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SUSTAINABILITY AND GROUNDWATER IN THE CONTEXT OF WATER-ENERGY-FOOD NEXUS: A REVIEW OF THE LITERATURE

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ABSTRACT

The sustainability of groundwater is contingent upon the Water-Energy-Food Nexus. In this context, the article aimed to analyze the state of the art in this field by using the Scopus database and the following keywords: “Sustainability”, “Nexus”, and “Groundwater”. The analysis was based on articles published over the last 79 years, from 1945 to August 2024. The results indicated that the production of articles on this topic started in 2008 and increased significantly from 2015 to 2023, with the USA having the highest number of publications. The publications encompass a multitude of disciplines, including environmental sciences, energy, engineering, social sciences, agricultural and biological sciences, earth and planetary sciences, business, management and accounting, biochemistry, genetics and molecular biology, chemical engineering, economics, econometrics, and finance. This demonstrates that the topic is inherently multidisciplinary, a conclusion supported by the variety of keywords identified. The keyword analysis yielded three clusters. The first area of focus is the nexus between climate change, agriculture (particularly crops and irrigation), energy, and sustainable water resources management. The second area of focus addresses the interrelationship between agriculture, ecosystems, food security, and the quality and availability of water resources. Moreover, the third area is related to hydrogeology and management of underground water resources. The identified gaps in the nexus include the lack of a comprehensive understanding of the nexus as a system, the absence of policy development to analyze synergies among all factors, the need for multi-sector integration, the dearth of socioeconomic impacts, the scarcity of local and specific data availability, and limited mention of the role of artificial intelligence and the Internet of Things in integrated water resource management. The identified trends highlight the convergence of climate change, agriculture, and water resource management, emphasizing food security and ecosystem protection. Technologies are becoming more energy-intensive, increasing the interdependence between water and energy. Mathematical models and machine learning are employed to predict the quality and quantity of groundwater.

Keywords: Groundwater sustainability; Water-energy-food nexus; Environmental impacts; Synergies modeling; Ecosystem balance; Climate adaptation.

RESUMO

SUSTENTABILIDADE E ÁGUAS SUBTERRÂNEAS NO CONTEXTO DO NEXO ÁGUA-ENERGIA-ALIMENTOS: UMA REVISÃO DA LITERATURA. A sustentabilidade das águas subterrâneas está condicionada ao Nexus Água-Energia-Alimentos. Nesse contexto, o artigo teve como objetivo analisar o estado da arte nesse campo utilizando a base de dados Scopus e as seguintes palavras-chave: “Sustentabilidade”, “Nexus” e “Águas Subterrâneas”. A análise foi baseada em artigos publicados nos últimos 79 anos, de 1945 a agosto de 2024. Os resultados indicaram que a produção de artigos sobre este tema começou em 2008 e aumentou significativamente de 2015 a 2023, com os EUA tendo o maior número de publicações. As publicações abrangem uma multiplicidade de disciplinas, incluindo ciências ambientais, energia, engenharia, ciências sociais, ciências agrícolas e biológicas, ciências da terra e planetárias, negócios, gestão e contabilidade, bioquímica, genética e biologia molecular, engenharia química, economia, econometria e finanças. Isso demonstra que o tema é inerentemente multidisciplinar, uma conclusão apoiada pela variedade de palavras-chave identificadas. A análise das palavras-chave resultou em três clusters. A primeira área de foco é o nexo entre mudanças climáticas, agricultura (particularmente culturas e irrigação), energia e gestão sustentável dos recursos hídricos. A segunda área de foco aborda a inter-relação entre agricultura, ecossistemas, segurança alimentar e a qualidade e disponibilidade dos recursos hídricos. Além disso, a terceira área está relacionada à hidrogeologia e gestão dos recursos hídricos subterrâneos. As lacunas identificadas no nexo incluem a falta de uma compreensão abrangente do nexo como um sistema, a ausência de desenvolvimento de políticas para analisar sinergias entre todos os fatores, a necessidade de integração multissetorial, a escassez de impactos socioeconômicos, a falta de disponibilidade de dados locais e específicos e a menção limitada do papel da inteligência artificial e da Internet das Coisas na gestão integrada dos recursos hídricos. As tendências identificadas destacam a convergência das mudanças climáticas, agricultura e gestão dos recursos hídricos, enfatizando a segurança alimentar e a proteção dos ecossistemas. As tecnologias estão se tornando mais intensivas em energia, aumentando a interdependência entre água e energia. Modelos matemáticos e aprendizado de máquina são empregados para prever a qualidade e quantidade das águas subterrâneas.

Palavras-chave: Sustentabilidade das águas subterrâneas; Nexus água-energia-alimentos; Impactos ambientais; Modelagem de sinergias; Equilíbrio dos ecossistemas; Adaptação climática.

RESUMEN

SOSTENIBILIDAD Y AGUAS SUBTERRÁNEAS EN EL CONTEXTO DEL NEXO AGUA-ENERGÍA-ALIMENTACIÓN: UNA REVISIÓN DE LA LITERATURA. La sostenibilidad de las aguas subterráneas depende del Nexo Agua-Energía-Alimentos. En este contexto, el artículo tuvo como objetivo analizar el estado del arte en este campo utilizando la base de datos Scopus y las siguientes palabras clave: “Sostenibilidad”, “Nexo” y “Aguas Subterráneas”. El análisis se basó en artículos publicados durante los últimos 79 años, desde 1945 hasta agosto de 2024. Los resultados indicaron que la producción de artículos sobre este tema comenzó en 2008 y aumentó significativamente de 2015 a 2023, siendo EE.UU. el país con el mayor número de publicaciones. Las publicaciones abarcan una multitud de disciplinas, incluidas ciencias ambientales, energía, ingeniería, ciencias sociales, ciencias agrícolas y biológicas, ciencias de la tierra y planetarias, negocios, gestión y contabilidad, bioquímica, genética y biología molecular, ingeniería química, economía, econometría y finanzas. Esto demuestra que el tema es inherentemente multidisciplinario, una conclusión respaldada por la variedad de palabras clave identificadas. El análisis de palabras clave arrojó tres grupos. La primera área de enfoque es el nexo entre el cambio climático, la agricultura (particularmente cultivos y riego), la energía y la gestión sostenible de los recursos hídricos. La segunda área de enfoque aborda la interrelación entre la agricultura, los ecosistemas, la seguridad alimentaria y la calidad y disponibilidad de los recursos hídricos. Además, la tercera área está relacionada con la hidrogeología y la gestión de los recursos hídricos subterráneos. Las brechas identificadas en el nexo incluyen la falta de una comprensión integral del nexo como sistema, la ausencia de desarrollo de políticas para analizar sinergias entre todos los factores, la necesidad de integración multisectorial, la escasez de impactos socioeconómicos, la falta de disponibilidad de datos locales y específicos y la mención limitada del papel de la inteligencia artificial y el Internet de las Cosas en la gestión integrada de los recursos hídricos. Las tendencias identificadas destacan la convergencia del cambio climático, la agricultura y la gestión de los recursos hídricos, enfatizando la seguridad alimentaria y la protección de los ecosistemas. Las tecnologías se están volviendo más intensivas en energía, aumentando la interdependencia entre agua y energía. Se emplean modelos matemáticos y aprendizaje automático para predecir la calidad y cantidad de las aguas subterráneas.

Palabras clave: Sostenibilidad de las aguas subterrâneas; Nexo agua-energía-alimentos; Impactos ambientales; Modelado de sinergias; Equilibrio de los ecossistemas; Adaptación climática.

1 INTRODUCTION

The United Nations Sustainable Development Goals (SDGs) outline the world's most urgent problems, and achieving them requires a holistic approach. One such approach is the water-energy-food nexus, a systems thinking concept that examines the interrelationships between resources and other subsystems (SCHLÖR et al. 2021). This approach facilitates the identification of synergistic effects and co-benefits that might otherwise go unnoticed in complex production systems and supply chains. It helps identify unexpected consequences and promote cooperation, coordination, and policy coherence. However, Nexus approaches require specialized knowledge across all relevant sectors rather than just one (LIU et al. 2018).

The combination of climate change, population growth, expansion of agricultural and livestock areas, suppression of native vegetation, and urbanization poses a significant threat to the availability and quality of water, particularly in developing countries such as those in Sub-Saharan Africa (BRANDONI & BOSNJAKOVIC 2017). Reusing treated wastewater is a promising solution to mitigate this challenge. Groundwater is also a valuable resource that can supplement surface water supplies without depleting aquifers (MORAES-SANTOS et al. 2021).

In developing countries, the groundwater extraction in rural areas is unregulated, and electricity prices are highly subsidized. These conditions have resulted in increased salinity and arsenic contamination. Additionally, in urban areas where electricity prices are high, and industries are required to treat wastewater, the lack of monitoring or policy enforcement can result in the discharge of untreated wastewater into the environment (HAMICHE et al. 2016). Energy-intensive technologies such as desalination, water recycling, water transfer, and groundwater extraction are becoming more common in all water-using sectors as traditional water sources become scarce due to droughts, stricter environmental regulations, and climate change (HAMICHE et al. 2016).

Water management and food security are challenges in India due to a mismatch between water availability and agricultural demand. Groundwater irrigation is crucial for food security in the country. However, sustainable practices can be achieved by investing in surface water projects that promote direct irrigation and replenish overexploited aquifers (MUKHERJI 2022).

The water-energy-food nexus and the rational use of resources should be present in all decisions linked to each citizen´s public policies or positive attitudes. However, the dearth of data availability, the inaccuracy of data on water and energy consumption, and the lack of knowledge regarding the total water extraction occurring in aquifers must be corrected for better decision-making (BRANDONI & BOSNJAKOVIC 2017).

Agricultural irrigation is highlighted as essential for food security, particularly in arid and semi-arid regions where the intensive water and energy consumption exerts significant pressure on ecosystems. ZHANG et al. (2024) developed a quantitative analysis framework using climate and socioeconomic scenarios to assess the interactions between water, energy, food, and the ecosystem. The results show that integrated management strategies can significantly increase sustainability by improving food production, protecting ecological flows, and reducing groundwater extraction.

Integrated Water Resources Management (IWRM) is an approach aimed at coordinating the management of water, land, and related natural resources to maximize social and economic well-being equitably without compromising the sustainability of vital ecosystems. It promotes the integration of surface and groundwater management, in addition to environmental management, and involves the participation of all stakeholders at all decision-making levels (PEIXOTO et al. 2019). According to these authors, the concepts underpinning IWRM include an integrated vision of water resources, whereby water, land, and natural resources are regarded as an interconnected system. It focuses on sustainable water resource management to ensure future generations' availability, balancing social, economic, and environmental needs. It promotes the efficient use of water resources, considering their economic and social value. It ensures that all social groups have equitable access to water resources (PEIXOTO et al. 2019).

The applications of IWRM include (a) planning and managing watersheds that consider all uses of water within a watershed, addressing both the quantity and quality of water, (b) creating public policies that encourage the sustainable and efficient use of water, integrating land use and water resources policies, (c) advanced technologies to monitor the quality and quantity of available water, including aquifer monitoring and artificial recharge methods and (d) education and training programs to increase public awareness and participation in water resources management (PEIXOTO et al. 2019).

The nexus is integrated into IWRM through (a) modeling tools that simulate the interactions between water, energy, and food, helping to predict the impacts of different policies and technologies, (b) developing policies that promote synergies between the three sectors, such as incentives for efficient technologies and integrated management strategies, (c) implementing technologies that improve the efficiency of water and energy use, such as efficient irrigation systems and artificial aquifer recharge methods. Management approaches considering the water needs for food and energy production ensure that decisions are integrated and sustainable.

Therefore, this article analyzes the interrelationship between sustainability and the water-energy-food nexus, focusing on groundwater, through bibliometric analysis. This research aims to identify trends, gaps, synergies and trade-offs that can inform decision-making in the context of public policy, sustainable practices, and strategies to address climate variability and its impacts. The article also addresses the creation of research, development, and implementation networks of advanced technologies within the country.

Section 2 presents the methodology employed, including the keywords used for the Scopus search and the software utilized for data analysis. Bibliometric analysis was selected because it allows for evaluating scientific production, identifying trends and gaps, mapping collaborations, and accessing relevant information for making evidence-based decisions. Section 3 presents the results and their discussion. Section 4 highlights the importance of the water-energy-food nexus in sustainable development and the need for comprehensive research. Furthermore, it identifies research gaps in data integration, economic aspects, temporal scenarios, and pollution control, which impedes the formulation of effective policies.

2 DATA AND METHODS

2.1 Data acquisition

The methodology employed is not considered conclusive but rather critical, allowing a first approach to groundwater management from the perspective of the nexus and sustainability.

A qualitative approach was employed in three phases: data acquisition, data processing, and data analysis using visualization maps. It was essential to obtain data from existing literature in order to identify the scientific articles from which conclusions could be drawn. The data utilized in this study were obtained from the Elsevier Scopus database, which is one of the largest repositories of abstracts and citations for peer-reviewed academic literature. The database encompasses various academic disciplines, including the physical and life sciences, the social sciences and the humanities. The articles indexed by this database are distinguished by their academic rigor and international credibility.

The documents utilized as sources were articles and reviews published in English worldwide. The existing literature was retrieved by employing keywords such as "sustainability," "nexus," and "groundwater." The search strategy included the title, abstract, and keywords of the articles in order to retrieve all relevant publications. To obtain a more comprehensive overview of the literature, the search period was defined as spanning the last 79 years, from 1945 to August 2024, in order to ensure a broader coverage of publications.

2.2 Data analysis

For data processing, the files were exported in CSV and RIS formats for later analysis using Vosviewer software version 1.6.16, Excel, and Qgis version 3.34.11. The third stage employed the method of bibliometrics, which is defined as a quantitative study of research on the development of science. This method allows measuring the impact of research and citation processes, as well as the mapping of current knowledge and its evolution in a domain based on large academic data sets (Figure 1). This method

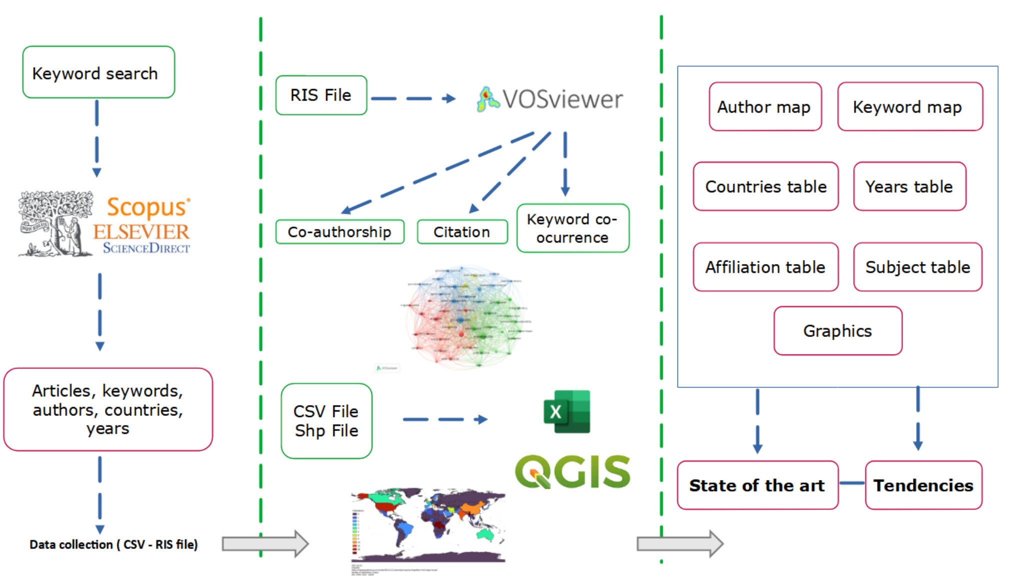

FIGURE 1 – Methodology flowchart delineating the methodology and its three phases: data collection, analysis, and results.

provides an overview of the research field, facilitating the visualization and mapping of knowledge domains in a holistic analysis (VAN ECK & WALTMAN 2010).

3 RESULTS AND DISCUSSIONS

3.1 Temporal distribution analysis

This systematic approach to data collection allowed the compilation of information on the period, authors, areas of knowledge, funding institutions, and notable keywords related to Nexus and sustainable development. This process yielded a total of 117 publications spanning a period of fourteen years.

The temporal distribution of publications allows us to identify the evolution of scientific production over time with regard to Nexus and sustainable development. The subject has only recently emerged as a topic of discussion, with the first publications occurring in 2008. Subsequently, there was a significant increase in the number of publications, reaching 117 by August 2024 (Figure 2). Therefore, it is a recent research topic gaining prominence in academia, as shown in the graph.

The initial record, published in 2008, signaled the beginning of significant academic interest in the water-energy-food (WEF) nexus. This period coincides with a growing global awareness of the interconnectedness of water, energy and food systems, driven by concerns about resource scarcity, climate change, and the need for sustainable development.

At the time, global discussions were heavily influenced by the World Economic Forum's 2008 call to action on resource security and the subsequent 2011 Bonn Conference on the Water, Energy and Food Security Nexus. These events highlighted the critical interdependencies between water, energy and food systems, and the need for integrated management approaches (SIMPSON & JEWITT 2019).

Early articles on the WEF nexus generally analyzed the interconnections between these sectors, emphasizing the need for integrated policies and management strategies to address the

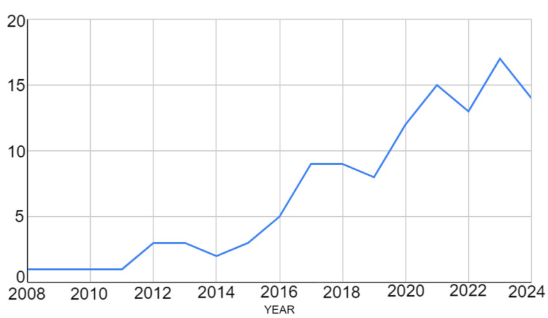

FIGURE 2 – Chart of publications per year on the topic nexus, sustainable development, and groundwater for the period from 2008 to August 2024

challenges of climate change, population growth, and resource depletion. They often provided frameworks for understanding synergies and trade-offs between water, energy, and food systems (SIMPSON & JEWITT 2019).

Events such as the World Economic Forum and the Bonn Conference have brought significant attention to the WEF nexus, encouraging researchers to explore this interdisciplinary field. These events highlighted the necessity for integrated approaches to resource management, leading to an increase in publications that aimed to address the complex interconnections between water, energy, and food systems (SIMPSON & JEWITT 2019).

At two conferences, the United Nations (UN) identified the interconnections between water, energy, and food. The first of these was the 2011 Bonn Conference, entitled "The Water, Energy, and Food Security Nexus - Solutions for the Green Economy," which aimed to develop a visionary approach to achieve sustainability. The second conference was the 2014 Climate Change Conference, which aimed to promote responsible governance of natural resources. In 2015, the same organization adopted the "Agenda 2030 for Sustainable Development" and the 17 Sustainable Development Goals (SDGs) (SCHLÖR et al. 2021). Therefore, these events have had a significant temporal impact on research and publications pertaining to the nexus and sustainable development.

3.2 Space distribution analysis

The spatial distribution of publications indicates that the countries with the highest number of articles are the United States (50), followed by India (26), China (14), Italy (9), and Iran (8), Portugal (5), the United Kingdom (5), Netherlands (4), Canada (4), Australia, and Qatar (4). Countries with three publications were France and Austria (Figure 3). A total of 18 countries from Europe, Asia, America, and Africa had one publication each, as detailed in table 1.

The high number of publications indicates a growing recognition of the importance of the WEF nexus in addressing global sustainability challenges. This highlights the need to combine insights from a range of disciplines, including environmental sciences, engineering, social sciences, and economics to develop comprehensive solutions. Furthermore, it encourages international cooperation to share knowledge and best practices. It is imperative to develop policies that consider the interdependencies between water, energy, and food systems in order to promote sustainable resource management.

The number of publications produced in a given country is often related to context and specific needs, as exemplified by the cases of India and China. India is the world's largest consumer

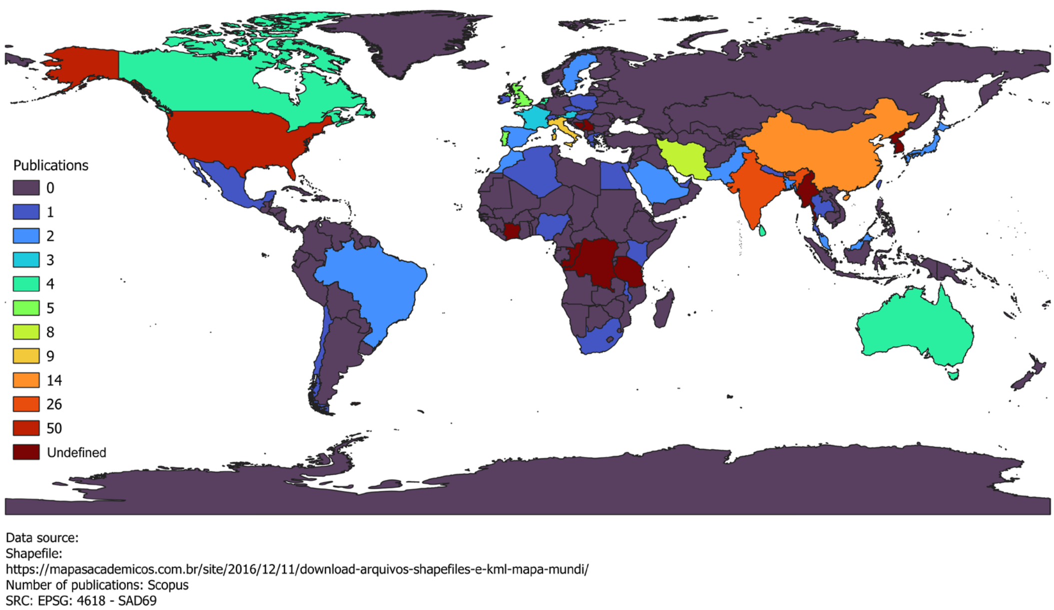

FIGURE 3 – Map of number of publications by country on the nexus theme, sustainable development, and groundwater.

TABLE 1 – Top ten countries with the highest number of publications. The principal countries are the United States, India, China, Italy and Iran.

Top	*Country/Territory*	*Publications*
1	United States	50
2	India	26
3	China	14
4	Italy	9
5	Iran	8
6	Portugal, United Kingdom	5
7	Australia, Canada, Netherlands, Qatar, Sri Lanka	4
8	Austria, France	3
9	Bangladesh, Brazil, Japan, Malaysia, Morocco, Pakistan, Saudi Arabia, Spain, Sweden	2
10	Algeria, Chile, Czech Republic, Egypt, Greece, Hungary, Ireland, Israel, Kenya, Kuwait, Malawi, Mexico, Nepal, Nigeria, Poland, Singapore, South Africa, South Korea, Switzerland, Taiwan, Thailand, United Arab Emirates, Undefined	1

of groundwater for irrigation, with 20 million wells used to produce water-intensive crops such as wheat and rice. The implementation of the Green Revolution model in the 1960s and 1970s gave rise to severe problems of overexploitation of aquifers and intense use of electrical energy, which have persisted over time (MUKHERJI 2022).

With a population of 21.54 million (as of 2022), Beijing, accounts for 14% of China´s cultivated land, and is responsible for the majority of energy and water comsuption, with 69% of the latter coming from aquifers (HU et al. 2013). In light of these considerations, it is evident that the nexus holds significant importance for the country. In the United States, research mainly focuses on climate change, managing water, energy, and ecosystems, and food production (LIU et al. 2018).

3.3 Knowledge area analysis

The areas of knowledge with the greatest number of publications on the research topic, in descending order of importance, are as follows: environmental sciences, energy, engineering, social sciences, agricultural and biological sciences, earth and planetary sciences, business, management and accounting, biochemistry, genetics and molecular biology, chemical engineering and economics, and econometrics and finance (Figure 4).

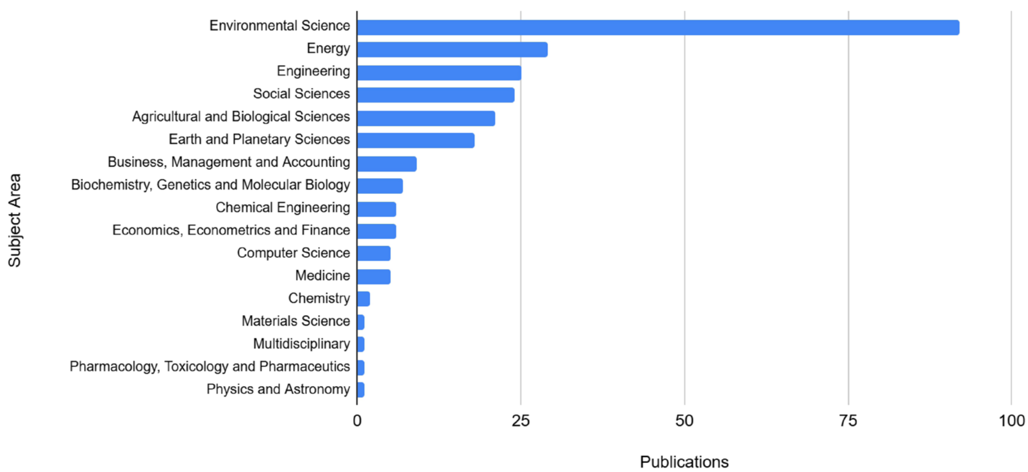

FIGURE 4 – Chart of publications by area of knowledge for the topic of nexus, sustainable development, and groundwater with more than six publications.

This multidisciplinary context highlights the need for a transdisciplinary approach, wherein researchers from different areas collaborate to address complex problems. A critical analysis reveals that the integration of diverse perspectives can lead to more holistic and effective solutions for the sustainable management of water, energy, and food resources. The authors of these studies often have backgrounds in a range of disciplines, including environmental sciences, engineering, social sciences, and economics. This reflects the interdisciplinary nature of research on the WEF nexus.

Many articles have been published in high-impact journals, indicating their importance and relevance to the field. To illustrate, the journal *Environmental & Science Policy* has a Citescore of 10.9 and an Impact Factor of 4.9, while *Renewable and Sustainable Energy Reviews* has a Citescore of 31.2 and an Impact Factor of 16.3.

The nexus and sustainable development are themes that transcend disciplinary boundaries and are considered multidisciplinary and interdisciplinary in nature, as they involve a systemic approach and need assessment from various actors. The energy-water nexus, which was previously overlooked, has recently gained increasing attention from researchers across various fields, including energy and water technology development, energy system analysis, water system analysis, and social management (HU et al. 2013).

Although the concept of the nexus is relatively easy to understand at first glance, it is complex and challenging to resolve, as it needs to be seen at many different scales and levels, from the biophysical to the political (SEMERTZIDIS et al. 2018). Decision-making is hampered regarding the food-energy-water nexus because the reality of natural and social processes in some scenarios is often not considered. Hence, it is essential to have a transdisciplinary perspective to address the feasibility challenges in the real world (ABDI et al. 2020).

Furthermore, data availability is also difficult, with generally inadequate data or monitoring to implement effective nexus-based management strategies. In Brazil, numerous decisions are reached within the context of basin committees, which do not equally represent the diverse sectors of knowledge and political-economic strength.

3.4 Authors and co-authors analysis

In the red cluster, prominent researchers on the topic include X. Zhang; M. Li, X. Xu, Y. Chen and Y. Zhou; in the green cluster, H. Li and Y. Yang (Figure 5).

The data extracted from the Scopus database included the institutional affiliations of the authors. Accordingly, the institutions that conduct the most research on this topic are the Kharagpur Indian Institute of Technology, the University of California, Hamad Bin Khalifa University, and the University of Lisbon. One illustrative example is that of Professor Junshan Zhang from the Department of Electrical and Computer Engineering at the University of California Davis (Table 2).

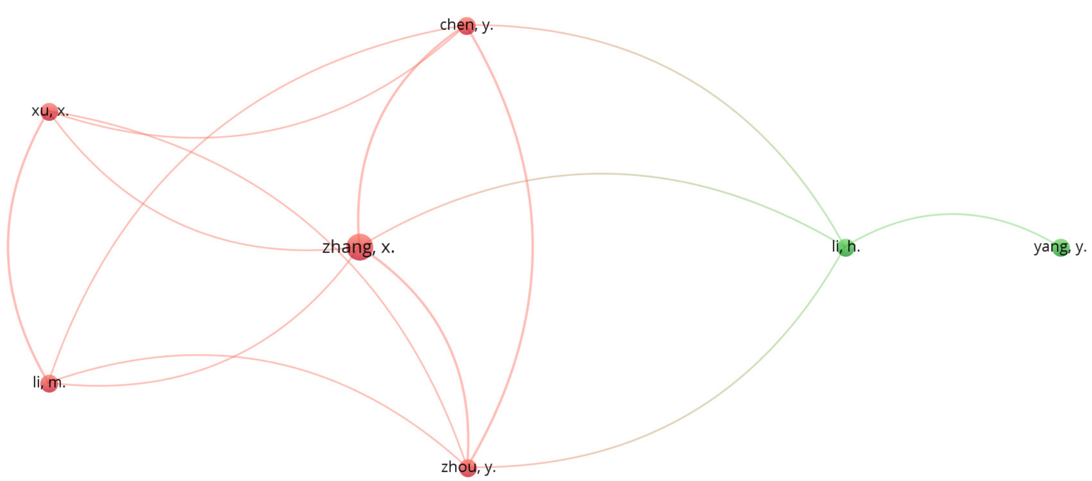

FIGURE 5 – Network map with two clusters of prominent authors and co-authors on the nexus topic, sustainable development, and groundwater.

TABLE 2 – Top ten institutions with the highest number of publications.

Top	*Affiliation*	*Publications*
1	Indian Institute of Technology Kharagpur	5
2	University of California, Davis	4
3	Hamad Bin Khalifa University	4
4	University of Lisbon	4
5	International Water Management Institute	3
6	Ministry of Education of the People's Republic of China	3
7	Punjab Agricultural University	3
8	The Ohio State University	3
9	The University of Arizona	3
10	Stanford University	3

3.5 Keywords analysis

The interrelationship between water resources, energy, and food has been the subject of intense investigation by the global scientific community, resulting in the emergence of a significant area of research known as the "water-energy-food nexus." These resources are essential for sustainable development and are subjected to analogous types of pressure, including demographic, economic, and climate factors (KITESSA et al. 2022).

The keyword analysis identified research trends, which were represented by three main clusters (Figure 6). The first cluster (indicated by the color red) encompasses terms such as climate change, crops, energy, energy utilization, food, production, food supply, groundwater, India, irrigation, surface water, sustainable development, water energy. The presence of these words indicates that the cluster is focused on the intersection between climate change, agriculture (especially crops and irrigation), energy, and sustainable water resources management. This cluster also reflects research trends related to the Water-Energy-Food Nexus, particularly in developing countries like India, where irrigation and agriculture play a crucial role in food security and sustainable development.

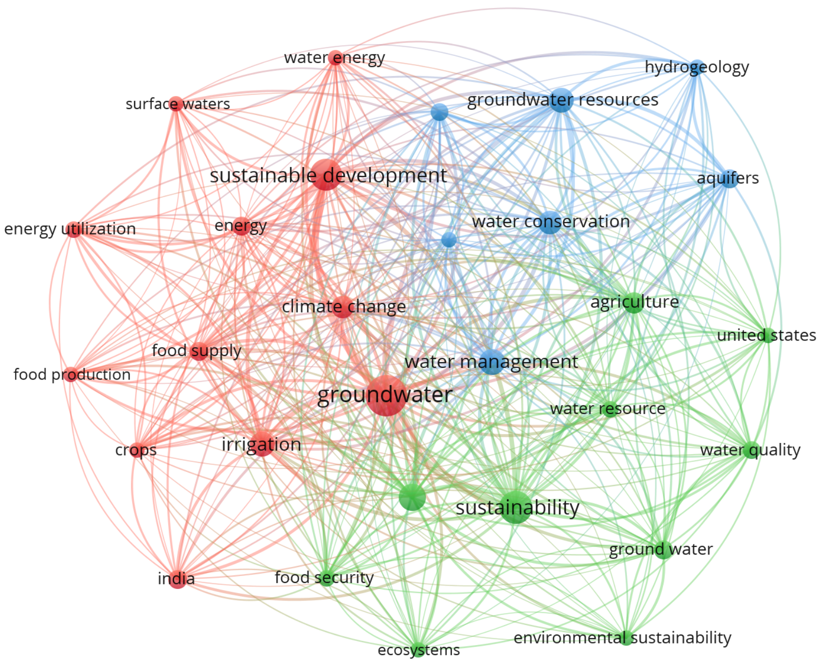

FIGURE 6 – Keyword cluster map on nexus, sustainable development, and groundwater theme.

"Large-scale" natural resource extraction and consumption can lead to the depletion of natural capital stocks and increase climate risk without equitable sharing of benefits (BIGGS et al. 2015). An example of groundwater exploitation for irrigation and its depletion is the severe case of India.

The Food and Agriculture Organization of the United Nations (FAO) and the UN predict that water consumption for irrigation will increase by 10% by 2050. Food consumption, particularly meat, is also likely to increase. This is a significant issue because it is estimated that each metric ton of beef requires 15,000,000 liters of water, a figure that is considerably higher than that required for other foods, such as soybeans, which require approximately 2,000,000 liters per ton (GARCIA & YOU 2016).

The intensification on currently irrigated practices contradicts sustainable water management. It is essential to conduct further research that is more locally oriented research to assess appropriate water management solutions (DROPPERS et al. 2021). In India, particularly within the Indian Ganges Basin, an alternative to establishing integrated management involves the capture of surplus surface water during the monsoon season and its subsequent injection into aquifers through managed recharge processes.

In the electricity sector, the consumption of water and emission of carbon dioxide vary according to the generation technologies and alternative energy sources in question. In the water sector, technological options are becoming increasingly energy-intensive, including desalination, water recycling, water transfers, and groundwater extraction. This is due to the depletion of traditional, easily accessible sources as a result of drought, stricter environmental regulations, and, in the long term, climate change (HAMICHE et al. 2016).

The second cluster, which is green in color, contains words such as agriculture, ecosystems, environmental sustainability, food security, groundwater, sustainability, USA, water quality, water resource, and water supply. It is focused on environmental sustainability and water resources management. This cluster addresses the interrelationship between agriculture, ecosystems, food security, and the quality and availability of water resources, with an emphasis on sustainability in the United States. The objective is to ensure water and food security while promoting environmental protection and long-term sustainability.

The implications of the nexus are felt worldwide, as increasing pressure from drought, climate change, industrial reform, and increased demand for water and electricity intensify this interaction (HAMICHE et al. 2016). There are interconnections among the Sustainable Development Goals (SDGs), many of which are explicit, particularly about water quality, operating from the municipal to the almost global scale (ALCAMO 2019).

The third cluster, which is represented by the color blue, includes words such as aquifers, groundwater resources, hydrogeology, water availability, water conservation, water management, and water use. It is focused on hydrogeology and management of underground water resources. This cluster addresses the availability and conservation of groundwater, aquifer management, and the efficient use of water resources, emphasizing the importance of groundwater in the sustainable management of water resources.

It is noteworthy that groundwater is a factor present in all three clusters, indicating its importance as a water resource for irrigation and as an alternative for the energy sector. Furthermore, it also emphasizes the necessity for the implementation of management of these water resources, coupled with an expansion of hydrogeological knowledge.

Nexus approaches highlight the need for, and potential benefits of, adopting a broad, multisectoral, multiscalar, and multiregional perspective to address global challenges such as those pertaining to the SDGs. In this way, the nexus can help uncover synergies and detect harmful trade-offs across different sectors, scales, and regions, reveal unintended consequences, and promote integrated planning, decision-making, governance, and management (WANG et al. 2019).

There is a strong positive correlation between precipitation and groundwater levels, particularly in regions where agriculture is a primary land use. In most cases, wells utilized for purposes other than agriculture demonstrate a relatively weak correlation (PRAJAPATI et al. 2021).

The nexus may be quantified through a variety of analytical methods, including life cycle assessment (LCA), numerical modeling, econometrics, productivity analysis, simulation/ optimization models, among others. These methods may, therefore, be qualitative, quantitative, or mixed (SCHLÖR et al. 2021). Accurately modeling groundwater quality and quantity is essential for the sustainable management of productive aquifers. This can be achieved using various mathematical and machine learning models to predict the groundwater´s specific conductance (SC) (ZOUNEMAT-KERMANI et al. 2022). In addition to specific conductance, other qualitative aspects must also be considered. Furthermore, mathematical models and machine learning have been extensively applied to establish the dynamics of underground flow, the influences on storage resulting from exploitation, climatic variations, and changes in land use. These models are also employed to predict the benefits of management actions, including reuse and managed recharge.

From a systematic analytical perspective, to reduce the risk of energy-water-food security, these three parts must be examined in regular operation and in coordination between them (NOROUZI 2022).

The current unsustainable trend in groundwater use in large parts of India can be attributed to food and electricity policies that were linked to the Green Revolution, which began in the 1960s. These policies aim to increase crop production with minimal water requirements and to implement technologies that reduce water usage in crop irrigation, in addition to other goals (SUKHWANI & SHAW 2020).

In a study published in 2018, ASHWELL et al. developed a dynamic model of groundwater extraction for irrigation on the Ogallala Aquifer in the United States, considering the impact of climate change and technical progress on groundwater use. The study showed that the optimal extraction rate can initially increase due to rising marginal benefits, peaking in 23 years. The incorporation of variables, including evapotranspiration, precipitation, crop improvements, irrigation technologies, energy for pumping, water value, and discount rates, resulted in increased management gains. The article highlighted that pumping costs rise as groundwater levels drop, raising operational costs. The irrigation enhances crop productivity, essential for food security, and advances in technology can further augment these benefits. Changes in precipitation and evapotranspiration patterns affect irrigation demand and groundwater's economic benefits. Optimal management considers dynamic variables in order to maximize economic benefits, justifying policy interventions for the groundwater conservation and its efficient use.

The study conducted by LAZARO et al. (2022), entitled "Ten years of research on the water-energy-food nexus: an analysis of the evolution of topics", identified several trends. Between 2012 and 2016, research on the World Economic Forum (WEF) nexus mainly focused on water issues and the security of natural resources, with four main thematic clusters: (a) biofuels, renewable energy, and cost-benefit analysis, (b) agriculture and irrigation water issues; (c) food security, climate change, and sustainable development, and (d) resource and urban planning. Between 2017 and 2018, research concentrated on water issues and sustainable development, highlighting the interdependence between water, energy, and food systems. Studies showed that the WEF nexus approach is crucial for efficiently implementating the Sustainable Development Goals (SDGs) and promoting the green economy. The research emphasized the importance of integrating economic policies to reduce water, energy, and food access inequalities. Food security was a predominant topic, with studies focusing on the competitive uses of natural resources for food and energy production, especially biofuels. From 2019 to 2021, research highlighted the importance of governance and policy integration to promote sustainability and efficient resource allocation. In 2019, the emphasis was on integrating resource and sector management into coherent policies, addressing challenges such as limited institutional capacity and the prevalence of "silo" decision-making. In 2020, the nexus concept was applied at different scales, mainly urban, addressing themes like the circular economy, waste management, and smart cities. In 2021, research highlighted urbanization and its links to the climate crisis, showing that the nexus approach is essential for natural resource management, policy, and governance, especially in urban contexts where most of the population and consumption are concentrated.

4 CONCLUSION

The current knowledge about the nexus and sustainable development shows a significant interest in surface and groundwater, based on their relationship with socioeconomic and biophysical aspects that influence water, energy, and food planning. The theme transcends the boundaries of knowledge areas, with comprehensive research contextualized in the global scarcity of resources, including epistemological, mathematical, spatial, climate, ecosystems, hydrological, technological, and innovation issues.

The review revealed a need for an integrated approach to address the identified research gaps. However, there is a lack of concrete examples illustrating how different sectors (water, energy, food) can collaborate effectively. The importance of local research is acknowledged, but there are few details about specific case studies or local data that could enhance the analysis. There is a paucity of examples illustrating the role of emerging technologies, such as artificial intelligence and the Internet of Things (IoT), in integrated resource management. Additionally, the analysis could be deepened with additional data concerning the socioeconomic impacts of resource management policies and practices, especially in communities that are susceptible to vulnerability.

There are many publications on water resource management, or integrated water resource management. There is a paucity of articles on the water-food-energy nexus, although there is a lot of scientific articles on the water-food nexus.

The lack of data integration with respect to resource flows is reflected in environmental, social, and economic policies, which are not mutually reinforcing and thus fail to achieve the expected outcomes.

The development of innovative technologies for water and sewage treatment plants is becoming more relevant, given the high energy demands of these processes and their significant potential for water reuse. Such tecniques contribute to applying managed aquifer recharge techniques, increasing water availability, and reducing pressure on aquifers.

Other actions presented in scientific publications as potential solutions include improvements in soil management, the implementation of efficient irrigation techniques (which reduce water usage), the encouragement of local community involvement, and the establishment of management strategies based on time-varying factors, including rainfall, evapotranspiration, land use, and recharge, among others.

A review of the literature revealed no publications examining the economic aspects linked to the nexus and sustainable development. Specifically, there is a lack of research employing an econometric approach to analyze the nexus interactions and their importance for development at different scales, from local to global. Likewise, no publications incorporated temporal scenarios into their analyses of the impacts of nexus flows. However, an article by ASHWELL et al. (2018) in the study "Optimal Groundwater Management under Climate Change and Technical Progress" identified several variables that serve to enhance groundwater management gains, in relation to climate change, technical progress, pumping costs, dynamic water demand, long-term planning, and discount rate.

Finally, 79 publications superficially addressed pollution. References were made to the quality of surface and groundwater, as well as their interactions in the context of the nexus. The water availability and its uses are directly linked to its quality.

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