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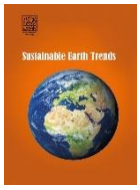

Systematic review and bibliometric analysis of research on system dynamic modeling of the water-food-energy nexus up to 2025

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ABSTRACT

Water, food, and energy are essential for the sustainable development of societies. However, climate change and population growth have increased pressure on the resources of these three sectors. In this context, the Water–Energy–Food (WEF) Nexus framework emphasizes the complex and interrelated interactions of these resources and seeks to develop integrated management strategies to address the associated challenges. System Dynamics Modeling (SDM), as a tool for modeling complex relationships—especially within the WEF nexus—enables the simulation of interactions and feedbacks within these systems. This study investigates the effectiveness of this method in modeling the water, energy, and food nexus. To this end, a systematic review of scientific literature up to the year 2025 was conducted using the PRISMA framework and bibliometric analysis. The Scopus database and software tools such as EndNote, VOSviewer, and Excel were selected as the main tools for data analysis. Out of 2,265 identified articles, 88 relevant articles were examined in detail. This research includes an analysis of publication trends, geographical distribution, leading journals, key countries, and identification of frequently used keywords in this field. The findings show a continuing upward trend in the number of published articles in the subject area. China leads research efforts in this field, followed by Iran. Science of the Total Environment, with 10 published articles, stands out as the most prominent journal in this area. Keywords such as "sustainable development" and "climate change" frequently appear in the reviewed articles, reflecting the primary research directions in this domain.

ARTICLE INFO

Keywords:
Bibliometric analysis
Systematic review
System dynamics modeling
WEF nexus
Water-Food-Energy nexus

Article history:
Received: 08 April 2025
Accepted: 04 June 2025

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Citation:
Jabarpour, E. et al., (2026). Systematic review and bibliometric analysis of research on system dynamic modeling of the water-food-energy nexus up to 2025, *Sustainable Earth Trends:* 6(2), (62-73).

DOI: 10.48308/set.2025.239820.1121

1. Introduction

Water, food, and energy are essential pillars for human development and the progress of nations. With the global population estimated to reach around 9.8 billion by 2050, the demand for these key resources is expected to rise substantially. Specifically, global water demand is projected to increase by 20–30% by mid-century, while energy consumption is expected to grow by 34%. The Food and Agriculture Organization (FAO) also predicts a significant surge in food demand, ranging from 60% to 110% (Solano-Pereira et al., 2025). As the demand for these vital resources continues to grow, meeting these needs is becoming increasingly difficult. Water systems, for example, are under greater pressure due to climate variability (Lee et al., 2023). Agriculture, which accounts for roughly 70% of global freshwater consumption (Ahmadi et al., 2020), is particularly susceptible to the impacts of climate change. On the energy front, the heavy reliance on fossil fuels not only contributes to higher carbon emissions but also raises concerns about the long-term sustainability of these energy sources (Karmian et al., 2022). These challenges underscore the pressing need for integrated and proactive resource management strategies. Among the

various comprehensive approaches, the Water-Food-Energy (WFE) Nexus stands out as one of the most widely acknowledged frameworks. Introduced at the World Economic Forum in 2011, its primary goal was to emphasize the interconnectedness of water, economic development, and resource security (Hoff, 2011). In practical terms, the Water-Food-Energy Nexus can be understood as a framework for evaluating, developing, and implementing policies that concurrently focus on the security of water, food, and energy (Bizikova et al., 2013).

Water, for instance, is essential for both food production and energy generation, while energy plays a crucial role in water treatment and agricultural activities. Likewise, ensuring reliable access to both water and energy is vital for food production (Bazilian et al., 2011). In order to better comprehend and tackle the interconnected challenges within the Water-Food-Energy (WFE) Nexus, researchers have increasingly turned to various quantitative modeling methods (Albrecht et al., 2018). Among these, System Dynamics Modeling (SDM) stands out as one of the most commonly used and successful approaches. Originally developed by Forrester in the 20th century to analyze industrial systems, SDM provides a dynamic framework for examining the interactions of different WFE nexus components over time, incorporating feedback loops and delays (Solano-Pereira et al., 2025). The model's focus on stocks, flows, feedback structures, and nonlinear relationships enables a thorough representation of the complexity inherent in these systems. SDM's bottom-up, systems-thinking approach is particularly valuable for understanding how WFE systems respond to driving forces such as population growth or policy changes (Sušnik et al., 2022). Despite the growing body of literature applying system dynamics within the WEF nexus, no prior study has conducted a comprehensive review that integrates bibliometric trends, methodological limitations, thematic patterns, and future research directions. Existing reviews often focus on specific subsystems or lack analytical synthesis across multiple dimensions. Therefore, this study addresses this research gap by systematically analyzing the evolution and characteristics of SDM-based WEF studies, providing an integrated perspective to guide future research and policy development.

2. Material and methods

In this study, a systematic review was initially conducted using the comprehensive SCOPUS database to identify and extract publications related to the applications of system dynamics modeling in the Water-Food-Energy (WEF) nexus. Following that, bibliometric and social network analyses (SNA) were performed using Excel and VOSviewer software.

2.1. Systematic review

Bibliometric analysis is a useful tool for examining research trends and identifying hot and emerging topics based on published literature (Otte et al., 2002). The data required for bibliometric analysis can be extracted from various databases such as Google Scholar, Web of Science, and Scopus. In this study, Scopus was selected for conducting the systematic review due to its comprehensive statistical coverage and widespread use. This review adhered to the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines (Moher et al., 2009), a well-established framework that ensures transparency and reproducibility in the systematic review process. To locate pertinent studies, an extensive search was carried out in the Scopus database, as detailed in Table 1.

Table 1. Database search strategy.

Search Parameters	Details
Database	Scopus
Search Strategy	TITLE-ABS-KEY (nexus) and TITLE-ABS-KEY (food) and TITLE-ABS-KEY (water) and TITLE-ABS-KEY (energy)
Language	English
Document Types	Peer-reviewed journal articles and conference papers
Total Records Retrieved	2,265
Date of Search	March 30, 2025

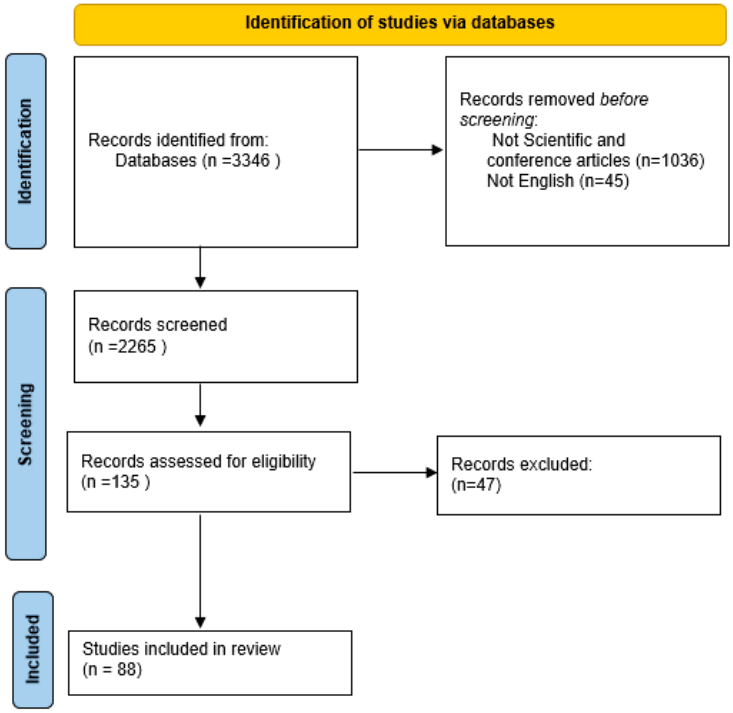

Fig. 1. The flowchart for the selection process.

A total of 2,265 articles were imported into EndNote and organized for further evaluation. The screening process began with a review of titles and abstracts to assess their relevance. This initial filtering was guided by predefined inclusion criteria, ensuring that only the most pertinent studies were selected for in-depth analysis.

2.2. Inclusion criteria

1. SDM approach: The research must employ system dynamics modeling to analyze the water-energy-food nexus.
2. Focus on the Water-Energy-Food Nexus: The research must concentrate on the water-energy-food nexus and explore the interactions between all three elements.
3. Published Articles: Only peer-reviewed journal articles and conference papers were included in the review.
4. Full-Text Access: Studies without accessible full texts were excluded from the review. The initial screening involved reviewing the titles and abstracts of 2,265 documents to determine their relevance based on the specified inclusion criteria. After eliminating studies that did not meet the requirements or lacked full-text availability, a total of 88 studies were chosen for the final analysis. The process used to select these articles is outlined in the flowchart shown in Fig. 1.

A systematic data extraction process was conducted for all 88 studies included in the review, utilizing a structured table that categorized the extracted information into clearly defined thematic groups, as detailed in Table 2. In this review, EndNote software was used for reference management, and data extraction was performed using Excel.

Table 2. Categorization of extracted data for this review.

Title	Description
Authors	Identification of the first author.
Year of Publication	Year of publication of the article, for analyzing temporal trends.
Subsystems and Priority Components	Number of subsystems and components of the water-energy-food nexus included in the model.
Software	Software (Stella, Vensim, etc.).
Spatial Scale	Spatial level of model implementation (local, regional, national, global).
Time Scale	Time horizon used in the model.
Journal Title	Identification of leading journals in the field of study.
Methods Used in the Study	Identification of methods combined with SD by researchers.
Model Simulation and Validation	Whether simulation was performed and the method of validation used.

2.3. Social network analysis

Social Network Analysis (SNA) is used to examine the relationships and interactions between entities (nodes) and the way they connect (links). In this study, the nodes represent keywords related to the topic, and the links depict the relationships between these nodes. For this analysis, VOSviewer version 1.6.6 was used, which is a well-established tool in social network and bibliometric analysis. This software, designed by Van Eck and Waltman from Leiden University, Netherlands, is capable of visualizing complex networks with large-scale data (Van Eck et al., 2010; Van Eck et al., 2017) VOSviewer is primarily used in bibliometric analyses, including the visualization of citation maps, co-citations, co-authorships, and keyword co-occurrence (Waltman et al., 2019). Due to its ability to process large datasets and accurately display graphical maps, it is an ideal tool for analyzing the complex relationships among scientific keywords. In this research, data related to keywords were analyzed in the form of social networks using this software, which helped identify trends and patterns in the data.

3. Results and discussion

This section includes the presentation of the results derived from the review and the discussion of the findings. The first section focuses on the analysis of the findings extracted based on Table 2, while the second section presents the social network analysis.

3.1. Publication trends

The Water-Energy-Food (WEF) Nexus has emerged in recent years as a prominent conceptual framework for addressing the complex interdependencies among essential resources, driven by escalating concerns regarding sustainability and resource security (Solano-Pereira et al., 2025). Given the relative novelty of the WEF Nexus, the application of system dynamics modeling as a tool to explore these interactions is a more recent advancement. As illustrated in Fig. 2, the number of scholarly publications in this domain has shown a consistent upward trend, reflecting growing academic interest in integrated and interdisciplinary methodologies.

The application of system dynamics to the study of the Water-Energy-Food (WEF) Nexus began in 2015, yet a marked growth in scholarly output did not emerge until 2018. Publication activity peaked in both 2021 and 2024, with 15 studies released in each of those years. This upward trajectory underscores the growing recognition of system dynamics as a valuable methodological approach for addressing the complex and interdependent challenges inherent in the WEF Nexus. It further highlights the rising enthusiasm among scholars and decision-makers to apply dynamic modeling techniques for a more thorough understanding and efficient management of the interconnected systems of these essential resources.

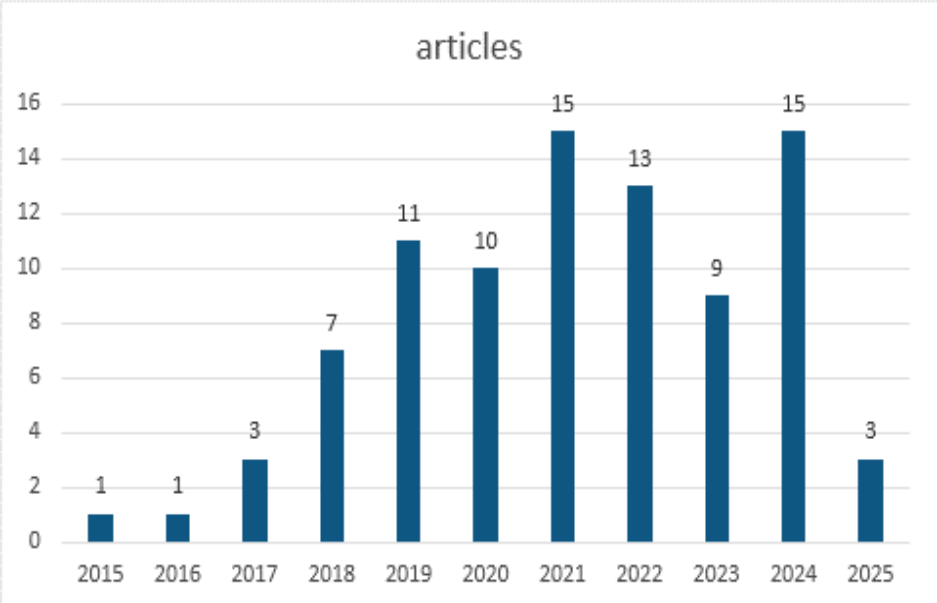

Fig. 2. Trend of article production.

3.2. Journals

Of the 88 studies reviewed, 84 were published in peer-reviewed scientific journals, while the remaining 4 were presented at academic conferences. These journal articles appeared across 39 distinct publications, reflecting the interdisciplinary appeal of applying system dynamics modeling to the analysis of complex water, energy, and food systems. Notably, the journal Science of the Total Environment accounted for the highest proportion of publications (11.9%), followed by the Journal of Cleaner Production (9.5%) and Water (Switzerland) (8.33%).

3.3. Countries

The use of system dynamics models for the integrated management of water, food, and energy resources has attracted significant global interest. As illustrated in Figure 3, the majority of studies have been conducted in Asia (52.27%) and Europe (28.40%), with a comparatively smaller proportion originating from North America (11.36%). Overall, these studies span 25 countries, with China (23.86%) and Iran (15.9%) contributing the largest shares of publications, highlighting their active engagement in Nexus-based modeling research. The global landscape of research activity indicates a strong regional focus, with the majority of studies concentrated in Asia and Europe, whereas regions such as Africa and Latin America have received comparatively limited scholarly attention. This disparity underscores the need to expand research efforts to include these neglected regions. Broadening the geographical scope will enhance the global applicability of the findings and ensure that the diverse challenges within the WEF Nexus are addressed on a global scale. The evaluation of case study locations and publication trends reveals that China holds a leading position, both in terms of the number of published works (21 papers) and as the primary focus of empirical investigations, with 19 studies specifically examining its context. This pattern illustrates China's influential role in driving the development and practical application of system dynamics within the Water-Energy-Food (WEF) Nexus framework. In a similar context, Iran ranks second, with 16 case studies, pointing to a notable commitment to utilizing the Nexus approach for addressing region-specific sustainability and resource governance issues.

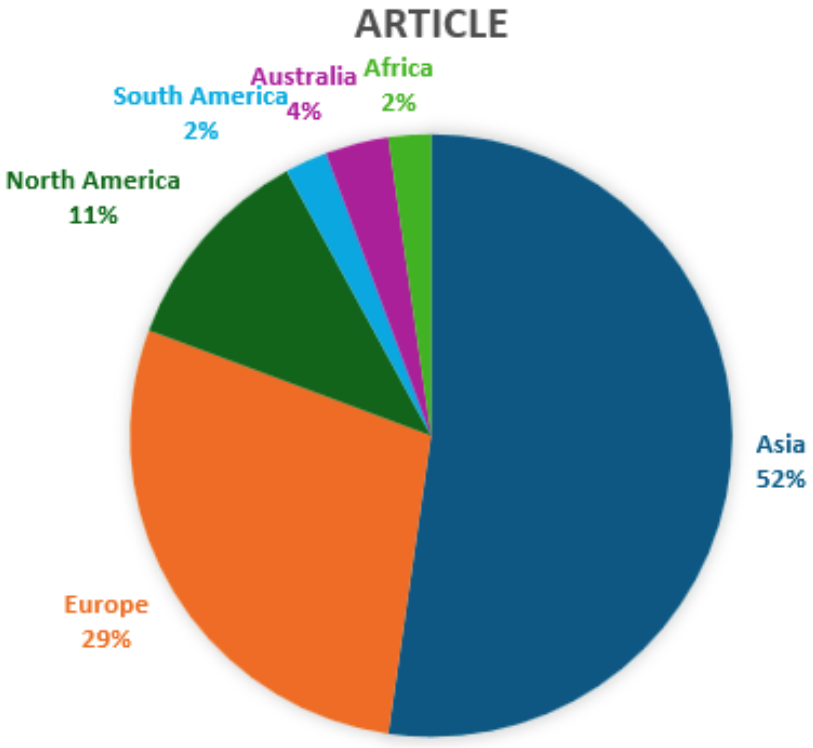

Fig. 3. Continental share in article production.

3.4. Spatial and temporal scales

A review of the spatial dimensions in the literature reveals a distinct preference for local-scale analyses, which constitute nearly 58% of the studies reviewed. Notably, 34 of these studies focused specifically on urban environments, where the complex interdependencies of water, energy, and food systems are particularly pronounced due to high population densities and intense resource demands. In contrast, only 17 studies addressed the national scale, seeking to capture broader systemic interactions and policy-level implications. These national-level perspectives emphasize the importance of adopting Nexus-based approaches for more strategic and comprehensive resource management across larger regions.

The time horizons used in the reviewed models varied significantly, influenced by the specific objectives of each study and the complexity of the systems being analyzed. A substantial proportion—approximately 61%—focused on long-term periods, with the majority examining the years between 2000 and 2050. However, only one study extended its projections to 2110, aiming to assess potential outcomes under critical future scenarios. Notably, some studies lacked temporal clarity: 14.23% did not specify a time frame, and 22.72% did not include one at all, typically because they employed conceptual frameworks rather than simulation-based models.

3.5. Number of subsystems and priority components

To better capture the interactions within the water–food–energy (WEF) nexus, researchers often integrate multiple subsystems into their dynamic models. In most cases, the focus remains on the core trio—water, food, and energy—which are combined in approximately 75% of the studies. Additionally, about 18.18% of the models incorporate other subsystems, such as social, economic, or environmental dimensions. While including these diverse components enhances the comprehensiveness of the models, it also introduces greater complexity and uncertainty into the analysis.

Among the reviewed studies, approximately half (Wang et al. 2023; Zhou et al. 2024) took a balanced approach, comprehensively examining the interconnected components of water, energy, and food. This balanced focus highlights the growing trend toward integrated WEF Nexus studies, which seek to explore the linkages and interdependencies between these resources. Additionally, 37% of studies (Bakhshian-Lamouki et al., 2020; Rahmani et al., 2023) focused specifically on water, underlining the critical importance of water security and its impact on other components of the Nexus. In contrast, studies centered on energy were notably fewer, with only four studies (Razaghi et al., 2025) addressing energy-related issues.

3.6. System dynamics software

Seven different software tools were utilized across the analyzed articles. The most frequently used was Vensim, which appeared in 35.7% of the studies, followed by STELLA, featured in 21.59% of the papers. These software packages are often chosen for their easy-to-use graphical interfaces. Other software tools like iThink, AnyLogic, NetLogo, and Simile were also utilized in some studies. However, it is important to note that in 29.54% of the studies, the software used was not specified.

3.7. Model validation and verification

In the reviewed studies, system dynamics models (SDMs) were validated through a combination of structural and behavioral pattern tests. These two validation approaches are essential for assessing the credibility and relevance of SDM models. Structural tests include direct evaluations, such as verifying the model's structure and ensuring dimensional consistency, as well as structure-behavior tests that assess the model's responsiveness to behavioral changes (Sterman, 2020). These evaluations help determine how accurately the model reflects real-world systems and highlight potential structural limitations. On the other hand, behavioral pattern tests focus on how well the model's outputs mirror actual system behaviors over time, often through the analysis of historical time-series data or by comparing the model’s results with mental models or established behavior patterns. Additionally, incorporating expert and stakeholder input during model development further enhances the validation process (Phan et al., 2021).

Notably, 29.54% of the reviewed studies relied exclusively on historical data to validate the SDM models applied within the water-food-energy nexus context.

The most frequently employed validation techniques for structure-behavior assessments were sensitivity analysis and critical condition tests. Sensitivity analysis typically involved adjusting key variable values (such as by 5% or 10%) to observe the effect of these modifications on the model's behavior. In contrast, critical condition tests focused on assigning extreme or critical values to certain variables and comparing the model's simulated outcomes with expected behavior. Additionally, 28.4% of the studies utilized a combination of three distinct validation methods. However, a notable portion—29.54%—did not address model validation at all. This omission likely stems from the conceptual nature of many models, which may have lacked access to the historical data required for empirical validation. Beyond these quantitative validation techniques, engaging stakeholders and experts also played a significant role in the validation process. Involving these stakeholders not only enhances understanding and confidence in the model's results but also improves its applicability in decision-making. Despite these benefits, only 13.63% of the studies incorporated stakeholder or expert feedback during validation.

3.8. Integration of system dynamics models with other tools

In the reviewed 88 studies, several researchers combined system dynamics (SD) models with other analytical tools to address challenges within the water-food-energy nexus. For example, two studies (Hu et al., 2019; Kheirinejad et al., 2024) integrated agent-based models with SD to better capture the intricate interactions among various agents that influence resource management decisions. Additionally, in one study (Soares et al., 2023), the Delphi method was employed in conjunction with SD models to identify critical system components. Moreover, some studies (Zeng et al., 2023; Zhou et al., 2024) combined machine learning techniques with SD models to address uncertainties and simulate errors within the model.

3.9. Social network analysis

3.9.1. Keyword analysis

In co-occurrence keyword analysis, the relationships between various keywords are examined to highlight how authors address interconnected topics within a single study. The resulting map offers a clear visualization, demonstrating that, while authors often concentrate on specific themes, they simultaneously engage with related concepts. This approach helps researchers identify key trends and emerging issues within a particular field. When two keywords frequently appear together in a paper, it indicates a stronger connection between them compared to others. The strength of this relationship is quantified by the number of papers in which these keywords co-occur. This keyword analysis aims to pinpoint central themes related to the WEF Nexus. Keywords are ranked based on their frequency across studies using VOSviewer software. To enhance the review's focus, common terms such as "article," "modeling," "dynamics," "simulation," "water," "food," "energy," and "water-food-energy nexus," which appear in the majority of studies, were excluded from the analysis. The most frequently mentioned keywords are listed in Table 3. As anticipated, "sustainable development" is one of the most frequently cited keywords in the reviewed studies. This is because sustainable development plays a critical role in promoting resource efficiency, conserving natural resources, and mitigating climate change, among other benefits. Incorporating sustainable development principles into the management of the water-food-energy nexus is essential to ensure these vital resources are used in a way that supports long-term environmental, social, and economic well-being.

3.9.2. Co-occurrence network map terms

For the co-occurrence keyword map analysis, all terms that appeared fewer than five times across the articles were excluded. This process left 85 keywords out of the original 1,060. Subsequently, these terms were manually screened to remove those related to dynamic modeling, simulation, causal loops, and other similar concepts.

Fig. 4 presents the keyword co-occurrence map, which highlights the most prominent research topics within the WEF nexus field. This map also serves to explore the relationships between different topics. The size of each node corresponds to the frequency with which a keyword appears in the articles—larger nodes

indicate more frequent usage. The thickness of the lines connecting the nodes represents the strength of the relationship between two terms, based on the number of abstracts in which both terms co-occur. Shorter lines between nodes indicate a stronger connection, suggesting that the two keywords are more likely to appear together in the same article.

Table 3. Ranking of keywords.

Rank	Keyword
1	Sustainable development
2	Climate change
3	Water energy
4	Water management
5	Water resource
6	Economics
7	Energy resource
8	Agriculture
9	Food industry
10	Economic and social effects

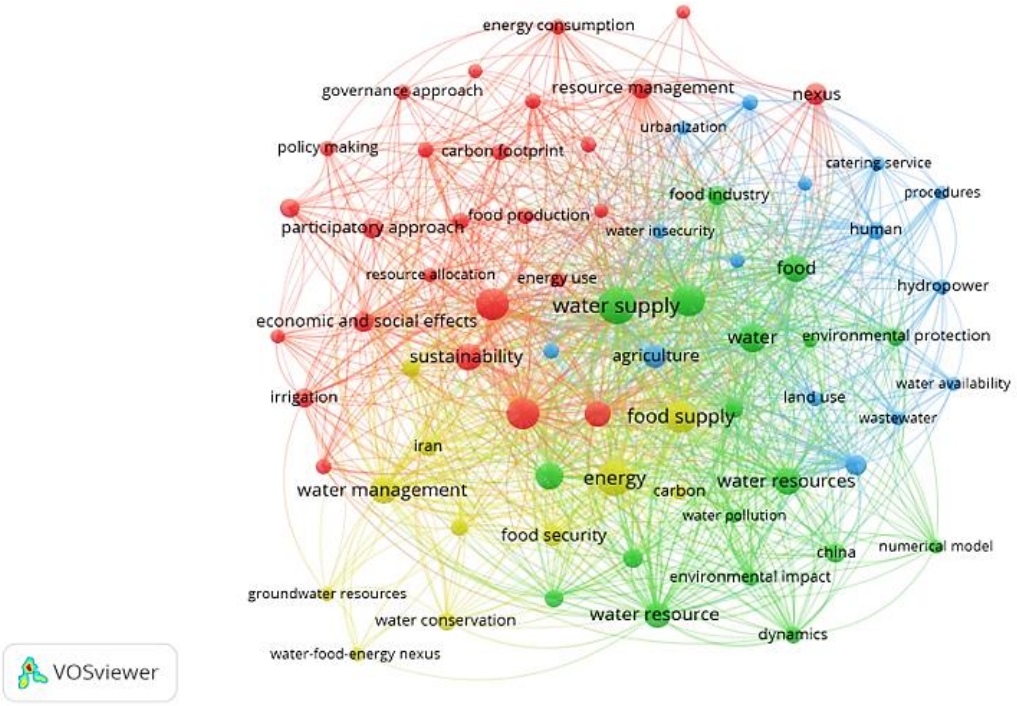

Fig. 4. Keyword co-occurrence map.

The VOS Viewer display also organizes nodes into clusters, grouping related items based on their thematic connections. These clusters are visually distinguished by different colors. In Fig. 4, four distinct clusters are represented, each with its own color. The green cluster centers on water supply and includes terms like "water used in energy production," "water resources," "food industries," and "water pollution." The blue cluster focuses on "agriculture" and encompasses terms such as "land use," "water waste," "water insecurity," "urbanization," and "drought." The yellow cluster is concerned with the intersection of "energy and food," highlighting topics like "carbon," "groundwater," "irrigation," and "food security." Finally, the red cluster is related to "sustainable development," covering issues such as "sustainability," "climate change," "policy making," and "economics".

The co-occurrence visualization is presented in Fig. 5. The nodes on this map are color-coded according to the publication year. Topics marked in purple and blue reflect areas that researchers initially focused on, which are linked to a more established body of literature. Keywords highlighted in green have gained prominence in recent studies and may evolve into major research themes in the future. Keywords shown in yellow represent emerging areas of research within the WEF nexus. Notable among these new fields are "sustainable development," "food security," "urbanization," "energy resources," "water resources," "water pollution," and "carbon".

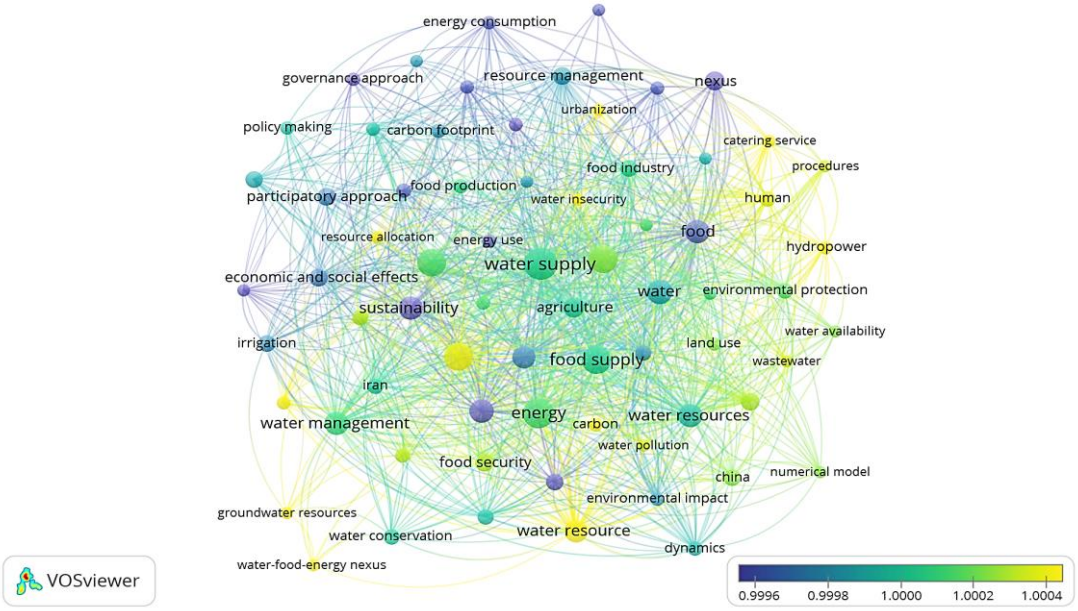

Fig. 5. Co-occurrence visualization map.

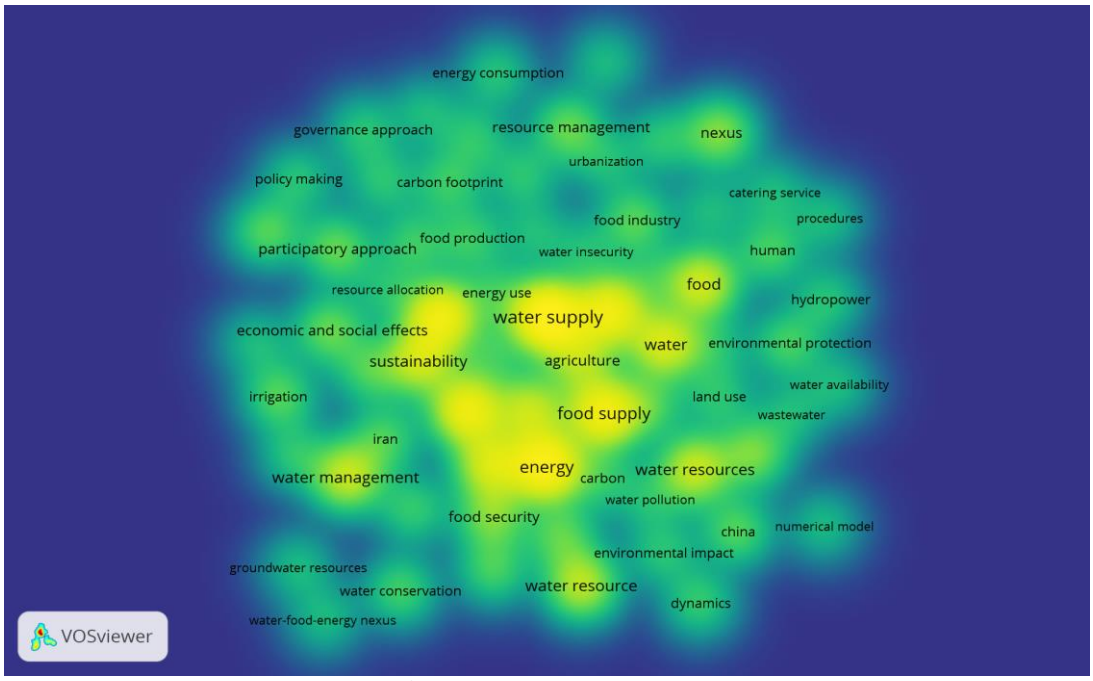

Fig. 6. Map of keyword co-occurrence density visualization.

Fig. 6 presents a density visualization that offers an overview of the map's structure, highlighting the most prominent areas. The color of the nodes in the visualization reflects their density, which is shaped by the quantity and significance of surrounding items. As the number of neighboring nodes increases and their proximity decreases, the node's color shifts toward yellow. Keywords are color-coded according to their frequency of occurrence, with those most strongly associated with the WEF Nexus moving toward yellow. The map indicates that fewer papers are linked to topics in the green regions or those further away from the yellow nodes, suggesting these areas may represent emerging research fields. The results of the keyword co-occurrence analysis (e.g., focus on sustainable development and water resources) are consistent with the results of the systematic review (e.g., focus on water subsystems and local modeling), indicating convergence of research themes and analysis tools in the WEF Nexus domain.

4. Conclusion

In this study, a systematic review, bibliometric analysis, and social network analysis were conducted on dynamic modeling of the Water-Energy-Food (WEF) Nexus up to 2025. The database used for this study was Scopus, and out of a total of 2265 articles assessed, 88 studies were selected for inclusion in the review and analysis. The first section reviewed general trends in the application of system dynamics models in the WEF Nexus, such as Nexus components, introduction of scientific journals, leading countries, etc. Finally, the second section focused on social network analysis. The results show that, although the WEF Nexus framework is still relatively new, it has steadily gained traction in both academic circles and policy discussions. As global sustainability challenges become more complex, the use of modeling approaches has expanded. A significant trend in the literature is the growing adoption of system dynamics as a key method for understanding and analyzing the complex interconnections between water, energy, and food systems. This review also underscored the incorporation of diverse subsystems—such as hydrological, social, economic, and environmental—in efforts to better capture the dynamics of the water-food-energy (WEF) nexus. Nonetheless, the majority of studies (75%) primarily focused on integrating the three core subsystems: water, food, and energy. An additional 18.18% of the studies extended their scope to include four or more subsystems. Incorporating multiple subsystems within a modeling framework is vital for sustainable resource management and planning, as it allows for a more comprehensive representation of system components and facilitates a deeper understanding of feedback loops and long-term behavioral dynamics. However, this increased complexity can introduce greater uncertainty into the modeling process. To address this, some studies complemented system dynamics models with other modeling tools designed to handle complex and uncertain systems. Thematically, the majority of studies emphasized a balanced integration of water, energy, and food systems, although water emerged as the most frequently examined component. In terms of geography, research was predominantly concentrated in Asia, highlighting a regional bias and revealing a lack of focus on other high-stress areas such as Latin America and parts of Africa. Spatially, most models operated at the local level, reflecting a strong interest in place-specific dynamics. However, this trend underscores the pressing need for more comprehensive and cross-scale modeling approaches capable of addressing the complex interlinkages within the WEF Nexus at both regional and global levels. Calibrating and validating water-food-energy (WFE) systems characterized by high complexity and uncertainty remains a significant challenge, largely due to discrepancies in subsystem scales and limited availability of comprehensive data across all variables. These difficulties are particularly pronounced when incorporating social, economic, and political subsystems, which are inherently more unpredictable and less quantifiable than physical components (Blair and Buytaert, 2016). In response to these challenges, 28.2% of the reviewed studies employed a combination of three validation methods to assess both model structure and simulation outputs, aiming to enhance model robustness and credibility. Finally, an analysis of the authors' keywords revealed frequent emphasis on themes such as sustainable development, climate change, and water management. Among these, water-related topics—such as "water resources," "water consumption for energy production," and "water management"—emerged as particularly prominent. The use of keyword density maps further enabled the identification of underexplored areas within the WEF Nexus literature. These less-studied topics may represent valuable opportunities for future research, especially for scholars seeking to address existing gaps and expand the scope of Nexus-related studies. Finally, as a summary of the study analysis revealed trends in publication activity, geographic focus, software use, and thematic concentration. Nevertheless, there are key limitations: underreporting of model validation, regional research gaps, and insufficient hybridization of methods, Future research should focus on incorporating stakeholder perspectives, validating models rigorously, and expanding into underserved geographies. Additionally, using multiple databases beyond Scopus and employing innovative computational methods will improve comprehensiveness and impact.

Acknowledgments

This article was not under any financial support.

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