Mediterranean (UfM) also plays a crucial role in promoting sustainable development in the Mediterranean area. It has initiated several projects aligned with the WEF nexus approach in this region. For instance, the UfM's Water, Environment and Blue Economy Division focuses on sustainable water management projects, while its Energy Division is engaged in advancing renewable energy development in the Mediterranean.

Other organizations working on WEF nexus solutions include the Food and Agriculture Organization of the United Nations (FAO), the International Center for Agricultural Research in the Dry Areas (ICARDA), and the Mediterranean Water Institute (IME). In the USA, the National Science Foundation (NSF) and the United States Department of Agriculture (USDA) are funding key climate priorities within the Natural Resources Conservation Service (NRCS), including establishing a soil health monitoring network that will include a network of soil sampling sites, integrating soil carbon monitoring into the

conservation planning process, and making efforts to increase the internal capacity of NRCS staff regarding key soil carbon and climate smart activities. The NSF launched the INFEWS program in 2015 with the mission to support research to conceptualize food, energy, and water, broadly and inclusively incorporating social and behavioral processes (NSF program solicitation 18-584). Despite the program being discontinued by 2021, its overarching goal of integrating these primary resources has remained a priority in many environmental, sustainability, and other related topics for NSF. Many universities in the US have established dedicated programs and initiatives in this area, including sustainability at Texas A&M and Harvard College, among others.

The analysis of the gaps Identified by review papers are summarized in Table 2.

**Table 2.** Recapitulation of identified gaps by review articles.

| References | Database | Focus of the Analysis | Methodology Used in the Bibliometric Analysis | Period, Number of Articles | Identified Gaps |
|---|---|---|---|---|---|
| Wang et al. [10] | Web of Science database | water–energy–food | CiteSpace | (2011–2022), 1547 | Relationship between the WEF nexus and wars, pandemics, and geopolitics. |
| Lazaro et al. [32] | Scopus | water–energy–food nexus | Supervised latent Dirichlet allocation (sLDA) | (2012–2021), 681 | - Difficulties in defining universal approaches, methods and tools in the field.<br>- Inclusion of socioeconomic analyses, particularly on the actors and institutions that shape access, distribution, and use of WEF resources<br>- WEFE science–policy. The two-way linkage between science and nexus policy can be improved by further digging into the science of the nexus by learning from its application. |
| Moreno Vargas et al. [33] | Scopus | WEF nexus related to biodiversity, conservation, and sustainability transitions in agriculture | Tree of science VoS viewer | (2009–2021), 876 | - Transdisciplinary approach to elucidate the state of sustainability transitions in the agricultural systems at the landscape level. |
| Rezaei Kalvani and Celio [31] | Scopus, ISIWeb of Science, PubMed, Google Scholar, and Science Direct | WEF nexus in European countries | No specific analysis | (2011–2023), 109 | - No study that evaluates the interlinkage between food security, water stress, land security, and the migration of people as a result of climate change.<br>- Lack of research on land use, land productivity, and land suitability.<br>- Water quality is rarely taken into consideration.<br>- Lack of attention paid to considering the circular economy. |
| Lucca et al. [34] | Scopus and Web of science | WEF nexus in Mediterranean countries | PRISMA Guidelines | (2011–2023), 142 | - Integration of socioeconomic variables and processes in biophysically-driven nexus assessments should be actively promoted.<br>- Implementation of the WEF nexus at large scale. |

Based on the co-occurrence network analysis, most research focused on the WEF nexus, climate change, resource security, ecosystem service, agricultural sciences, sustainable development, and governance, with future gaps to address as follows:

- Health component in the WEF nexus: The health component holds a pivotal role within the water–energy–food (WEF) nexus due to its intrinsic connection with water, energy, and food resources [35]. Access to clean water, nutritious food, and reliable energy directly influences public health, making it a fundamental element for human well-being. Moreover, health is intimately intertwined with the efficient use of these resources and the resilience of communities in the face of climate change. Recognizing

the interdependencies within the WEF nexus and managing them effectively is essential for promoting better health outcomes, ensuring sustainability, and advancing progress towards global development goals.

- WEF nexus and socioeconomic analysis: A conspicuous gap in the field of WEF nexus research lies in the limited attention given to socioeconomic analyses, particularly in the context of understanding the various actors and institutions that play a crucial role in shaping the access, distribution, and utilization of WEF resources. While there has been significant progress in assessing the interconnections between water, energy, and food systems, a comprehensive examination of the social, economic, and political dimensions remains relatively underdeveloped. This deficiency is of paramount importance because it is these actors and institutions that influence the policies, regulations, and decision-making processes governing WEF resources. Their actions and interactions have far-reaching implications for resource management, sustainability, and the equitable allocation of these critical resources. To truly grasp the complexity of the WEF nexus and devise effective strategies for its sustainable management, it is imperative to bridge this analytical gap and delve deeper into the socioeconomic dynamics that underpin the intricate web of WEF resource utilization.
- WEF nexus and SDGs: While there has been a significant surge in studies focusing on the nexus in recent years, only a limited number of these studies establish clear links with the Sustainable Development Goals (SDGs). In fact, as noted by Boas et al. [36], the connections between many of the SDGs often lack coherence and fail to acknowledge the intricate interplay among various sectors. The nexus is explicitly recognized within five SDGs, namely SDG 2 (addressing food security), SDG 6 (ensuring clean water access), SDG 7 (promoting modern energy solutions), SDG 13 (mitigating climate change), and SDG 15 (preserving terrestrial ecosystems). A strong focus on economic development poses a significant risk to the realization of the social and environmental Sustainable Development Goals [37].
- WEF nexus and agriculture: The state of the nexus is underdeveloped within the agriculture sector, leading to missed opportunities for water and energy savings and the subsequent reduction of greenhouse gas emissions. This is consistent with Nazmul Islam et al. [38] who emphasized the potential of precision technologies to enhance nexus research by offering real-time agricultural production data.
- Research methodologies: The predominant methodologies employed in most research studies involve qualitative or semi-quantitative analyses, such as econometric models, decision-making targeting, literature assessments, and expert evaluations. However, it is noteworthy that a limited number of investigations delve into the intricacies of correlating multiple systems. This encompasses research focused on elucidating the intricate mechanisms underpinning the interplay within the WEF nexus, thereby highlighting a gap in the existing body of literature.
- 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 trade-offs, lack of research on this aspect is not conducive to narrowing the gap between theory and practice [39].
- Spatiotemporal data: Spatiotemporal evolution data that accurately capture the correlation process of a system are scarce [40]. Woodard et al. [41] suggested that the creation of a data warehouse capable of integrating diverse data sources, including satellite imagery, public surveys, climate, and market data, while ensuring data privacy could significantly bolster the effectiveness of resource optimization policies within the WEF nexus.
- Social dimension and social–ecological systems in the WEF nexus: Social–ecological systems play a pivotal role in the nexus, highlighting the intricate web of relationships between human societies and their surrounding ecosystems. These systems underscore the fact that decisions and actions regarding water, energy, and food resources have profound impacts on the environment and, in turn, feedback effects on human

well-being. Recognizing the interdependence of these components is essential for sustainable resource management and resilience, as it allows for a more comprehensive understanding of the consequences and trade-offs associated with WEF decisions, ultimately aiding in the development of more effective, holistic, and adaptive policies.

- WEF nexus–policy interface: Despite the large amount of literature about the nexus, there is still a debate about how best to transform it from a theoretical system to real policies [42]. Transforming WEF nexus science into effective policies is a vital endeavor, given the intricate interdependencies and global significance of these resources. Several constraints impede the transformation of WEF science into policies. Political and economic interests often clash with sustainability goals, as policies that prioritize short-term gains may undermine long-term resource management. Additionally, a lack of comprehensive data and information can hinder policymaking, as can institutional fragmentation, where different government agencies and departments work independently, leading to disjointed efforts. Resistance to change from established practices and vested interests can also be formidable barriers. Convincing decision-makers and powerful stakeholders to embrace new approaches and prioritize long-term sustainability can be challenging. The short political cycles under which many policy decisions are made often do not align with the long-term perspective necessary for addressing WEF challenges. To overcome these constraints and successfully transform WEF science into policies, a multifaceted approach is required. It involves building partnerships, advocating for policy coherence, enhancing data sharing and transparency, and fostering a shared understanding of the importance of the WEF nexus among policymakers, stakeholders, and the general public. Additionally, it may require sustained commitment and perseverance to achieve meaningful policy change in this complex and vital domain.
- Tools and Models continue to be an issue, related to the level of complexity, type of simulation, and approaches. While process-based modeling and optimization offer good knowledge about interactions, in many cases, this complexity is not needed.
- System representation is a challenge for new and veteran WEF nexus users. The literature is very split regarding the dimensions of the Nexus. Adding health, ecosystem, climate, education, and other dimensions, while legitimate concerns, add complexity to the system. The question remains of how to consider these dimensions while maintaining manageable system interactions and data. Inclusion of these dimensions can be used constraints, as one possibility.
- Governance of the nexus, encompassing aspects of ownership, financing, and management, continues to be a significant challenge. There is a pressing need for new governance structures that can effectively challenge and transform the current status. The existing models may not be sufficient to empower decision-making for this complex system. These systems need to also be tested to promote real and large-scale implementations.

## 5. Conclusions

This paper provides valuable insights through bibliometric analysis into nexus studies conducted worldwide between 2011 and 2023. It raises awareness of the gaps that still exist and poses unresolved issues that researchers and academics should pay close attention to in the near future.

Research on the WEF nexus experienced a notable increase after the 2011 Bonn Conference, with the growth rate significantly accelerating after 2015.

The bibliometric analysis identified thematic trends in the literature, with governance, ecosystems, and policy and decision-making recently identified as key themes.

While extensive research exists, some emerging issues lack adequate attention such as the integrating of the health component, the WEF nexus–policy interface, the WEF index incorporating biophysical and socioeconomic components, and digital twin integration. Digital twin technology presents a significant opportunity for advancing the understanding

and management of the WEF nexus in the future, offering real-time insights and enhanced decision-making capabilities.

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