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The Food Water Energy Nexus in Agriculture: Understanding Regional Challenges and Practices to Sustainability

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Abstract: This study explores global research trends, regional challenges, and methodological approaches in food–water–energy (FWE) nexus research within agricultural contexts from 2000 to 2024. A bibliometric analysis of 929 articles indexed in the Web of Science and Scopus was conducted. A sharp increase in research output has been observed after 2014, with the United States and China identified as dominant contributors. European countries have been recognized as key connectors in international research networks. Thematic evolution indicates a transition from foundational concepts to more advanced approaches, incorporating machine learning, optimization techniques, and circular economy strategies. Regional disparities in research capacity and thematic focus have been highlighted, influenced by differing resource constraints and socio-economic conditions. The energy dimension of the nexus has consistently been identified as a cross-cutting challenge, primarily due to increasing energy demands in agriculture. Methodological preferences have been found to vary across regions: scenario analysis is emphasized in North America, optimization models are commonly applied in East Asia, and stakeholder-centered approaches are more prevalent in developing regions. These findings suggest a need for enhanced international collaboration, greater methodological diversity, and stronger engagement with underrepresented regions, particularly South and Southeast Asia and Africa. Strengthening the FWE nexus framework through inclusive and adaptive research strategies is essential for promoting sustainable agricultural management under increasing global resource pressures.

Keywords: food–water–energy nexus; agriculture; bibliometric; preferred reporting items for systematic reviews and meta-analyses (PRISMA); regional disparities; research methodologies; sustainable development; climate impacts

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Academic Editor: Piotr Prus

Received: 9 April 2025
Revised: 7 May 2025
Accepted: 11 May 2025
Published: 13 May 2025

Citation: Mai, E.N.Z.; Inoue, N.; Uenishi, Y. The Food Water Energy Nexus in Agriculture: Understanding Regional Challenges and Practices to Sustainability. *Sustainability* **2025**, *17*, 4428. https://doi.org/10.3390/su17104428

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1. Introduction

The global agricultural sector plays a critical role in sustaining livelihoods and economies by ensuring food security and providing employment to billions worldwide [1]. Despite its importance, agriculture remains the largest consumer of global freshwater resources, while water is essential for producing nearly all forms of energy. Additionally, more than one-quarter of global energy consumption is devoted to food production and distribution. According to the FAO (2017), agriculture accounts for approximately 70% of global freshwater withdrawals, making water a critical resource for agricultural production, with its availability and utilization shaped by regional climatic conditions, agricultural systems, and infrastructure [2]. Advanced irrigation systems and groundwater extraction technologies enable high-efficiency crop production [3]. In contrast, rain-fed agricultural

systems remain vulnerable to seasonal variability and increasingly erratic weather patterns due to climate change [4]. Regardless of the water source, water availability fundamentally influences crop productivity and long-term sustainability. Consequently, the modernization of agricultural systems, influenced by global drivers such as population growth and climate change and characterized by the adoption of advanced irrigation technologies, greenhouse climate control, mechanized farming practices, and increased use of fertilizers, has substantially increased the sector's dependence on energy [5,6]. While these innovations enhance agricultural productivity, they concurrently place greater demands on energy systems, raising concerns about long-term sustainability. Accordingly, the interdependence of food, water, and energy systems is especially pronounced in the context of agriculture, where each resource acts as both a critical input and a limiting factor. Water is indispensable for crop cultivation and livestock, while energy is essential for operating machinery, powering irrigation systems, and processing agricultural products. In this way, agriculture and the food system place an increasingly significant demand on both water and energy resources, from crop and livestock production to processing, storage, and distribution. The food–water–energy (FWE) nexus approach captures these complex interlinkages, emphasizing how inefficiencies or decisions in one domain can significantly impact the others. By integrating cross-sectoral perspectives, the FWE nexus concept provides a valuable framework for promoting holistic and sustainable resource management in agriculture [7].

While existing studies on the FWE nexus often focus on global-scale analyses, they tend to overlook important regional differences in how these systems interact. This broad approach makes it difficult to understand how specific environmental, economic, and institutional factors influence the implementation of the FWE nexus in different contexts. For instance, some regions may face more severe water shortages, weaker infrastructure, or distinct agricultural systems, all of which affect how food, water, and energy are managed together. As noted by Endo et al. (2020) and Leck et al. (2015), many global models do not fully reflect these regional realities [8,9]. The FAO (2021) also emphasizes the need for context-specific strategies, particularly in areas that are vulnerable to climate change and resource scarcity [7]. Because regions face distinct but interlinked challenges, understanding local contexts is key to developing more effective global strategies. This underscores the importance of international research collaboration, as agricultural challenges such as water scarcity, climate change, and food insecurity span multiple regions and require shared knowledge and expertise. The FAO highlights that stronger regional and international cooperation is essential to share agricultural knowledge, expand access to diverse expertise, improve adaptation strategies, address transboundary challenges, and promote the development of solutions that are globally informed and locally adapted. These goals can be achieved through joint research, knowledge exchange, technology transfer, and capacity building [10]. In response to this need, the FAO launched the Global Framework on Water Scarcity in Agriculture (WASAG) in 2017. This framework stresses the importance of international partnerships in addressing these interconnected challenges [11]. Accordingly, understanding international research collaboration patterns in FWE nexus research can provide valuable insights into global research priorities, knowledge-sharing mechanisms, and opportunities for coordinated policy development. Despite its importance, comprehensive reviews on how international research collaboration patterns and regional differences in FWE challenges and solutions are studied remain scarce. This study aims to address this gap by analyzing regional diversity in FWE nexus research. It compares agricultural challenges, research methods, and trends across regions, offering a more localized understanding of how different conditions shape sustainable agricultural practices within the nexus framework.

To address this gap, the study explores four key research questions: (1) What global trends and international collaboration patterns define current FWE nexus research on sustainable agriculture, and how have they evolved over time? (2) Which FEW nexus-related challenges and constraints emerge across different geographical regions, and how do they reflect region-specific vulnerabilities in agricultural systems? (3) Which methodological approaches dominate FWE nexus research in agriculture, and what core objectives do they pursue? (4) Which socio-economic, environmental, and governance factors drive regional differences in methodological approaches?

Guided by these questions, the study pursues three main objectives: (1) to analyze global research trends and patterns of international collaboration in FWE nexus studies related to sustainable agriculture, with a focus on the evolution of scientific priorities and geographical cooperation over time; (2) to identify and compare regional differences in FWE nexus-related challenges and constraints, exploring how geographical, environmental, and socio-economic contexts shape agricultural vulnerabilities and sustainability strategies; and (3) to identifies the FWE nexus methods and evaluate the effectiveness and regional relevance of methodological approaches employed in the research, assessing their ability to manage resource interdependencies and support informed decision-making in diverse agricultural contexts.

This study will enhance understanding of the FWE nexus by exploring global trends and regional variations in sustainable agriculture. It aims to provide context-specific insights into regional challenges and solutions, while refining methodologies in FWE research. The findings will contribute to a deeper understanding of how the FWE nexus can be applied in diverse agricultural contexts, offering insights that could inform future research and policy discussions on sustainable resource management.

2. Materials and Methods

This study employs a combination of a systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and bibliometric analysis. The PRISMA guidelines provide a framework for the transparent and complete reporting of systematic reviews, ensuring consistency and reproducibility in how the methodology and findings are presented [12,13]. While other frameworks such as AMSTAR (A Measurement Tool to Assess Systematic Reviews) primarily evaluate the methodological quality of systematic reviews, PRISMA serves as a reporting standard designed to guide authors in structuring and presenting their reviews clearly and thoroughly [14,15]. Rhouma et al. (2024) applied the PRISMA methodology in their review of FWE nexus research, demonstrating its effectiveness in synthesizing studies across different disciplines and contexts [16].

Following the PRISMA framework, the article search, exclusion, and final selection process involved the following steps (Figure 1). This study selected Scopus and Clarivate Analytics Web of Science as the primary academic databases because they are recognized for their comprehensiveness and credibility in indexing peer-reviewed literature across various disciplines [17]. Scopus, operated by Elsevier, offers extensive journal coverage with strong representation in the social sciences, humanities, and environmental sciences, making it particularly suitable for interdisciplinary topics such as the FWE nexus. Likewise, Web of Science, maintained by Clarivate, is highly regarded for its inclusion of high-impact journals and its robust citation indexing capabilities, which facilitate the assessment of research influence and trends [18,19]. Using both databases ensured the retrieval of the broadest range of relevant literature while minimizing database-specific bias. This dual-database strategy enhanced the methodological rigor of our systematic review by maximizing both the breadth and depth of source material. The article search was conducted between

2–13 December 2024. The search strategy utilized a combination of keywords—"food", "water", "energy", "nexus", "sustainable agriculture", and "farm management"—with "AND" used to refine the results and "OR" applied to capture a broader range of relevant studies. These keywords were carefully selected to capture studies addressing the FWE nexus within the context of agricultural sustainability and farm management. The initial search yielded a total of 1691 articles: 373 from Scopus and 1318 from Web of Science. After applying specific exclusion criteria, 762 articles were removed: 328 were not related to agriculture, 147 were non-peer-reviewed articles, 86 were non-English language articles, and 201 were review articles. This screening process resulted in the final selection of 929 articles for further bibliometric analysis. This approach ensured that only relevant, original articles in English, focusing on agricultural practices, farm management, and sustainability in relation to the FWE nexus, were included in our bibliometric analysis.

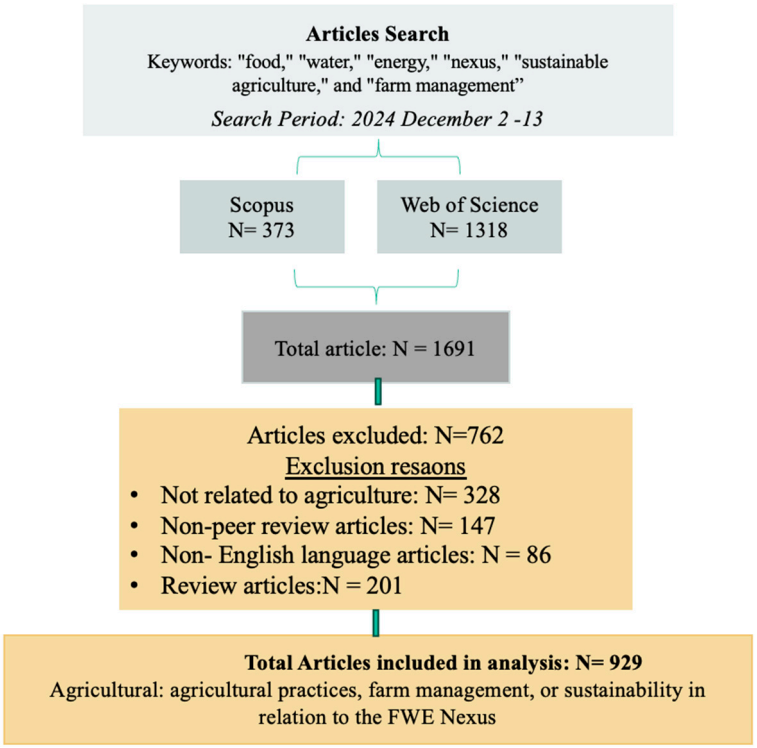


Figure 1. PRISMA flow diagram illustrating the systematic article selection process.

Building on the systematic review and article selection process, we used a multifaceted analytical framework grounded in established bibliometric and network analysis methodologies to examine the selected articles. This framework included four key components: trend analysis, network analysis, knowledge production analysis, and agricultural context analysis. Each component investigated the integration of the FWE nexus within agricultural systems. These components were chosen to achieve the objectives of understanding the temporal evolution of research, patterns of scholarly collaboration, knowledge production trends such as methodological developments, and region-specific challenges and practices in the FWE nexus in agriculture. We conducted trend analysis, network analysis, and knowledge production analysis using Biblioshiny in RStudio (version 2022.07.2+576), which provides robust tools for visualization and interpretation [20]. Agricultural context analysis was performed using text mining techniques in RStudio, allowing us to identify regional challenges and methodological patterns related to the FWE nexus in agriculture. The analyses were structured as follows:

(1) Trend analysis focused on understanding global research patterns and the evolution of FWE nexus studies in agriculture by examining annual publication trends and the distribution of publications across journals;
(2) Network analysis mapped international collaboration by examining country-specific publication counts and co-authorship relations, derived from authors' institutional affiliations. To analyze co-authorship patterns, the Spinglass clustering algorithm was employed due to its demonstrated effectiveness in detecting research communities within large-scale networks, particularly those formed by shared academic interests [21,22]. For robustness, an association normalization technique was applied to adjust co-occurrence frequencies, mitigating biases and providing a more accurate measure of collaborative ties [23]. This approach visualized global research dynamics and regional disparities, offering insights into international collaboration patterns and variations in the focus of FWE nexus studies across countries and regions;
(3) Knowledge production analysis examined the evolution of research topics and methodologies in articles published between 2000 and 2024 through two main approaches: (1) topic trend analysis using authors' keywords and (2) thematic development analysis through abstracts. For topic trend analysis, the authors' keywords were analyzed using a standardized list of synonyms, including terms such as FEW, FWE, food–water–energy nexus, water–food–energy nexus, sustainability, and sustainable development, to ensure uniformity and clarity in identifying key research topics. For thematic development analysis, a synonym list and bigram analysis were used to capture co-occurring and recurring themes in the abstracts. To assess thematic evolution over time, the abstracts were classified into distinct timeframes, allowing for the identification of trends and shifts in research focus across different periods;
(4) Agricultural context analysis used a systematic text mining approach to identify and analyze the FWE nexus challenges and methods in agricultural sustainability across different regions. The analysis was conducted using RStudio, where several custom functions were developed to categorize the articles, identify regional challenges, and assess common methodologies. Below is a detailed outline of the steps involved in the analysis:

- Categorization of articles: The 929 selected articles were categorized into nine major geographical regions (East Asia, Southeast Asia, South Asia, Middle East, Africa, Europe, Oceania, North America, and South America) using text-mining techniques in RStudio. A custom R function, "classify_region()", was developed to detect country names within the text by applying a predefined list of countries mapped to their respective regions through case-insensitive exact matching. To create a comprehensive text corpus, multiple fields from each article were extracted and combined, including the title (TI), descriptors (author' keywords) (DE), identifiers (ID), abstracts (AB), and author addresses (C1). Articles without any country-related terms are categorized as "others" and excluded from further analysis.
- Limitation: This method may miss regionally relevant papers that use general terms (e.g., "Mekong region", "Sub-Saharan Africa") without specifying country names. Additionally, misclassification could occur due to country names used in non-geographical contexts.
- Identification of regional challenges: After classifying the articles by region, a keyword-based text mining approach was employed to identify key challenges related to the FWE nexus in agriculture. This analysis was conducted in RStudio using a custom function, "analyze_challenges()", designed to detect a predefined vocabulary of challenge-related terms (e.g., scarcity, pollution, irrigation, innovation, climate change, and health impacts). These terms were mapped to broader challenge categories, includ-

ing water scarcity, water quality, infrastructure, management issues, climate impacts, agricultural challenges, technology gaps, social and economic constraints, environmental degradation, urban water issues, energy-related concerns, data limitations, governance challenges, and health-related impacts. The vocabulary and categories were informed by the comprehensive overview of FWE nexus challenges outlined by the World Business Council for Sustainable Development (WBCSD, 2014) [24]. The function systematically extracted relevant terms from the text corpus and matched them to the corresponding challenge categories, enabling a structured regional analysis of agricultural nexus issues.

- Limitation: Semantic ambiguity can affect accuracy; for example, the word "scarcity" may appear in different contexts not directly related to the challenge categories. Also, variations in terminology may cause under-detection. Manual validation of a sample or integration of contextual phrase analysis could help mitigate this limitation.
- Frequency calculation of challenges: The data were subjected to text standardization, and a region-challenge matrix was created to quantify the frequency of challenges for each region, providing statistical insights into their prevalence.
- Limitation: While frequencies highlight commonly discussed challenges, they may not fully reflect contextual depth or the relative severity of issues across regions. Additionally, high-frequency terms may be influenced by research trends rather than real-world urgency. Further qualitative review could complement the frequency analysis.
- Identification of common methods: To systematically identify common methodologies prevalent in FWE nexus research, text mining techniques were applied in RStudio, leveraging a predefined keyword-matching approach. This approach was structured based on a classification scheme adapted from key analytical methods identified in prior systematic reviews of nexus studies [25,26]. Based on this framework, a dictionary-based classification system is developed and divided into 12 key categories: system dynamics, life cycle assessment, multi-criteria decision analysis, resource modeling, remote sensing, optimization, crop modeling, hydro-economic analysis, integrated assessment, stakeholder analysis, scenario analysis, and input–output analysis. The classification function, "analyze_methods()", was designed to detect occurrences of method-related keywords (e.g., "system dynamics", "causal loop", "LCA", "multi-criteria", "GIS", "optimization") within the text corpus. This function uses string pattern matching and case-insensitive keyword detection to assign each paper to one or more methodological categories based on the presence of relevant terms in the title, abstract, and keyword sections. The classification not only facilitates a systematic organization of methodological trends but also helps to simplify and standardize method-related terminology, which is often inconsistent across studies. Given the diverse ways in which FWE nexus methodologies have been described, grouping similar approaches under broader categories enhances clarity and comparability. This structured approach enables a more effective analysis of how different methods contribute to understanding and managing FWE nexus challenges. Additionally, a region-method matrix was constructed to assess the distribution of methodological approaches across geographical regions, providing insights into regional variations in FWE nexus research.
- Limitation: The diversity of terminology in methodological descriptions means that some methods might be misclassified or overlooked. For instance, papers using unique or less common terms for standard approaches may escape detection. Moreover, keyword detection cannot capture methodological depth or implementation rigor. Including a manual review of selected cases could enhance accuracy.

Figure 2 illustrates the conceptual framework of the study, outlining a systematic approach to analyzing FWE nexus research in agriculture, guided by three core research objectives. The first objective seeks to reveal global trends and patterns of international collaboration within FWE nexus studies. This is addressed through research question 1, which investigates the evolution of global FWE research and collaboration networks, supported by analyses of publication patterns, network mapping, and knowledge production. The second objective focuses on identifying and comparing regional differences in FWE-related challenges. Research question 2 explores how these challenges and constraints vary geographically and reflect region-specific vulnerabilities, analyzed through an agricultural context-specific assessment of FWE nexus challenges. The third objective aims to evaluate the effectiveness and regional relevance of methodological approaches used in FWE research. Research questions 3 and 4 examine the dominant methods employed in the field, their core objectives, and how socio-economic, environmental, and governance factors influence methodological choices. These are addressed through a focused analysis of FWE nexus methods and contextual discussion. Together, the framework provides a comprehensive structure for understanding global and regional dimensions of FWE Nexus research in agriculture.

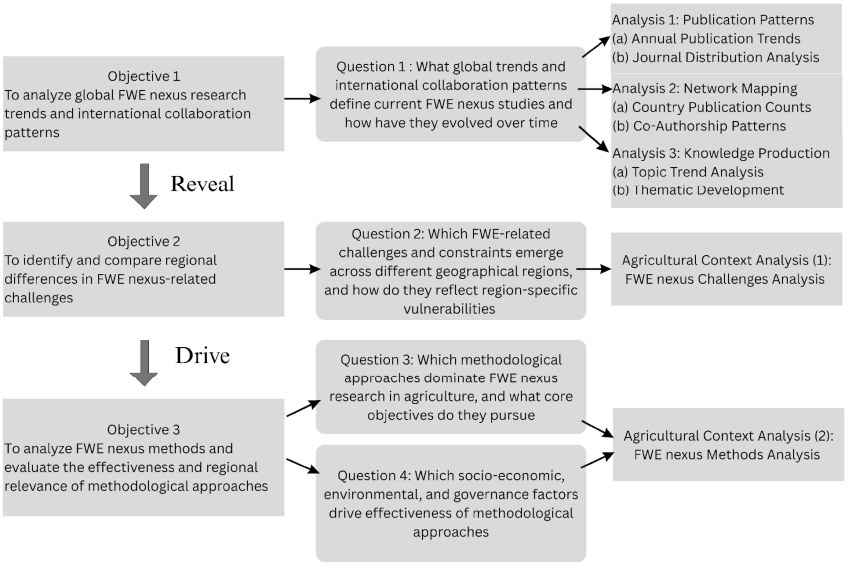


Figure 2. Conceptual framework of the study: research objectives, research questions, and analytical approaches for the FWE nexus in agriculture.

3. Results

This section presents the study's findings, structured into four main analytical components. First, this study explores trends in FWE nexus research, focusing on the distribution and publication patterns in the scientific literature. It also examines publication counts by journal, highlighting key academic outlets for FWE research. The second component assesses country-specific publication counts and co-authorship relations, highlighting international collaboration and research connectivity. Next, the evolution of knowledge production in the field is analyzed by identifying significant shifts and emerging topics. Finally, this study explores the agricultural contexts in which the FWE nexus is applied, highlighting specific challenges and methods relevant to different regions.

3.1. Trends in Research on the FWE Nexus

3.1.1. Distribution of Scientific Publications

Figure 3 illustrates the temporal distribution of scientific publications on the FWE nexus in agricultural contexts from 2000 to 2024. No publications appeared before 2008, but

the modest initiation in that year marked the start of FWE-related discourse in agriculture. A significant upward trend began around 2014, coinciding with the global policy shift towards integrated resource management and the adoption of the Sustainable Development Goals (SDGs) in 2015 [27]. This momentum was further catalyzed by the release of the FAO's landmark report in 2014, which emphasized the critical interdependencies between food, water, and energy systems and advocated for a more integrated approach to resource governance [28].

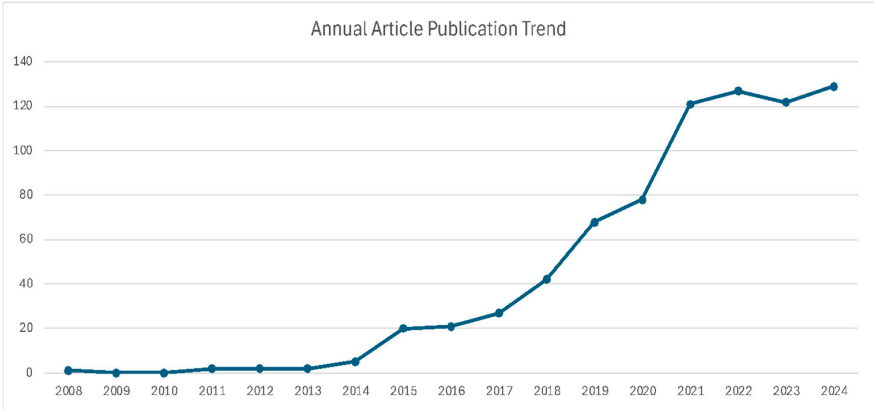


Figure 3. Distribution of annual articles on FWE nexus research from 2008 to 2024.

3.1.2. Number of Scientific Publications by Journals

Figure 4 shows the top contributing journals. Science of the Total Environment, Sustainability, and the Journal of Cleaner Production dominate, suggesting that the FWE nexus is still largely situated within interdisciplinary and sustainability-focused journals rather than traditional agricultural science outlets. This suggests that the nexus approach is being driven more by environmental and systems science communities than by conventional agronomic or rural development disciplines. In contrast, journals such as Agricultural Water Management and Agronomy-Basel reflect a growing but still smaller representation of core agricultural publications. Notably, high-impact energy or environment journals (e.g., Applied Energy and Environmental Science and Policy) contribute more significantly, hinting at the dominant influence of policy, environment, and energy concerns in agricultural nexus research.

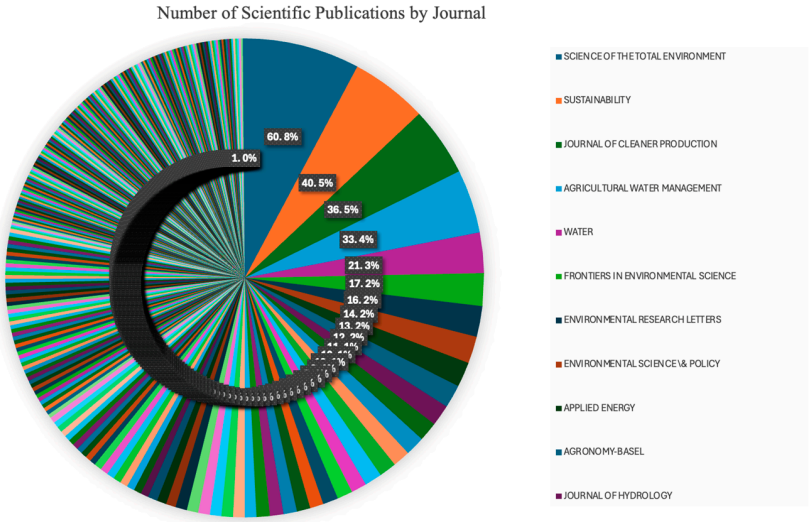


Figure 4. Number of scientific publications by journal.

3.2. Network Analysis

The following section presents the results of the network analysis, focusing on two key aspects: country publication count and co-authorship relations. The country publication count highlights the contributions of different countries to FWE nexus research, providing insights into global trends in this area. Co-authorship relationship analysis examines the collaborative networks between authors, shedding light on interconnectedness and collaboration patterns within the research community. These analyses offer a deeper understanding of international collaboration and its contributions to FWE nexus research in agriculture.

The analysis of country-specific research output reveals distinct patterns in both publication volume and international collaboration in FWE nexus research (Figure 5). The United States of America (USA) leads in both total publications, with over 150 documents, and a significant proportion of multiple-country publications (MCPs). China ranks second in terms of productivity, demonstrating strong international collaborative efforts, as indicated by its highest MCP ratio. Iran ranks third in overall publications, though it has a relatively low proportion of international collaborations. European nations, including Germany, Italy, and the United Kingdom (UK), show moderate publication outputs with balanced distributions between single-country publications (SCPs) and MCPs. Emerging economies, such as Brazil, South Africa, and India, also make notable contributions, each demonstrating varying degrees of international collaboration. The data suggests that, while established research powers maintain leadership, considerable research activity occurs across both developed and developing countries, with varying levels of international partnerships. The diversity of top contributors, spanning both developed and developing economies, highlights the global relevance and engagement in FWE nexus research across different socioeconomic contexts. This publication pattern suggests a gradual evolution of FWE nexus research, from predominantly domestic studies to increasingly collaborative international efforts, particularly among leading research nations. The variation in SCP–MCP ratios across countries may reflect differences in research infrastructure, funding mechanisms, and policy priorities in addressing FWE nexus challenges.

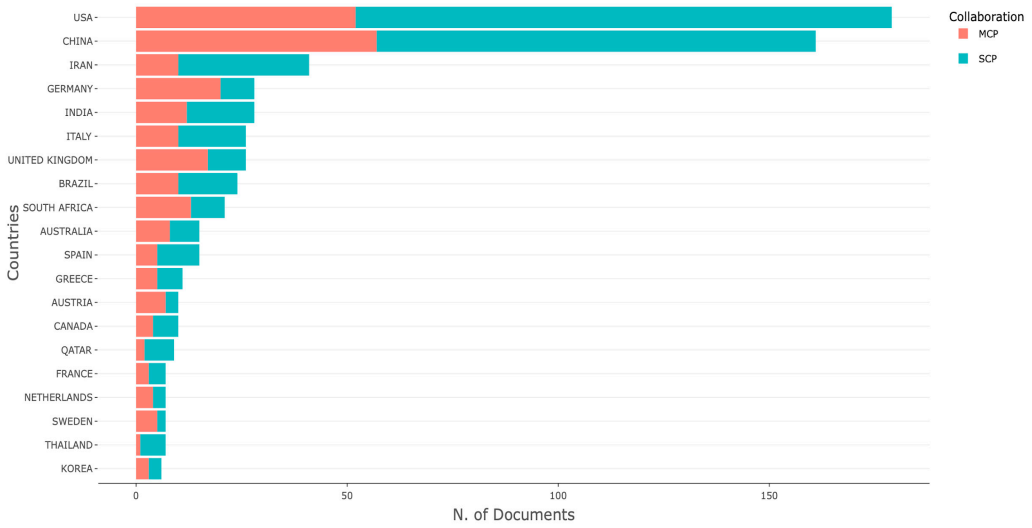


Figure 5. Countries with the most publications (SCP: single-country publication, MCP: multiple-country publication).

To gain deeper insight into global scientific connectivity, Figure 6 presents the co-authorship network, analyzed using the Spinglass clustering algorithm, revealing distinct patterns of international collaboration in FWE nexus research. In this visualization, node

size indicates publication volume, while the thickness of connecting lines represents the strength of collaborative relationships between nations. The USA and China stand out with notably larger nodes, indicating their substantial publication output in FWE nexus research. The USA appears to have the highest publication volume, forming the center of a red cluster with thick connecting lines to several countries, particularly to the UK and Canada, indicating strong, established collaborative relationships. These thick connections suggest frequent co-authorship and sustained research partnerships that likely facilitate significant knowledge exchange. China anchors a purple cluster with prominent connections to other Asian countries such as Indonesia, Malaysia, and Thailand. The moderate thickness of these connections suggests developing but meaningful collaborative relationships within this regional network. Interestingly, the connection between the USA and China appears particularly thick, highlighting the importance of collaboration between these two research powerhouses despite their distinct regional spheres of influence. European countries, particularly the UK, Germany, and Italy, show moderate node sizes but numerous connections of varying thickness. Their position in the network suggests they serve as important intermediaries, with the thickness of their connections to both the USA and various African nations indicating their role in bridging different research communities. The UK's particularly thick connection to the USA suggests a special relationship in FWE nexus research. The green cluster featuring Brazil, Spain, Australia, and Switzerland reveals a distinctive collaboration pattern with nodes of varying sizes connected by moderately thick lines, indicating established collaborative relationships focused on specific research themes or methodological approaches. The network reveals structural imbalances in research output and collaboration intensity. African countries generally display smaller nodes with thinner connecting lines, suggesting lower publication output and less intensive collaborative relationships. However, countries like South Africa, Kenya, and Ethiopia show slightly larger nodes within this group, indicating their relatively stronger representation in FWE nexus research compared to other African nations. The varying thickness of connections between Global North and Global South countries suggests different levels of engagement, with some partnerships appearing more substantial than others. Countries appearing at the periphery with smaller nodes and fewer, thinner connections likely represent emerging contributors with limited but growing engagement in the field. Their positioning suggests opportunities for strengthening international collaboration to enhance their integration into global knowledge networks.

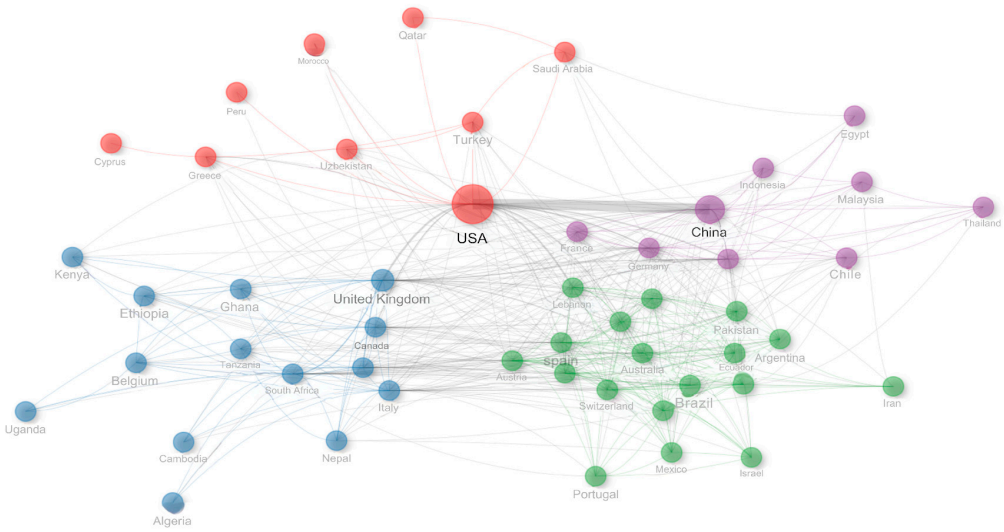


Figure 6. Co-authorship relations between countries using the Spinglass clustering algorithm and association normalization.

3.3. Knowledge Production Analysis

The knowledge production analysis focuses on two key areas: topic evaluation and research-theme development. Topic evaluation identifies the key subjects and trends emerging in FWE nexus research, providing insights into the most studied aspects of this field. Research theme development examines how these topics have evolved over time, revealing shifting focus areas and emerging themes in FWE nexus research. Together, these analyses offer a comprehensive understanding of the trajectory of scientific knowledge production and the evolving research landscape in this area.

The topic trend analysis of FWE nexus research, as shown in Figure 7, reveals significant evolutions from 2000 to 2024. Although the analysis spans this entire period, publications specifically addressing the FWE nexus began to emerge in 2008. In the early years, foundational terms such as "water-energy nexus" and "bioenergy" were prominent, reflecting a theoretical orientation focused on bilateral relationships and energy transitions, particularly in the context of evolving global environmental policy discussions [29,30]. From 2013 to 2016, a thematic shift became apparent with the introduction of governance-related terms such as "dynamics", "water use efficiency", and "trade offs", indicating a move toward practical management concerns. This period coincided with global discussions on sustainability, culminating in the 2015 adoption of the United Nations Sustainable Development Goals (SDGs). Key SDGs, including SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 7 (Affordable and Clean Energy), influenced the emergence of integrative terms such as "food security" and "sustainable agriculture" [27,31]. During 2017 to 2019, research expanded further to include terms such as "governance", "integrated assessment", "irrigated agriculture", and "resilience", reflecting a growing recognition of systemic interdependencies [32]. These developments align with major global milestones, particularly the IPCC Special Report on Climate Change and Land (SRCCL), which highlights the urgent need for integrated, multiscale strategies to address the escalating impacts of climate change on food security, agricultural systems, and water resources [33].

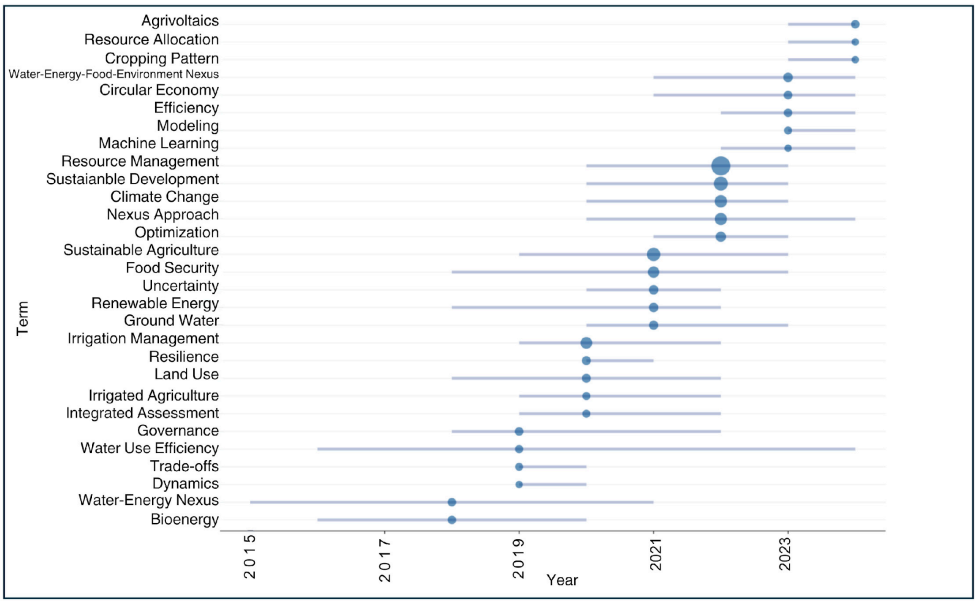


Figure 7. Trend of FWE nexus research topics in agriculture up to 2024.

Between 2021 and 2024, a pronounced shift toward technological and climate-responsive paradigms became evident. Terms such as "agrivoltaics", "machine learning", "circular economy", and "resource allocation" signaled increasing analytical sophistication and the integration of innovation in nexus research. The growing relevance of concepts like

"uncertainty", "groundwater", "climate change", and "sustainable development" underscores the field's response to intensifying environmental pressures. These evolving themes are well aligned with FAO's focus on climate-smart agriculture and digital agriculture, both of which promote sustainable, resilient agricultural practices and contribute to global efforts to address climate change and enhance food security [34,35].

The Sankey diagram in Figure 8 further illustrates the evolution of research themes across four distinct periods (2008–2024). In the initial stage (2008–2012), the research was narrowly focused on productivity, efficiency, and resource management, laying the groundwork for nexus-based inquiry [29]. From 2013 to 2016, the field expanded, with new themes such as food security, water quality, and energy-water dynamics gaining traction. This shift marked a transition from sector-specific studies to a more integrated, systemic approach, strongly influenced by global policy discussions around sustainability and the SDGs [27,31]. The 2017–2020 period was characterized by the synthesis of earlier themes into more comprehensive management frameworks, emphasizing river basin management, integrated assessment, and resilience. This evolution aligned with international momentum on climate adaptation, including the IPCC SRCCL report, which highlighted the need for integrated, multiscale responses to climate-related threats in agriculture and water systems [33]. Most recently, between 2021 and 2024, research has increasingly embraced climate-responsive strategies. While resource management remains central, there is a clear pivot toward data-driven, adaptive approaches, with topics such as climate change, efficiency, and digital innovation reflecting the field's growing sophistication. This period aligns with global efforts toward climate action, particularly through initiatives such as FAO's climate-smart agriculture and digital agriculture frameworks, which support the transition to more sustainable and resilient agricultural systems [34–36].

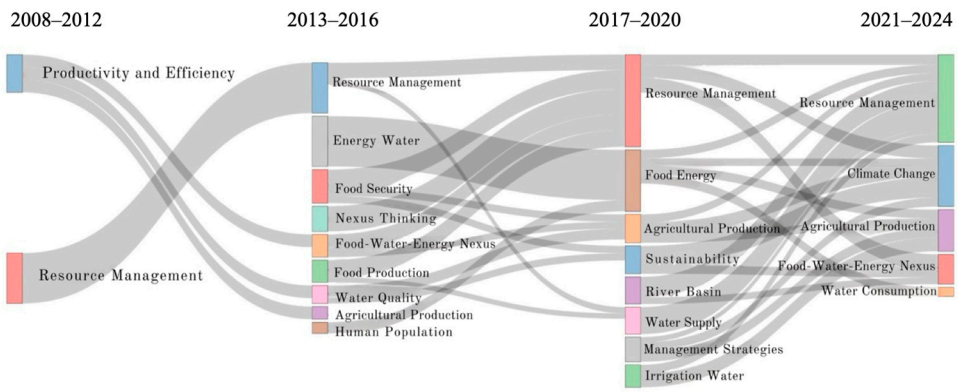


Figure 8. Evolution of FWE nexus research topics in agriculture up to 2024.

Overall, the evolution of FWE nexus research reflects a clear trajectory from foundational bilateral concepts to integrated, multi-dimensional approaches that address complex global challenges. The increasing inclusion of cross-cutting environmental issues, often represented by themes such as irrigation, river basin management, water quality, and resource allocation, demonstrates how the FWE framework has matured to encompass broader systemic interrelationships. These themes reflect a shift from narrow, sectoral analysis to holistic, sustainability-oriented thinking, closely aligned with global development agendas such as the SDGs and climate adaptation strategies. Furthermore, the recent incorporation of digital tools and climate-resilient practices, evident in emerging topics like machine learning, agrivoltaics, climate change, and circular economy, highlights the growing analytical sophistication and practical relevance of the FWE nexus in addressing the intertwined challenges of food security, water scarcity, and energy use in a rapidly changing world.

3.4. Agricultural Context Analysis

This section presents the results of the study in six parts. First, it classifies the research articles into nine major regions based on text mining analysis, highlighting the geographical distribution of FWE nexus research in agriculture. Second, it categorizes and groups the major FWE nexus challenges identified from the literature, facilitating a clearer understanding of the thematic focus areas. Third, it analyzes the distribution of these challenges across different regions, providing insights into how agricultural challenges vary geographically. Fourth, it groups the methodological terms extracted from the literature into coherent categories to improve clarity in methodological analysis. Finally, it examines the regional distribution of methodologies, illustrating variations in research approaches across different geographical and contextual settings. Finally, it presents a comparative analysis of regional differences, considering key dimensions such as research capacity, governance and policy structure, and infrastructure and technological context.

3.4.1. Regional Classification of Research Articles

The geographical distribution of FWE nexus research articles reveals distinct patterns of scholarly activity across global regions (Table 1). North America leads with 161 articles, primarily contributed by the USA. East Asia follows closely with 131 articles, largely driven by research from China. A notable disparity exists within Asia, with South Asia producing 69 articles and Southeast Asia contributing 20. The research field shows consistency across several regions, with Europe, the Middle East, and Africa contributing 64, 65, and 63 articles, respectively, demonstrating balanced engagement with FWE nexus research in these areas. South America maintains a moderate presence with 42 articles, while Oceania shows limited involvement with 11 articles. This global distribution pattern reflects varying regional research capacities and highlights different priorities in addressing FWE nexus challenges across geographical boundaries. The comprehensive analyses encompass 929 articles, including some outside these regional classifications, providing a thorough overview of the global research landscape of the FWE nexus, particularly in the context of agriculture.

Table 1. Distribution of FWE Nexus Articles by Geographic Regions (2008–2024).

Regions	Countries	Number of Papers
North America	The USA, Canada, United Mexican States	161
East Asia	China, Japan, Republic of Korea (South Korea), Taiwan (Republic of China), Hong Kong Special Administrative Region of China, Mongolia	131
South Asia	Republic of India, Islamic Republic of Pakistan, People's Republic of Bangladesh, Democratic Socialist Republic of Sri Lanka, Federal Democratic Republic of Nepal, Kingdom of Bhutan, Republic of Maldives	69
Middle East	Islamic Republic of Iran, Republic of Iraq, Kingdom of Saudi Arabia, State of Qatar, United Arab Emirates, Republic of Yemen, Sultanate of Oman, Hashemite Kingdom of Jordan, Lebanese Republic, Syrian Arab Republic, State of Israel	65
Europe	Republic of Austria, Kingdom of Belgium, Republic of Bulgaria, Republic of Croatia, Republic of Cyprus, Czech Republic (Czechia), Kingdom of Denmark, Republic of Estonia, Republic of Finland, French Republic, Federal Republic of Germany, Hellenic Republic (Greece), Hungary, Ireland, Italian Republic, Republic of Latvia, Republic of Lithuania, Grand Duchy of Luxembourg, Republic of Malta, Kingdom of Netherlands, Republic of Poland, Portuguese Republic, Romania, Slovak Republic, Republic of Slovenia, Kingdom of Spain, Kingdom of Sweden, United Kingdom of Great Britain and Northern Ireland, Kingdom of Norway, Russian Federation	64
Africa	Arab Republic of Egypt, Federal Republic of Nigeria, Republic of Kenya, Republic of South Africa, Federal Democratic Republic of Ethiopia, Republic of Ghana, Kingdom of Morocco, Tunisian Republic, People's Democratic Republic of Algeria, United Republic of Tanzania	63

Table 1. *Cont.*

Regions	Countries	Number of Papers
South America	Federative Republic of Brazil, Argentine Republic, Republic of Chile, Republic of Colombia, Republic of Peru, Bolivarian Republic of Venezuela, Republic of Ecuador	42
Southeast Asia	Kingdom of Thailand, Socialist Republic of Vietnam, Republic of Indonesia, Federation of Malaysia, Republic of the Philippines, Republic of Singapore, Republic of the Union of Myanmar, Kingdom of Cambodia, Lao People's Democratic Republic, Brunei Darussalam	20
Oceania	Commonwealth of Australia, New Zealand, Republic of Fiji, Independent State of Papua New Guinea	11
Other	Papers that do not mention the above countries' names	303
	Total	929

3.4.2. Categorization of FWE Nexus Challenges in Agriculture

The challenges in the FWE nexus within agriculture are organized into 15 main areas. These include agricultural issues that focus on the effects of extreme weather events on productivity and the adoption of sustainable practices. Climate impact addresses the broader effects of climate change on water, energy, and food security. Data limitations emphasize the need for improved data collection and accessibility. Economic constraints focus on financial and market-related challenges. The energy nexus explores the interconnections between water and energy systems. Environmental effects concern ecosystem sustainability and biodiversity. Governance challenges involve policy enforcement, planning, and institutional coordination. Health impacts highlight concerns regarding food and water safety. Infrastructural challenges relate to the development and maintenance of water systems. Management issues center on effective governance, strategic planning, and policy implementation. Social challenges emphasize community participation, equity, and awareness. Technological gaps point to the need for innovations in digital tools and monitoring systems. Urban water issues concern the management of water demand in growing cities. Lastly, water scarcity and quality issues address concerns regarding availability, pollution, and safety. Taken together, these challenges provide a comprehensive understanding of the complex issues affecting agricultural systems within the FWE nexus. Table 2 illustrates the categorization of the FWE nexus challenges based on the literature analysis.

Table 2. Classification of Key Agricultural Challenges in the FWE Nexus.

Challenges Category	Challenges
Agricultural challenges	Irrigation, farming, crop, agricultural, cultivation, food security, water use efficiency, agricultural productivity, sustainable agriculture, crop yield
Climate impacts	Climate change, weather, drought, flood, precipitation, extreme event, temperature, variability, adaptation, resilience, vulnerability, climate risk
Data limitations	Data, monitoring, measurement, assessment, evaluation, uncertainty, accuracy, reliability, gap, missing, quality control, validation, standardization
Economic constraints	Economic, financial, cost, investment, pricing, funding, budget, economic viability, affordability, market, commercialization, revenue
Energy nexus	Energy, power, electricity, hydropower, pumping, water–energy nexus, efficiency, renewable, consumption, carbon footprint, greenhouse gas
Environmental impacts	Environmental, ecosystem, biodiversity, conservation, sustainability, ecological, habitat, environmental flow, watershed, river basin, aquifer
Governance challenges	Governance, policy, regulation, compliance, enforcement, legal, institutional, transboundary, water rights, water law, corruption, transparency

Table 2. *Cont.*

Challenges Category	Challenges
Health impacts	Health, disease, sanitation, hygiene, waterborne, public health, risk, exposure, contamination, pathogen, water quality standard, safety
Infrastructure	Infrastructure, system, network, facility, maintenance, pipeline, distribution, storage, reservoir, dam, water supply, hydraulic, construction
Management issues	Management, governance, policy, regulation, planning, institutional framework, strategy, decision making, coordination, implementation, enforcement
Social challenges	Social, community, public, awareness, participation, stakeholder, behavior, perception, acceptance, cultural, equity, gender, education, communication
Technology gaps	Technology, innovation, digital, smart, monitoring, automation, sensor, modeling, simulation, prediction, forecasting, optimization, remote sensing, data analysis
Urban water issues	Urban, city, municipal, residential, industrial, commercial, urbanization, water demand, sewerage, stormwater, drainage, urban planning
Water quality	Quality, pollution, contamination, treatment, purification, water safety, drinking water, groundwater quality, surface water, wastewater, salinity, toxicity
Water scarcity	Scarcity, shortage, deficit, stress, demand, availability, water security, access to water, water crisis, limited resource

3.4.3. Regional Analysis of FWE Nexus Challenges

Figure 9 illustrates the regional distribution of FWE nexus challenges in agriculture, revealing that the energy nexus represents the most substantial challenge across all regions (approximately 10,000 total mentions), followed by agricultural challenges (7000 mentions) and management issues (6000 mentions). However, distinct regional variations emerge, influenced by geographical, socio-economic, and technological contexts.

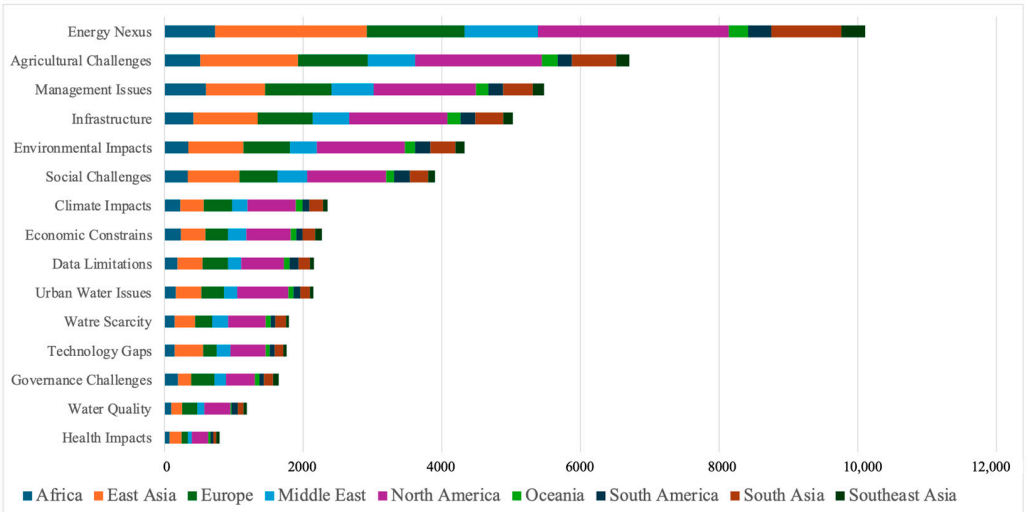


Figure 9. Regional distribution of FWE nexus challenges. The horizontal axis represents the cumulative frequency of mentions or occurrences of each challenge in the analyzed articles.

In North America, particularly the USA, challenges are predominantly centered on the energy dimension of the nexus, comprising a substantial share of the region's documented issues. This emphasis likely reflects the region's energy-intensive agricultural systems and the widespread adoption of industrialized farming practices [37]. While agricultural challenges are also visible in North America's profile, urban water issues appear as a

relatively higher segment in the visualization compared to other challenges, such as data limitation, economic constraints, and water scarcity.

East Asia presents a profile with substantial representation in both the energy nexus and agricultural systems challenges. Infrastructure and management issues are clearly visible in East Asia's distribution, forming a notable component of its overall challenge profile. This pattern aligns with China's rapid industrialization, intensive agriculture, and evolving resource governance systems, particularly in countries experiencing significant economic transitions [38].

Europe demonstrates a more balanced distribution of challenges, though energy nexus issues remain dominant. Environmental impacts are visible in Europe's challenge profile, reflecting the continent's stringent environmental regulations and climate policy frameworks [39]. Infrastructure challenges also feature prominently, likely related to aging agricultural and water management systems requiring modernization [40].

The Middle East places the strongest emphasis on energy nexus challenges, reflecting the region's reliance on energy-intensive processes such as desalination and groundwater extraction [41]. Water scarcity and economic constraints also emerge as significant concerns, underscoring persistent resource limitations and financial vulnerabilities. Furthermore, social challenges, particularly those related to inequalities in resource access and community resilience, add further complexity to sustainable agricultural management in the region.

South Asia and Africa face distinct but overlapping challenges related to agricultural sustainability. In South Asia, the primary concerns revolve around the region's agricultural economic base and dense rural populations, with a strong focus on agricultural challenges. Water quality issues and governance challenges are significant, with technological gaps also present, though not as pronounced as institutional barriers. Similarly, in Africa, while energy nexus challenges are notable, management issues such as governance, strategic planning, and policy implementation also feature strongly. The region is further burdened by agricultural challenges, infrastructural limitations, and social inequalities. Governance challenges are particularly pronounced in Africa, emphasizing the need for improved institutional capacity and coordinated policymaking to address the complex FWE nexus issues and enhance agricultural sustainability.

3.4.4. Categorization of Methodological Approaches

Table 3 provides an overview of the methodologies employed in FWE nexus research, highlighting the conceptual similarities and diverse tools used to address these regional challenges. Methodologies such as circular economy analysis, hydro-economic modeling, crop modeling, and life cycle assessments are employed to assess material flow, resource efficiency, and environmental impacts. These approaches allow for a deeper understanding of the interdependencies within the FWE nexus and provide insights into the sustainability of agricultural systems. In addition, methodologies such as system dynamics, multi-criteria decision analysis, and stakeholder analysis are commonly used to model complex systems and support decision-making processes, reflecting their application in governance and resource flow assessments.

Table 3. Categorization of Methodologies used in FWE Nexus Research in Agriculture.

Methodology Category	Methodology
Crop Modeling	crop model, yield prediction, crop simulation, agricultural model
Hydro Economic	hydro economic, water allocation, economic analysis, cost–benefit
Input–Output	input–output, material flow, resource efficiency, circular economy
Integrated Assessment	integrated assessment, nexus approach, holistic approach, systems approach
Life Cycle Assessment	life cycle assessment, environmental impact, footprint analysis

Table 3. *Cont.*

Methodology Category	Methodology
Multi-Criteria	multi-criteria, analytic hierarchy, decision analysis, trade-off analysis
Optimization	optimization, linear programming, genetic algorithm, multi-objective
Remote Sensing	remote sensing, satellite, GIS, spatial analysis, land use
Resource Modeling	water balance, energy balance, resource flow, mass balance, nutrient cycle
Scenario Analysis	scenario, forecast, projection, future pathway, alternative scenario
Stakeholder Analysis	stakeholder, participatory, focus group, interview, survey
System Dynamics	system dynamics, causal loop, stock flow, feedback loop

3.4.5. Regional Analysis of Research Methodologies

The regional distribution of these methodologies, as shown in Table 4, further elucidates the differences in approach across regions. For instance, North America leads with the highest methodological mentions, with a strong emphasis on scenario analysis (23.1%), reflecting a focus on long-term policy planning. In Europe, scenario analysis is also prevalent (24.5%), signifying a similar focus on policy evaluation. In East Asia, optimization methods dominate (28.6%), highlighting the region's drive for efficiency in resource management, particularly through technological innovation.

Table 4. Regional Distribution and Diversity of FWE Nexus Methodologies in Agriculture.

Region	Total Methods	Most Common Methods	Proportion of Most Common Method	Method Diversity
North America	953	scenario analysis	23.1%	12
East Asia	660	optimization	28.6%	12
Europe	601	scenario analysis	24.5%	12
Middle East	381	scenario analysis	23.9%	11
Africa	266	stakeholder analysis	24.1%	11
South Asia	213	remote sensing	25.8%	11
South America	212	stakeholder analysis	25.5%	10
Oceania	117	stakeholder analysis	18.8%	11
Southeast Asia	88	stakeholder analysis	20.5%	11

Values represent regional methodological frequencies in the FWE nexus articles, where Total Methods = total frequency of methodological mentions; Most Common Methods = leading methodology; Proportion of Most Common Method = percentage of most common method to Total Methods; Method Diversity = number of distinct methods used (max = 12).

Developing regions, such as Africa, South America, and Southeast Asia, show a higher reliance on stakeholder analysis and participatory approaches, reflecting a greater emphasis on governance challenges and the involvement of local communities in decision-making. In South Asia, remote sensing (25.8%) is the most frequently used method, underlining the importance of satellite-based monitoring for resource assessment in areas with limited infrastructure.

3.4.6. Interpreting Regional Variations Through a Comparative Framework

To gain a deeper understanding of regional variations in the FWE nexus challenges, it is important to examine these differences through the lens of three key factors: research capacity, governance and policy structure, and infrastructure and technological context.

- Research Capacity: It is reflected in the volume of publications, and the diversity of methodologies used varies significantly across regions. Developed regions such as North America, Europe, and East Asia benefit from robust research infrastructures and institutional support, which contribute to a higher volume of publications and

a broad array of methodological approaches. These regions focus on optimizing resource use, addressing sustainability, and integrating technological innovations. In contrast, regions such as Africa, South Asia, and Southeast Asia generally have lower research capacities. This is reflected in a more limited methodological diversity, with a stronger emphasis on addressing immediate, fundamental challenges such as resource management, climate impacts, and governance issues;

- Governance and Policy Structure: Governance and policy frameworks play a decisive role in shaping how regions address FWE nexus challenges. In developed regions such as North America, Europe, and East Asia, well-established institutional structures facilitate the integration of water, energy, and food security policies. This strong policy coordination enables the implementation of comprehensive management strategies, allowing these regions to prioritize challenges such as environmental sustainability, system optimization, and long-term resource planning. In contrast, developing regions, including Africa, South Asia, and Southeast Asia, often contend with fragmented governance systems and weak policy integration. These structural limitations exacerbate challenges related to resource allocation, equitable access to resources, and institutional capacity building. The prevalence of issues such as water scarcity, economic constraints, and social inequalities in these regions underscores the urgent need for strengthened governance mechanisms. Consequently, research and practice in developing regions tend to emphasize participatory governance approaches, stakeholder engagement, and strategies aimed at improving policy coherence. This comparison highlights a clear divergence: while strong governance systems in developed regions enable a shift toward proactive, integrative management, weaker governance structures in developing regions often necessitate a reactive focus on addressing immediate institutional and policy deficiencies to advance sustainable agricultural management;
- Infrastructure and Technological Context: Variations in infrastructure and technological development significantly influence how regions approach FWE nexus challenges. In regions such as East Asia, North America, and Europe, well-established technological systems enable the adoption of advanced methodologies focused on system optimization, integrated resource management, and sustainability innovation. Challenges in these areas tend to emphasize the modernization of aging infrastructure, the integration of emerging technologies, and the pursuit of high-efficiency, low-impact resource use. Conversely, regions with limited infrastructural development, including Africa, South Asia, and Southeast Asia, face challenges centered around basic resource provision, infrastructure reliability, and the management of vulnerability to environmental and socio-economic stresses. Methodological responses in these regions vary: in South Asia, remote sensing and geospatial technologies are widely applied to monitor and manage resources across dispersed and often underserved agricultural landscapes. In Africa and Southeast Asia, where access to advanced technologies may be even more constrained, strategies tend to focus on strengthening institutional frameworks, enhancing local monitoring systems, and promoting adaptive, community-based management practices.

By analyzing regional variations through the lens of research capacity, governance and policy frameworks, and infrastructure and technological contexts, a more nuanced understanding of the factors shaping FWE nexus challenges and the methodological approaches employed to address them is achieved. This comparative analysis underscores the influence of structural factors on the strategies adopted for sustainable agricultural management across diverse global contexts. It provides valuable insights into region-specific approaches for mitigating the complex challenges of the FWE nexus, offering a deeper understanding

of how these factors contribute to the effectiveness of resource management practices in different geographical settings.

4. Discussion

4.1. Global Research Trends in the FWE Nexus (2000–2024)

Our bibliometric analysis reveals a complex evolution of FWE nexus research in agricultural contexts, characterized by distinct phases of conceptual development and geographic participation patterns. Publications began emerging in 2008, followed by a rapid increase after 2014, driven largely by global policy frameworks such as the SDGs and the FAO's landmark report [27,28]. This growth pattern suggests that international policy instruments have played a crucial role in legitimizing and institutionalizing emerging research paradigms, transforming theoretical concepts into actionable research agendas. The dominance of interdisciplinary journals such as Science of the Total Environment, Sustainability, and the Journal of Cleaner Production over traditional agricultural outlets indicates that the nexus approach initially gained traction within environmental and systems science communities rather than conventional agricultural disciplines. This shift highlights both the opportunities and challenges of integrating knowledge across traditionally separate fields.

Geographically, there is a significant imbalance in research production, with the USA and China emerging as dominant contributors. The USA leads in overall scientific output, while China exhibits the highest rate of international collaboration, as measured by MCPs. Despite publishing fewer papers overall than the USA, Chinese researchers tend to engage more frequently with international co-authors, indicating a distinct pattern in collaboration. At the same time, European countries play a crucial role as bridges between different regional research clusters. This highlights the strength of established research powers but also the untapped potential for broader international cooperation. However, this dominance of high-output regions contrasts sharply with the limited research output from developing countries, which warrants further scrutiny. Several structural factors contribute to the research output gap between high-output and developing regions, including the following:

1. Limited research infrastructure: Developing regions often face inadequate access to well-equipped laboratories, reliable internet connectivity, and comprehensive scholarly resources [42,43];
2. Constrained funding: Limited funding, poor infrastructure, and unfavorable policies in low-income countries hinder research activities, often forcing researchers to self-fund and driving brain drain, which deepens underdevelopment [44];
3. Insufficient institutional support: Interdisciplinary research in Africa is limited by rigid academic structures, disciplinary silos, fragmented data-sharing mechanisms, and inadequate funding, which hinder researchers' ability to address complex challenges [45];
4. Restricted access to comprehensive datasets: Developing countries often have limited access to datasets covering all three nexus dimensions, making it difficult for researchers to engage in cross-disciplinary work [46].

These facts also reveal that international collaboration, particularly through MCP, is essential in FWE nexus research. It facilitates knowledge transfer, access to funding, and the sharing of resources and datasets across regions facing different challenges. Collaborative efforts enable the integration of diverse perspectives and expertise, fostering context-specific solutions for complex issues like climate change, water scarcity, and food security. This partnership not only promotes innovative methodologies but also helps address research gaps, improve policy-making, and overcome resource and infrastructure limitations, ensuring more effective and sustainable solutions.

Thematically, the evolution in the field reflects a shift from bilateral relationships, such as the water–energy nexus and bioenergy, to more integrated concepts like governance, resilience, and climate adaptation. Recent developments in technology-driven themes, such as agrivoltaics, machine learning, and the circular economy, alongside climate-responsive frameworks, highlight a growing emphasis on solution-oriented approaches. These trends align with major global policy milestones, including the IPCC Special Report on Climate Change and Land and the FAO's climate-smart agriculture framework, demonstrating the field's increasing responsiveness to urgent sustainability challenges [33–36]. The transition from focusing on narrow productivity studies to broader, multidimensional analyses reflects intellectual growth and practical adaptation to complex global issues. Furthermore, the FWE nexus framework contributes significantly to broader debates on resilience, climate adaptation, and resource equity by fostering interdisciplinary approaches that integrate environmental, social, and economic dimensions of sustainability. This shift underscores the framework's potential to inform sustainable policies and strategies that address interconnected global challenges.

4.2. Regional Challenges in Agricultural FWE Nexus

The energy nexus stands out as the most prominent challenge within the broader FWE nexus, with significant implications for agricultural sustainability across regions. Numerous FWE nexus studies have underscored the accelerating global demand for the three resources that are driven by factors such as population growth, urbanization, dietary shifts, and climate change [47–49]. As the demand for these resources intensifies, their interdependencies become increasingly intricate, particularly in agricultural systems that heavily rely on energy for essential processes like irrigation, machinery operation, and food processing [5,6]. The energy–water–food interdependencies vary across regions, influenced by distinct socio-economic, infrastructural, and policy contexts. These regional disparities are critical to understanding how nexus challenges are addressed in the context of broader sustainability goals, such as those outlined in the United Nations's SDGs, and how national agricultural policies are shaping responses to these challenges.

In North America, energy nexus challenges are particularly prominent in industrial agriculture, where the region's heavy reliance on energy for irrigation, fertilizer production, and machinery has increased competition for vital resources like land and water. According to the U.S. Department of Agriculture Economic Research Service (2023), U.S. farms have significantly increased their adoption of precision agriculture technologies over the past two decades. In 2023, 52% of midsize farms and 70% of large-scale crop-producing farms used guidance auto-steering systems, while 68% of large-scale farms utilized yield monitors, yield maps, and soil maps [50]. These advancements in precision agriculture aim to enhance resource efficiency, directly supporting SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) by reducing energy consumption and minimizing agricultural waste. National policies, such as those outlined in the U.S. Department of Agriculture Economic Research Service (2023) report, focus on precision agriculture as a means of optimizing energy use in farming and reducing the environmental footprint, aligning with the broader goal of transitioning to more sustainable and energy-efficient agricultural practices [50].

In East Asia, energy-related challenges are particularly evident, especially in China, where agricultural modernization has significantly increased energy use, especially through the extensive deployment of irrigation systems and greenhouses. Despite having only 9% of the world's arable land, China leads globally in greenhouse area [51,52]. In 2023, the country added a total of 1835.87 hectares of new greenhouses, with 1094.1 hectares (approximately 60% of the total) dedicated to plastic film greenhouses. Additionally, 234.32 hectares were

used for glass greenhouses, 12.48 hectares for polycarbonate greenhouses, 144.17 hectares for solar greenhouses, and the remaining area for other types of greenhouses [51]. According to the FAO (2023), China represents a leading example of integrating technology into agriculture to optimize resource efficiency in large-scale farming operations [53–56]. These advancements address critical challenges related to water and energy management, aligning with SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). In response, the Chinese government has prioritized policies aimed at improving agricultural efficiency, including the adoption of renewable energy-powered irrigation systems and innovative water-saving technologies. These efforts are particularly significant in arid regions, where they help balance food security, resource management, and climate change adaptation.

In Southeast Asia, water scarcity and energy inefficiencies in agriculture are critical challenges, particularly with the increasing impacts of climate change. These issues are closely aligned with SDG 2 (Zero Hunger) and SDG 13 (Climate Action), as the region works toward sustainable agricultural practices under increasingly erratic climatic conditions. National policies across the region focus on enhancing irrigation systems, improving water use efficiency, and integrating renewable energy solutions, such as sustainable biomass energy, to improve resilience against climate impacts. For example, the International Renewable Energy Agency (IRENA) (2022) highlights the role of renewable energy in enhancing agricultural productivity, while the ASEAN (2020) strategy emphasizes sustainable biomass energy for rural development [57–59].

South Asia faces significant challenges related to the energy nexus and agricultural resource constraints. The region's ongoing need for sustainable water management, coupled with the growing demand for energy to support agricultural mechanization, places considerable pressure on resources. These issues are central to achieving SDG 7 (Affordable and Clean Energy) and SDG 6 (Clean Water and Sanitation). National agricultural policies in South Asian countries focus on improving irrigation infrastructure, increasing access to renewable energy in rural areas, and supporting energy-efficient agricultural practices. For instance, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) scheme in India aims to enhance irrigation coverage and promote water-efficient practices, including pressurized irrigation systems such as drips and sprinklers. Additionally, the PM Kisan Urja Suraksha evam Utthaan Mahabhiyan (KUSUM) scheme, launched in 2019, seeks to provide solar-powered irrigation pumps to farmers, reducing dependence on diesel and promoting renewable energy use in agriculture [60].

In Africa, challenges related to energy nexus, water scarcity, and agricultural resource constraints are pervasive, affecting countries such as Kenya, Nigeria, and South Africa. These challenges are directly linked to SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). National policies, such as Kenya's Vision 2030, emphasize the need for sustainable agriculture by incorporating climate-smart agricultural practices, improving energy access, and enhancing water management systems in rural areas [61–64].

Oceania faces significant challenges related to water scarcity and energy efficiency in agriculture. Despite the low frequency of energy-related research in the region, these issues are crucial for addressing SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). Policies like Australia's National Water Initiative aim to enhance agricultural water management and increase resilience to climate change [65].

4.3. Methodological Approaches and Their Effectiveness in FWE Nexus Research

The effectiveness of methodological approaches in addressing FWE nexus challenges varies significantly across regions, influenced by research capacity, governance and policy structure, and technological context. These disparities reflect how local contexts shape

the choice and outcomes of methodologies. For instance, regions typically classified as developed, such as North America, Europe, and East Asia, tend to use more sophisticated approaches such as optimization and scenario analysis, which are particularly suited for predictive modeling and decision-support systems. These methods facilitate long-term strategic planning, resource allocation, and policy-driven decision-making, making them highly effective in settings where research capacity, data availability, and computational infrastructure are robust [66–68]. Scenario analysis, frequently employed in these regions, underscores a focus on evaluating future resource trade-offs under varying environmental and economic conditions, highlighting the region's emphasis on adaptive policies for sustainable resource management [69]. Similarly, optimization techniques in East Asia are aligned with the region's industrialized agricultural and water management systems, striving to maximize resource efficiency in the context of intensive resource use [70].

In contrast, developing regions such as Southeast Asia, South Asia, Africa, and South America face methodological constraints shaped by research capacity, governance and policy structure, and infrastructure and technological context, which often limit the effectiveness of certain approaches. The dominance of stakeholder analysis in these regions suggests a heavy reliance on engagement and governance mechanisms to address institutional fragmentation and resolve conflicting resource claims [71]. While stakeholder analysis can foster participatory decision-making, its success is contingent on the presence of inclusive governance structures, transparent institutional frameworks, and political stability. In regions affected by political or economic instability, the impact of such methods may be diminished [72,73]. The challenge in these regions is that methodological choices are often adapted to resource constraints and local contexts rather than being optimized for long-term sustainability. For example, remote sensing technologies play a vital role in addressing data scarcity, particularly in South Asia, where their usage is common. However, their effectiveness is often constrained by limitations in technical expertise, funding, and integration with policy mechanisms. While these methods provide valuable insights, they also underscore the limited methodological diversity in these regions and the challenges in applying more complex, interdisciplinary approaches necessary to address the interconnectedness within the FWE nexus [74,75].

Moreover, the effectiveness of these methodologies has evolved over time, with a clear trend toward more technology-driven approaches in response to the growing complexity of FWE challenges. The interconnectedness of food, water, and energy systems requires interdisciplinary research that integrates both technical solutions and governance-based strategies. This approach is vital for enhancing resilience, climate adaptation, and resource equity. Moreover, the uneven distribution of research, both in terms of volume and regional focus, limits the generalizability of some findings. Developed regions remain overrepresented in the literature, while studies from certain developing areas are scarce, potentially skewing broader conclusions. These limitations underscore the importance of contextualizing methodological effectiveness within institutional and policy environments and recognizing how regional priorities shape both research agendas and analytical approaches.

5. Conclusions

This study examines global research patterns, evolving methodological trends, and regional disparities in the challenges and solutions associated with the FWE nexus in agricultural systems. It emphasizes the complexity of addressing interconnected sustainability challenges. Research hubs in the USA and China are supported by robust international collaboration networks, yet significant gaps persist in developing regions. These disparities underscore the critical need for more equitable and inclusive global research efforts. These imbalances hinder the development of context-specific solutions and limit the global appli-

cability of findings. Notably, the study identifies a shift in FWE nexus research from isolated or bilateral collaborations to more integrated, interdisciplinary frameworks that incorporate governance, resilience, and climate adaptation and often in combination with advanced technical methodologies such as machine learning. This progression reflects increasing sophistication in addressing complex sustainability challenges and has been enabled by cross-border knowledge exchange and collaborative networks. These evolving trends and collaboration patterns emphasize the need for more inclusive, globally coordinated research efforts to support sustainable agriculture across diverse regional contexts.

Regional assessments reveal that energy, water, and food resources manifest differently across geographies, and that methodological approaches vary according to research capacity. Developed regions tend to focus on energy concerns within industrial agricultural systems and apply advanced methodologies such as optimization modeling and scenario analysis supported by robust data, integrated frameworks, and long-term planning capacities. In contrast, developing regions often prioritize issues related to governance, institutional capacity, and limited resources, and rely on methods such as stakeholder analysis and remote sensing to navigate fragmented governance and data scarcity. The effectiveness of these approaches is highly dependent on institutional stability and the availability of technical expertise. These variations highlight that each region faces unique challenges and has distinct strengths, making it crucial to develop effective, context-specific solutions. Collectively, these findings demonstrate that the complexity and interconnectedness of FWE challenges across regions cannot be effectively addressed through isolated efforts; rather, a strong international research nexus is essential for integrating diverse knowledge systems, bridging methodological gaps, and co-developing adaptable, context-specific solutions that enhance global sustainability outcomes. While formal multi-country partnerships may not always be feasible for localized or small-scale research, fostering collaboration through data sharing, joint training, and comparative studies remains essential for adapting innovations to diverse contexts and promoting equitable, sustainable resource management.

From a policy perspective, the findings underscore the imperative to invest in capacity-building efforts within developing regions. Key priorities include enhancing data accessibility, reinforcing research infrastructure, and expanding training opportunities in advanced analytical methodologies. Global research platforms play a pivotal role by equipping researchers in resource-constrained settings with the necessary tools, knowledge, and institutional support to engage meaningfully in sustainability research and contribute to globally relevant solutions. The FWE nexus presents both profound challenges and substantial opportunities for advancing sustainable agricultural management practices. The findings of this study provide a foundational framework for future research, emphasizing the need for context-specific solutions, increased interdisciplinary collaboration, and the strengthening of global partnerships. Addressing existing regional disparities and fostering a more inclusive and collaborative research environment are essential for advancing sustainable agricultural practices that are both locally grounded and globally impactful. It is crucial for policymakers and practitioners, particularly those in developing regions, to be actively engaged in international research networks, enabling them to leverage cutting-edge innovations and co-develop solutions that are sustainable, contextually adaptable, and culturally appropriate.

Author Contributions: Conceptualization, E.N.Z.M., N.I. and Y.U.; methodology, E.N.Z.M. and Y.U.; formal analysis, E.N.Z.M.; investigation, E.N.Z.M.; resources, Y.U. and N.I.; data curation, E.N.Z.M.; writing—original draft preparation, E.N.Z.M.; writing—review and editing, N.I. and Y.U.; visualization, E.N.Z.M.; supervision, N.I. and Y.U.; project administration, N.I. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially supported by JSPS KAKENHI, grant number JP22K05865, JP25K09314.

Institutional Review Board Statement: Not applicable. This study did not involve any humans or animals.

Informed Consent Statement: Not applicable. This study did not involve humans.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this study.

Acknowledgments: The authors gratefully acknowledge the support of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) scholarship for their Ph.D. program. This study was also partially supported by JSPS KAKENHI, Grant Numbers JP22K05865 and JP25K09314. The authors extend their gratitude to the Laboratory of Farm Management at the Department of Agricultural and Resource Economics, Kyushu University, for providing funding to cover the publication fees. All individuals and organizations acknowledged have given their consent to be included.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FWE	Food–Water–Energy
FAO	Food and Agriculture Organization
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SCP	Single-Country Publications
MCP	Multiple-Country Publications
UK	United Kingdom
UN	United Nations
USA	United States of America

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