Agricultural Water Management 333 (2026) 110650

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Mapping the Water-Energy-Food-Ecosystem (WEFE) nexus: Insights and limitations from a systematic literature review on interconnected resource management

Dimitra Despoina Tosiliani [a,*], Marios Vasileiou [a], Leonidas Sotirios Kyrgiakos [a,e], Fadi Abdelradi [b], Christina Kleisiari [a], Kyriaki Kechri [a], Georgios Kleftodimos [c,d], George Vlontzos [a]

[a] Department of Agriculture, Crop Production and Rural Environment, University of Thessaly, Fytoko, Volos 38446, Greece
[b] Department of Agricultural Economics, Faculty of Agriculture, Cairo University, Giza 12613, Egypt
[c] CIHEAM-IAMM (Institut Agronomique Méditerranéen de Montpellier), Montpellier 34090, France
[d] MoISA, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France
[e] Department of Agriculture, University of Western Macedonia, Florina, 53100, Greece

ARTICLE INFO

Handling Editor: Dr. Brent Clothier

Keywords:
Core-periphery Nexus
Ecosystem integrity
Cross-sectoral governance
Socio-economic indicators
Water-use efficiency
Bibliometric co-occurrence analysis

ABSTRACT

The importance of Water-Energy-Food-Ecosystem (WEFE) resources is strongly based on their interdependence, since the efficient management of each pillar contributes to ecological integrity, economic viability, and social stability. In the face of exacerbating resource challenges, including water scarcity, food insecurity, energy source exploitation, and ecosystem deterioration, the WEFE Nexus framework has emerged as a response to these threats. Understanding the intricate interconnection among WEFE pillars can contribute to sustainability enhancement and resource conservation, to a degree that depends on how far the management objectives of the individual pillars are jointly optimized rather than pursued in isolation. Despite the holistic WEFE Nexus performance, several studies fail to incorporate the ecosystem pillar, understood here as ecosystem services and ecological integrity rather than a spatial scale, adequately, thereby overlooking the central role of ecosystem preservation in resource management. In the same line, the concurrent assessment of societal, economic, and governance dimensions is frequently neglected in Nexus assessments, leading to an inadequate analysis that overlooks key drivers of sustainability and resilience. In light of this, the present study aims to address these gaps by incorporating the governmental, economic, and societal dimensions into the WEFE Nexus context and comprehensively assessing the interdependencies of the WEFE pillars. The methodology follows the Systematic Literature Review (SLR) incorporated in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. From 406 articles identified, 120 were selected and reviewed, following the sequential removal of ineligible document types, inaccessible and non-English records, duplicates, and full texts that were not relevant to the study scope. Subsequently, the assessment of the selected articles led to 7 thematic categories and 26 criteria, which were derived from established WEFE Nexus indicator frameworks and refined through full-text coding of the study. The findings of this study highlight the growing recognition of the WEFE Nexus framework as a theoretical and empirical approach for managing sustainability issues and advancing efficacy resource strategies. Publication activity peaks in 2024–2025, and the study concentrates on a few near-universal indicators (energy production 92%, food availability 89%, agricultural water withdrawal 88%, and ecosystem services 88%), whereas ecosystem-integrity and equity indicators such as clean air (15%), the prevalence of undernourishment (16%), and employment (18%) remain markedly under-represented. A phi-coefficient co-occurrence analysis further shows that indicator associations cluster within pillars while cross-pillar links, including the frequently invoked water-energy interface, remain weak or statistically absent. Ultimately, this review implements the concurrent incorporation of societal, economic, and governmental dimensions alongside the four main WEFE pillars for the integrated evaluation of the Nexus approach, extending it

* Corresponding author.
E-mail addresses: ditosiliani@uth.gr (D.D. Tosiliani), mariosvasileiou@uth.gr (M. Vasileiou), lkyrgiakos@uth.gr (L.S. Kyrgiakos), fadi.abdelradi@agr.cu.edu.eg (F. Abdelradi), chkleisiari@uth.gr (C. Kleisiari), kkechri@uth.gr (K. Kechri), kleftodimos@iamm.fr (G. Kleftodimos), gvlontzos@uth.gr (G. Vlontzos).

https://doi.org/10.1016/j.agwat.2026.110650
Received 28 April 2026; Received in revised form 16 July 2026; Accepted 16 July 2026
Available online 20 July 2026

beyond its biophysical perspectives and integrating socio-economic and governance-related aspects for an efficient Nexus performance.

1. Introduction

The Water-Energy-Food-Ecosystem (WEFE) Nexus framework is significantly gaining worldwide attention as it is closely connected to sustainability consciousness in resource management (Terrapon-Pfaff et al., 2018). According to the review of Wang et al. (2026), there is a steady rise in WEFE-related literature, highlighting a clear shift from the traditional three-pillar Water-Energy-Food (WEF) model to a broader, four-part framework that explicitly includes ecosystems. Delving into the importance of resource management, the literature emphasizes that water use efficiency, renewable energy production, food security, and ecosystem integrity are prerequisites for human existence, and their interdependence indicates the synergies and trade-offs that are hidden behind this dynamic system (Abera et al., 2024).

To begin with, water demand exceeds water availability, resulting in severe water shortage and unequal water allocation (Sievers et al., 2025). For this reason, water security has emerged as a crucial issue recently, prompting efforts to optimize water usage. Furthermore, initiatives have been implemented to promote integrated water management through multi-sector cooperation, emphasizing the need for stakeholders' engagement on water availability issues (Correa-Cano et al., 2022). The aforementioned points indicate that water plays a central role in agriculture, household consumption, industrial activities, and ecological maintenance; therefore, its absence negatively impacts various sectors (Halytsia et al., 2024). In addition, the energy pillar and, more specifically, the orientation to renewable energy production have been excessively rising lately, as clean energy sources mitigate ecosystem deterioration (Raihan et al., 2024). An important finding of Sethi et al. (2024) underscores the necessity of incorporating renewable energy sources in the agricultural sector as a result of increased crop productivity and sustainability across agricultural activities. Moreover, renewable energy sources lead to diminished energy overexploitation and a reduction in conventional energy consumption, which frequently harms the environmental resources. However, limitations regarding the adoption of clean energy sources exist due to various reasons, including financial obstacles for farmers in developing countries and an absence of environmental consciousness (Lin and He, 2020; Onah et al., 2024). The replacement of conventional energy should be prioritized to address these challenges (Schwanitz et al., 2017). Moving to the food pillar, it is essential to underline its strong dependence on crop yields, as food security is ensured if agricultural productivity is thriving (Ioannidou et al., 2022). Considering the continuous global population growth as well as the urbanization trends, food security is an issue of major importance for sustaining life on earth (Taghdisian et al., 2022). Addressing food insecurity and managing excessive food demand lead to long-term food security and equivalent food alleviation (Araujo et al., 2021). Last but not least, the ecosystem services play a significant role in sustainable development and long-term viability. As Hong et al. (2022) mention, ecosystems are recently experiencing severe impacts from climate change, agricultural practices, and human activities, leading to resource degradation and a decline in environmental quality, which necessitates ecosystem protection. Natural ecosystem preservation contributes to the mitigation of the detrimental effects of human activities and the maintenance of natural resources (Hurtado et al., 2024). Furthermore, ecosystem maintenance contributes to long-term food security, water availability and energy generation, indicating its prominent position among the Nexus dimensions and its role as a keystone for efficient resource management (Recanati et al., 2017).

Regardless of the prominence of the aforementioned WEFE pillars, various obstacles have emerged that decrease their efficient management and harm each of them. Considering the intensified resource crisis the planet is facing, including water scarcity, energy overexploitation, food insecurity, and ecosystem degradation, the need to address these challenges has become an urgency (Cui et al., 2024; Demir and Alp, 2025). The escalating demand and relative scarcity are hindering economic development, access to basic resources, resilience against societal and environmental shocks, and human well-being. A more efficient use of resources is necessary for sustainable development and global resource security (Correa-Cano et al., 2022). For this purpose, the WEFE Nexus initiative has emerged as a response to these threats by enhancing sustainability, improving future resilience, and decreasing systemic vulnerability (Cui et al., 2024). Many scientific fields have shown interest in adopting this concept as a solution to these detrimental impacts, and multidisciplinary coordination is demanded (Liu et al., 2021). At the watershed scale in particular, the Nexus has been operationalized to design optimal agricultural management patterns that jointly account for soil, water, energy, and food, underlining the value of integrated watershed management for balancing resource trade-offs (Sharifi Moghadam et al., 2019, 2023; Sadeghi et al., 2020; Sadeghi and Sharifi Moghadam, 2021). Understanding and operationalizing the interdependencies among resource systems, previously managed individually, forms its foundation. The relationships among WEFE resource systems are not only biophysical but also determined by socio-economic context and governance structures (Correa-Cano et al., 2022). The Nexus context depicts the relationship between water, energy, food, and ecosystem pillars as a whole, rather than assessing them individually. This ensures the comprehensiveness of the framework and promotes long-term management of the four elements while maintaining economic and social stability (Malagó et al., 2021). In addition, the term "Nexus" describes the connections among the water, ecosystems, food, and energy pillars, highlighting *(i)* how these resource systems are related to each other, *(ii)* how to make better use of these resources, and *(iii)* how to create policies that work across sectors (Abera et al., 2024; Malagó et al., 2021). Furthermore, solutions for increased efficiency and policy coherence can be achieved through well-structured collaborations across governance sectors. The implementation of the Nexus approach should go beyond quantifying resource flow among nodes and consider management and governance structures determining resource allocation and use among multiple sectors (Hurtado et al., 2024).

The growth of research on the WEFE nexus is shaping how the approach is understood. The Nexus approach is based on the traditional definition of security (Bidoglio and Brander, 2016; Hoff, 2011) and focuses on the availability, access, affordability, and sustainability of resources, including the stability of the supply (Kumar, 2018). It is an essential part of human health and a requirement for peace, strength, and environmental sustainability, as these can affect the availability of food and other goods, which could lead to conflict over resources that are getting scarcer. Regulatory services can also change how often and how severe disasters are. A lot of Nexus literature does not consider sectoral security problems or how securities are linked to each other. The Nexus approach stresses the need to look at both sectoral and global security issues in resource systems (Staupe-Delgado and Coombes, 2020; Zhang et al., 2018).

Lucca et al. (2023) point out that the WEFE nexus approach is primarily focused on the interdependence between water and energy resources, driven by the energy-intensive nature of water distribution systems necessary for meeting drinking and irrigation demands. Climate change and water scarcity make the need for integrated approaches even more crucial. However, the WEFE nexus approach is still limited in how it can be expanded to include more parts, like ecosystems. Most studies exclusively examine the impact on the physical environment and climate, neglecting feedback dynamics (Meng et al., 2023;

Solano-Pereira et al., 2025). Nexus parts need to be more fully integrated. There aren't many large-scale assessments of Nexus research in the Mediterranean; most of it is based on small case studies. Some countries, particularly those in the Western Balkans, are not conducting adequate research regarding the WEFE Nexus framework. Transdisciplinarity and its effects on the economy are becoming more important. They extend beyond biophysical assessments to include also societal and governmental functions. In this context, the WEFE Nexus serves as an integrated, cross-sectoral management and governance framework aimed at assessing the complex biophysical interdependencies and trade-offs among natural resources, while also considering the economic and societal pillars necessary for sustainability compliance (Correa-Cano et al., 2022; Vrachioli et al., 2025). From a governmental viewpoint, the Nexus confronts heterogeneous institutional structures, necessitating strict policy coherence and multidimensional governance systems that promote cross-border collaboration and align regulatory procedures across several governmental agencies (Al-Saidi and Elagib, 2017; Weitz et al., 2017). In particular, Mooren et al. (2025) introduce the WEFE Nexus Governance Approach, setting the ecosystem element in the center of the WEFE Nexus governance conceptualization. This framework emphasizes the necessity of incorporating policy consistency and stakeholder engagement as core components of the Nexus approach, facilitating its implementation across various scales and Nexus fields, and fostering the transition to robust governance-oriented Nexus mechanisms concerning ecosystem services. Viewing the WEFE Nexus framework from an economic perspective, the assessment of economic viability and market efficacy, as well as their connection to long-term sustainability and resource resilience, promotes circular economic strategies and enhances decision-making processes with high participatory aspects (Vrachioli et al., 2025; Shehadeh et al., 2024). In addition, the inclusion of the societal dimension of the WEFE Nexus framework, combined with economic prosperity and governance quality schemes, leads to the comprehensive resource management, centering sustainability and prioritizing human welfare (Malagó et al., 2021; Shehadeh et al., 2024).

The holistic assessment of the WEFE Nexus in agriculture is still in its initial stages, posing intricate challenges for which the existing literature review has not yet provided an integrated response. Hence, it is essential to define the Nexus relationships based on existing knowledge and contribute to a more comprehensive understanding of this topic. This study implements a SLR as a methodological framework to assess and combine previous studies regarding the WEFE Nexus. Table 1 depicts a brief description of the trends in the WEFE nexus framework by examining the published literature review papers.

The assessment of the most recent literature reviews reveals that there are a few SLRs elaborating on the WEFE Nexus approach, along with numerous research gaps regarding the definition of the WEFE Nexus from a sustainability perspective. As illustrated in Table 1, the most recent literature reviews neglect the ecosystem pillar of their assessments, instead focusing solely on water, energy, and food dimensions. This indicates insufficiency and inaccuracy in their study findings. This study aims to advance the WEFE Nexus framework by incorporating the concurrent assessment of its core pillars (water, energy, food, and ecosystem) alongside critical economic, societal, and governmental dimensions. This expanded, multidimensional approach establishes a more robust and comprehensive methodology for evaluating and fostering long-term sustainability and enhancing future resilience. The integration of the three additional pillars is fundamental for a holistic analysis. This aligns with previous research conducted by Sun et al. (2025), who highlight the vital roles of both the economy and policy in managing each element of the WEFE Nexus, as well as in promoting sustainable development. Additionally, the Zhang et al. (2025) study expands the WEFE Nexus framework into the WEFEE (Water-Energy-Food-Ecosystem-Economy) Nexus approach by incorporating the economy into the water, energy, food, and ecosystem nexus. This addition leads to a more integrated assessment of sustainable

Table 1
List of recent systematic literature reviews regarding WEFE Nexus.

Source	Contributions	Shortcomings	No. of Articles examined
Meng et al. (2023)	• Present the interlinkages between Green and blue infrastructure (GBI) and (Food-Water-Energy) FWE Nexus in urban areas. • Most research predominantly examine the FWE advantages or life cycle environmental effects of GBI from a fragmentation approach. • Discuss the adoption of a comprehensive, dynamic framework for the more efficient comprehension of the urban FEW nexus and GBI in urban regions.	• This study does not encompass the ecosystem pillar into the Nexus framework.	456
Shrimpton and Balta-Ozkan (2024)	• Investigate the adoption of socio-technical systems in the Water-Energy-Food (WEF) Nexus framework. • Suggest the enhancement of social and environmentally just and sustainable infrastructure interventions to face the climate change induced impacts and ensure sustainable livelihoods.	• PRISMA guidelines were not implemented through the SLR process. • This study does not encompass the ecosystem pillar into the Nexus framework.	29
Chapagain et al. (2024)	• Present the recent Nexus progression, practices, opportunities, and future pathways for utilizing these opportunities. • Identify the development of new methods and tools for assessing Resource Nexus. • Introduce a conceptual framework for the optimizing Resource Nexus management.	• Only Scopus database was included, excluding the WoS database on the identification process. • The study was conducted from a water perspective, not ensuring the comprehensive assessment of the Nexus context.	203
Morales-García and Rubio (2023)	• Present the contributory role of Water-Energy-Food Nexus considering the sustainability of an economy and their interdependence. • Identify various methods, scales, and variables to homogenize the reviewed studies.	• This study does not encompass the ecosystem pillar into the Nexus framework. • Only the 106 articles (case studies) were examined to classify specified criteria.	141

(*continued on next page*)

Table 1 (*continued*)

Source	Contributions	Shortcomings	No. of Articles examined
Solano-Pereira et al. (2025)	• Present a thorough study of system dynamics in Water-Energy-Food (WEF) modelling and how the economy is part of this system. • Indicate the robust role of water element among the other two pillars and the limited contribution of the economic factor into the WEF system. • Identify limitations in the existing literature considering the interlinkage between the economy and the WEF Nexus.	• This study does not encompass the ecosystem pillar into the Nexus framework. • Theoretical studies were not included in the review process, so conceptual modelling was not considered	36

development both at a national and worldwide level, pointing out the need to integrate the economy element into the WEFE Nexus framework. Both studies elaborate on the importance of including the economy in the WEFE Nexus approach, indicating that the current form of the framework lacks integrity and comprehensiveness; thus, it is insufficient to properly represent sustainable development without considering the economic factor. Furthermore, Jain et al. (2023) suggest future research directions to look into governance problems, make data more accessible, and get stakeholders involved in a meaningful way to accomplish long-term WEFE management. They also underscored that combining research efforts can make nexus strategies more effective and help with long-term resource management. Amorim-Maia and Olazabal (2025) in the same line, advocate for cross-sectoral collaboration, inter-institutional research, and updated policies to promote knowledge transfer and community preparedness for climate adaptation. Their work calls for moving beyond traditional siloed management of natural resources to achieve global and local sustainability goals. While the aforementioned studies have recognized the limitations and deficiencies of the WEFE Nexus framework, attempts to enhance it have remained incomplete. Specifically, in addition to the main four pillars (water, energy, food, and ecosystem), they have included only the economic pillar and, in some instances, the governmental dimension alongside it, while failing to incorporate the societal pillar. For instance, although Lucca et al. (2023) and Jain et al. (2023) explicitly discuss socio-economic and policy dimensions, they treat them as qualitative background rather than coding them as measurable indicators, and neither integrates the economic, societal, and governance dimensions concurrently with the full set of four WEFE pillars across a common corpus. The distinguishing contribution of the present study is therefore not the mere acknowledgement of these dimensions but their simultaneous, indicator-level operationalization alongside water, energy, food, and ecosystem. Despite advancements in the field, the concurrent evaluation and integration of all core WEFE pillars remains to a significant extent underexplored; therefore, this study provides a comprehensive solution to bridge this critical limitation.

Water, energy, food, and ecosystem pillars, combined with economic, social, and policy-related elements, are pivotal for ensuring sustainable development not only across the Mediterranean region but beyond it. When studying the aforementioned terms, it appears that each of them is strongly interlinked with the others, leading to their high interdependence (Nikolaidis et al., 2025). The insights derived from the study of Mellios et al. (2026), highlight the imperative for robust governance structures, transparent communication pathways, and strategic stakeholder alignment to fully leverage the synergies of the WEFE nexus. Moreover, this paper advances the discourse on integrated resource management by offering an empirical perspective on the implementation, efficacy, and broader impacts of the WEFE framework, thereby enriching the extant literature on sustainable resource utilization. The addition of the economy, society, and governance elements in the precedent WEFE approach unlocks innovative pathways towards sustainability and integrates mitigation measures against various threats. Facilitating the integrated and concurrent stewardship of these pillars is of paramount importance in order to strengthen sustainability consciousness while increasing agricultural outputs. This is due to the fact that agricultural outputs totally depend on both the WEFE Nexus and economy, society, and governance, and this robust dependence will be subsequently analyzed. The employment of the WEFE indicators, in the section below, contributes to the more efficient description and determination of the WEFE framework. This paper is organized as follows: 2 presents the methodology implemented for this paper. 3 analyzes the results along with the criteria examined through the SLR process. 4 discusses the limitations and gaps of WEFE Nexus, while 5 concludes the article.

2. Methodology

2.1. Preliminary

The main methodological framework for conducting scientific research and ensuring the accuracy and validity of the results is the "Literature Review" process (Varsha P S et al., 2024). Regardless of scientific field and research topic, the identification and assessment of prior, relevant studies is essential for the determination of scientific questions (Snyder, 2019). Through the implementation of the literature review method, basic scientific gaps are identified, and new theories and frameworks are expressed (Xiao and Watson, 2019). Knowledge exchange has to be based on the outcomes of previous studies, which stem from the comprehensive analysis of the literature review and subsequently facilitate the development of new subject areas (Paul and Barari, 2022). There are different types of literature reviews, such as systematic, semi-systematic, narrative, scoping, integrative, and meta-analyses. In this article, the SLR approach is chosen as the most suitable method for evaluating and analyzing the existing studies in a structured and strict context. More specifically, unlike other literature reviews, which encompass authors' points of view, a SLR entails a more scientific aspect, and its key features are transparency, consistency, and reproducibility at each stage to mitigate the risk of discrimination (Lame, 2019). Moreover, the major purpose of a SLR is the conduction of comprehensive scientific studies while maintaining the quality and reliability of the scientific outcomes and reducing any possible subjectiveness and prejudice (Liberati et al., 2009; Petticrew, 2001).

This section elaborates on the methodological approach that has been followed to assess and integrate existing research regarding the WEFE Nexus context in agriculture. The SLR has been executed in the lens of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page, Moher, et al., 2021), applying the three main stages that are necessitated for the final selection of the research studies: (*i*) identification, (*ii*) screening, and (*iii*) disclosure of the review sample (Hiebl, 2023). The two main goals of implementing the PRISMA guidelines are: (1) to facilitate the conduction of a structured systematic review, ensuring transparency, genuineness and consistency of the research and (2) to enable authors to display their methodologies, outcomes, and frameworks in a comprehensive and scientific approach (Page et al., 2021). In light of this, the purpose of this study aligns with PRISMA guidelines' objectives.

2.2. Methodology applied

An initial search was conducted, employing the Scopus and Web of Science (WoS) databases. Both databases are internationally recognized and prominent citation databases, entailing scientific journals, books, and conference proceedings (Basumatary et al., 2025; Zhu and Liu, 2020). These databases are mainly used for academic research, guaranteeing clarity, disciplinary subjects, and high-quality content (Chadegani et al., 2013). After using the terms "WEFE Nexus", "Water Energy Food Ecosystem Nexus", and "Agriculture" in the full search of articles, a total of 16,497 documents have emerged (16,240 from Scopus and 257 from WoS). These results were exported and subsequently entered into the VOS Viewer software (van Eck and Waltman, 2010). The VOS Viewer outcomes are illustrated in Fig. 1 and three clusters emerge: (*i*) agriculture-climate change, (*ii*) sustainable development-sustainability-ecosystems, and (*iii*) water energy-water management-economic and social effects. These terms are highly connected and dependent on the WEFE Nexus context, including all four pillars, as determined by their interlinkages in the clustering process.

Due to the wide scope of the initial search, several documents were considered irrelevant to the study's objectives, as the keywords were mentioned anywhere in the text, from title to reference. Hence, the research was limited to the documents' title, abstract, and keyword, returning 406 documents for screening (Scopus=186 + WoS=220). This pronounced reduction, from 16,497 records to 406 (approximately 97.5%), is both expected and methodologically desirable; the unrestricted search retrieved every document in which the query terms appeared anywhere in the record, including reference lists and incidental mentions, so the overwhelming majority were only tangentially related to the WEFE Nexus. Restricting the query to the title, abstract, and keyword fields retains only those studies in which the Nexus is a central subject rather than an incidental citation, thereby raising the topical relevance of the screened set. To further narrow down the results, book chapters, books, conference papers, notes, errata, meetings, editorial material, dissertation theses, early access, and review articles (129 in total) were excluded from this research to ensure methodological rigor, completeness, consistency, a finalized dataset, and primacy of original peer-reviewed research. More precisely, conference papers ("grey literature") frequently contain preliminary findings and may not have been subjected to the same level of strict peer review as journal articles (Paez, 2017). Dissertations and theses may not have undergone independent exterior peer review, and their extensive length can make them unsuitable for data extraction and quality assessment within the defined structure of a SLR (Yudha et al., n.d.). To confirm that this study is based on the final, citable version of each document, early access articles were generally omitted in favor of their final published counterparts (Zhu, 2025). Furthermore, excluding review articles of this study mitigates the risk of perpetuating biases, since including them would lead to a review of reviews (Palmatier et al., 2018). Similarly, books and book chapters often present broad overviews of existing research rather than presenting an original, empirical, innovative study. Such sources were therefore excluded from this study to preserve the primacy of peer-reviewed primary research; nonetheless, seminal conceptual contributions published as book chapters are still cited in the narrative framing of this review where they inform the conceptual background. Notes, errata, meetings, and editorial material mainly depict opinions and declarations, with a lack of the detailed methodology, results, and discussion necessary for critical evaluation and data retrieval (Adorno et al., 2019; Erfanmanesh and Morovati, 2019; Forsetlund et al., 2021). One (1) non-English document was removed, and seven (7) documents were inaccessible. Subsequently, the duplicates were removed (96), resulting in 173 articles for full-text assessment. During this assessment, articles in which comprehensive and integrated information and data were absent, or their objectives and content were not relevant to this study, were excluded (53 articles), resulting in 120 articles that were included in the study.

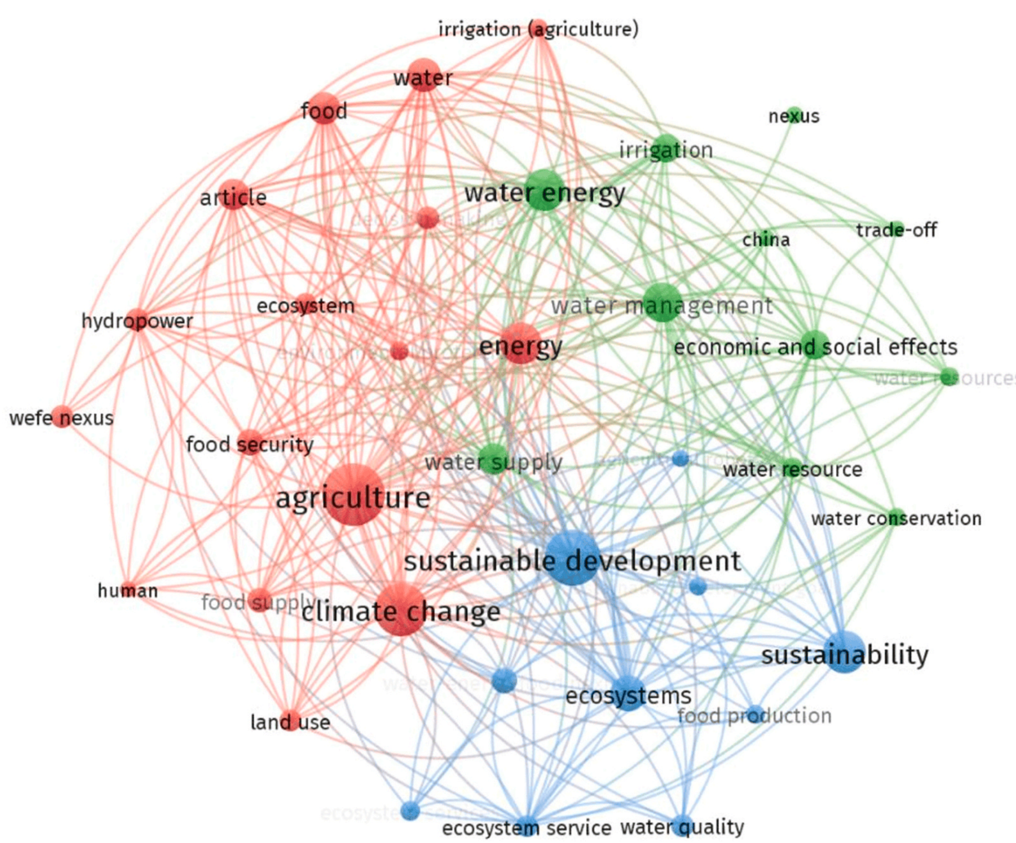

Fig. 1. Relationship of the keywords regarding "WEFE Nexus", "Water Energy Food Ecosystem Nexus", and "Agriculture".

To strengthen the transparency and reproducibility of the search, the query was designed around the established Nexus terminology together with its principal synonyms and lexical variants, namely water-energy-food nexus, WEF nexus, water-energy-food-ecosystem nexus, WEFE nexus, and resource nexus, each combined with the agricultural qualifier (agriculture, agricultural, irrigation, farming, cropland). The records returned did not show a statistically significant difference from the 120 studies already included in the study, which indicates that the original search string already captured the relevant literature and that synonym expansion would not have materially changed the included set. The full query strings, together with the synonym set, are reported in Appendix A. Restricting retrieval to the title, abstract, and keyword fields rather than the full text was a deliberate precision-oriented choice: the unrestricted full-text query returned a very large and largely off-topic corpus of 16,497 records, whose keyword structure is visualized in Fig. 1. Fig. 1 is, accordingly, a term co-occurrence network in which node size reflects occurrence frequency, link thickness reflects the strength of co-occurrence between terms, and colour denotes the three modularity-based clusters that organize the field; a red agriculture and climate-change cluster, a green water-energy and water-management cluster, and a blue sustainability and ecosystems cluster. The bridging position of the terms water, energy, and sustainable development between clusters indicates that these concepts form the connective core of the literature, whereas ecosystem-, governance-, and equity-related terms occupy more peripheral positions, an early signal of the imbalance that the indicator analysis subsequently quantifies. This bibliometric component is confined to a static term co-occurrence map; it does not yet quantify inter-cluster link strength or node centrality, nor does it incorporate time-sliced (temporal) co-occurrence to trace the evolution of research hotspots or author- and institutional-collaboration network analyses. These extensions, which would characterize how the field is structured and how it has evolved over the 2015–2025 window, are identified among the priority directions for future bibliometric work.

Both empirical and theoretical studies were entailed and evaluated in this study providing comprehensiveness and objectiveness to the final outcomes, as well as major insights into the WEFE Nexus framework. The whole research was conducted for the period 2015–2025, as the central objective of this study is to examine current trends and contemporary findings; thus, the inclusion of outmoded and invalid documents is not intended. Both empirical and theoretical (conceptual) studies were retained so that the review captures the full spectrum of Nexus scholarship, from modelling and case-study evidence to conceptual and framework-building contributions. Because these designs carry different evidentiary weight, the synthesis distinguishes the two study types throughout and, for the empirical subset, attends to the dominant methodological approaches encountered in the corpus; system-dynamics and simulation-optimization modelling, coupled hydrological-economic modelling, index- and footprint-based accounting, econometric and statistical analysis, and single- or multi-site case studies. The systematic comparison of empirical and theoretical studies is developed in Subsection 3.9. A formal, item-by-item methodological quality appraisal of every included study, for instance through the Joanna Briggs Institute (JBI) Critical Appraisal tools, stratifies the evidence base by quality level; the heterogeneity of designs across the corpus means that no single appraisal instrument applies uniformly to optimization models, biophysical accounting, and qualitative governance analyses alike. Accordingly, a design-specific critical appraisal was carried out for all 120 included studies, applying the JBI Critical Appraisal Checklists appropriate to each design, namely those for analytical cross-sectional studies, for qualitative research, and for text and opinion, and complementing them with the Mixed Methods Appraisal Tool for studies that combine designs (Barker et al., 2023; Hong et al., 2018). Each study was scored on the items applicable to its design, and a quality tier was assigned from the proportion of criteria met; high (at least 70% of applicable items), moderate (50–69%), and low (below 50%). Because the frequency counts record how often an indicator is addressed rather than the methodological strength of the evidence, the appraisal is reported separately, and the resulting quality distribution together with a synthesis stratified by quality level is presented in the Results, in the subsection on the methodological quality of the included studies. Fig. 2 depicts the SLR methodology under PSISMA guidelines performed in this study.

The search was conducted on 25th August 2025, thus including articles up until that date.

3. Results

This section aims to improve understanding of the WEFE Nexus framework in agriculture by incorporating economic, societal, and governance dimensions to better illustrate the Nexus performance with respect to sustainability. During the thorough examination of the selected articles, seven thematic categories were identified. These studying areas consist of general information, water pillar, energy pillar, food pillar, ecosystem pillar, governance pillar, and social & economic pillars, as illustrated in Fig. 3.

These thematic categories were further divided into a total of 26 criteria (26 WEFE indicators), identified during the full text assessment and based on The WEF Nexus Index (n.d.) & WEF NEXUS Indicator Framework Content (2020), which were subsequently used for further comprehension and classification of the articles. These criteria are demonstrated in Table 2 and are explicitly analyzed below.

3.1. General information

The "General Information category" includes three main criteria (*i*) source type, (*ii*) publication year, and (*iii*) type of the study. Regarding the "source type", 71% of the selected articles were obtained through the Scopus database, and 29% of them were obtained through the WoS database Fig. 4.

Furthermore, Fig. 5 indicates a significant increase in articles relevant to the WEFE Nexus in agriculture from 2021 onward. The vast majority of the published articles have been noted in 2024 (22 articles), followed by the year 2025 (20 articles) (Fig. 5). It should be noted that the 2025 count is partial, since the search was closed on 25 August 2025; the full-year 2025 total is therefore expected to be higher, and the apparent levelling-off relative to 2024 is likely an artefact of this truncation rather than a genuine decline. These findings indicate the rising trend to examine and elaborate on the WEFE Nexus framework, either with a theoretical or empirical perspective. Meanwhile, since WEFE Nexus facilitates transdisciplinary preoccupation and engagement in its management, significant interest has grown to clarify its precise and accurate definition.

As illustrated in Fig. 6, the classification of the selected articles was conducted according to their respective content types, theoretical (35) and empirical (85). This classification ensures comprehensiveness and objectivity in this review while incorporating the crucial findings of each article type.

3.2. Water pillar

Fig. 7 illustrates the quantity of reviewed articles categorized by the five water-related indicators. Each bar represents a particular indicator, accompanied by the corresponding number of articles and the percentage of each displayed underneath. The thorough examination of the water indicators provides a comprehensive clarification of the water pillar.

3.2.1. Water withdrawal in the agricultural sector

The most frequently referenced indicator is the "total water withdrawal in the agricultural sector", cited in 106 articles, accounting for 88% of the total selected articles. This finding underlines the crucial role of agricultural water usage in sustainability concerns, indicating its

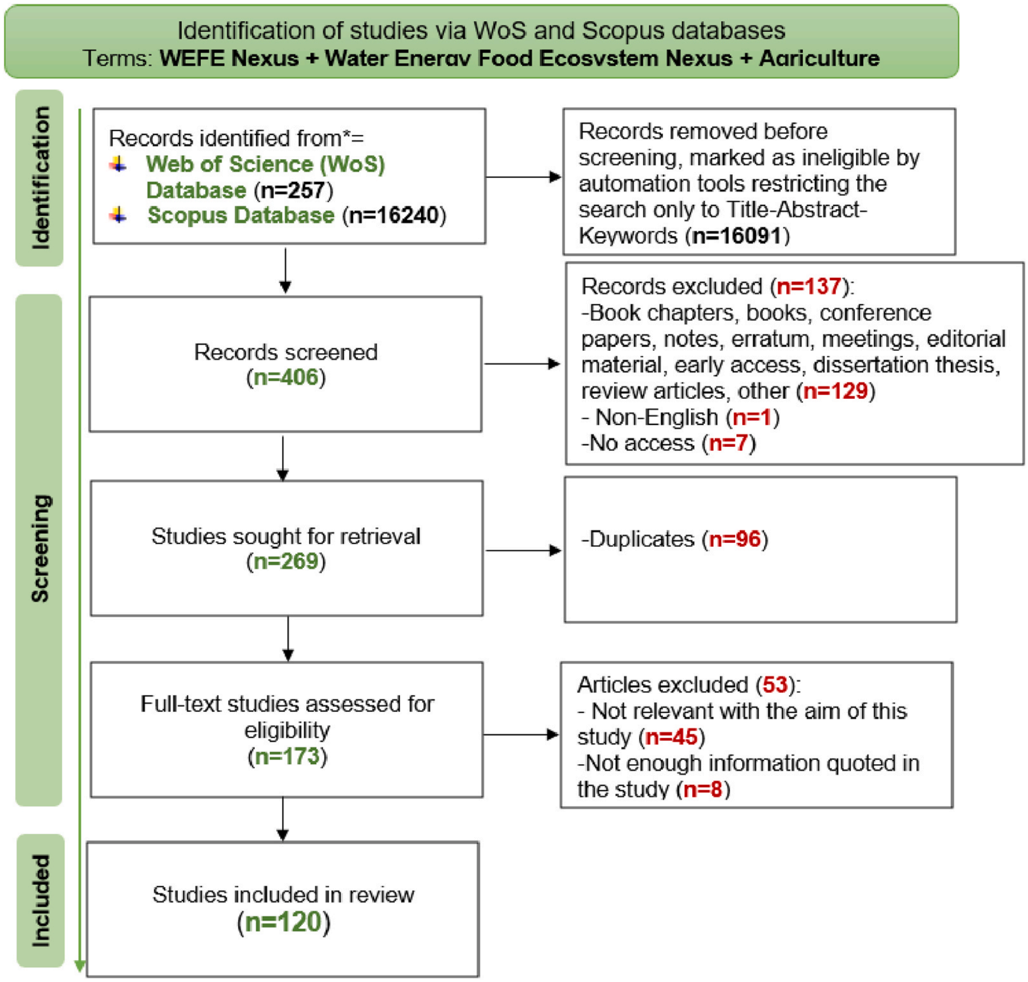

Fig. 2. SLR methodology using PRISMA guidelines.

prominent position in total freshwater consumption and its major influence on food security and resource management. More specifically, Carriço et al. (2025) point out the challenges agriculture is facing due to increasing irrigation needs, drought, and desertification, as well as the vertical demand of the global population for food production, which is directly dependent on crop yields. Furthermore, Demir and Alp (2025) provide a holistic framework for evaluating the water and agricultural capability in water reuse, as agricultural water requirements are escalating to meet the demands of agricultural activities. Their study highlights the necessity of utilizing urban wastewater to ensure WEFE safety while enhancing the circular economy. Bakhshianlamouki et al. (2020), in their research, underline the excessive water requirement of the agricultural sector, since its activities consume the largest amount of water within the Mediterranean region. Along with water requirements, high energy consumption follows, impacting the agricultural economy. Finally, Guo et al. (2024) underline that agricultural water plays an important role in energy production, food security, and ecosystem preservation while maintaining economic and social stability.

3.2.2. Water availability & supply

The next commonly referenced indicator is “water availability & supply”, which is captured in 101 articles (84%). This notable percentage highlights the contributory role of water resources quantification, which is provided to ecosystems, households, agriculture, industry, and other sectors.

The most important water supplies for a region are groundwater resources and surface water flows, which are directly dependent on rainfall water frequency (Falchetta et al., 2023). The rising demand for irrigation water has been exacerbated due to intensified agricultural practices and the unsustainable irrigation methods, resulting in the need to establish strategies to restore water availability through the over-exploitation of groundwater resources (Malamataris et al., 2023). Another study conducted by Zhang et al. (2024) underline the detrimental role of climate change in water availability and supply and employ two climate models to assess different sustainable scenarios, considering Nexus resources. The results indicate that the integrated management of the WEFE resources leads to more efficient elimination of groundwater overextraction. Furthermore, water supply is strongly connected to energy generation, according to the study of Liu et al. (2021), in which they demonstrate that water supply in Zhangjiakou is a high consumer of energy and water; thus, effective measures for sustainable water and energy use are necessary. In conclusion, the detrimental effects of climate change have an impact on water availability and supply, which in turn influences water security, agricultural yields, energy generation, and ecosystem maintenance.

3.2.3. Water security

“Water security” is the third most frequently cited indicator in the selected articles (67% – 80 articles), demonstrating its distinctive interest, which is constantly rising, as it is affiliated with all dimensions of sustainable development.

Delving into the examined articles, a multitude of methods, practices and innovations are described to foster water security. Firstly, the growing tension between decreasing water supplies and escalating

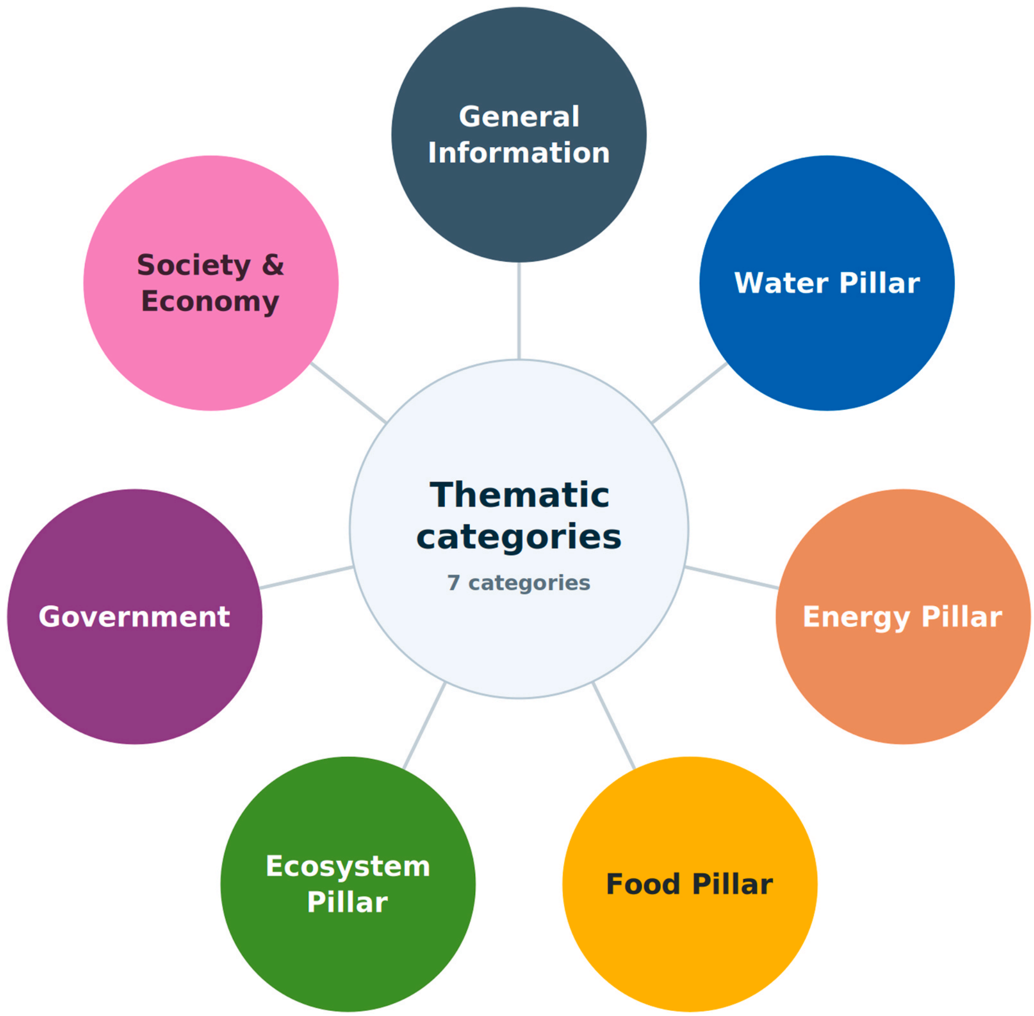

Fig. 3. SLR Thematic categories of criteria.

demand underscores the critical need for synergistic approaches to managing agricultural water (Li et al., 2022). Ravar et al. (2020) point out the contributory role of shifting crop patterns and increasing crop yields combined with the method of controlling groundwater withdrawal, which leads to water security and reduced water requirements for food and energy production. Additionally, various tools, such as a Multi-Objective Linear Fractional Programming (MOLFP) approach in southwestern China, are developed to assess water security, taking into account other determining variables (crop yields, ecosystem preservation, weather, and land conditions). In this way, Water-Ecosystem-Agriculture (WEA) Nexus concerns are targeted and confronted (Niu et al., 2019). Moreover, Muhirwa et al. (2025) underline the urgency for transition to renewable energy sources to reduce the dependence of the energy sector on huge amounts of water quantities; thus, ensuring water-saving practices, leading to water security. Concluding, water security directly affects environmental integrity, social welfare, and economic development, since its absence impacts severely all sectors, as well as the sustainable development across them (Sánchez-Zarco and Ponce-Ortega, 2023).

3.2.4. *Integrated water resource management (IWRM) implementation*

The “IWRM implementation” indicator is mentioned in 77 articles (64%), indicating its major contribution to the simultaneous management of water, land, and related resources, fostering economic and social well-being in full alignment with sustainable ecosystems. For instance, Ding et al. (2024), in their research, introduce an integrated approach for water, energy, and food management to ensure ecological optimization while maintaining agricultural lands. Additionally, Papadopoulou et al. (2022) underline the pressing need to adopt a comprehensive framework that evaluates synergies, trade-offs, and interlinkages, with a focus on optimal resource management, including water security in the center. Through the aforementioned studies, sustainable development and resource efficacy will be accomplished on a long-term scale. Furthermore, de Vito et al. (2017) point out that IWRM benefits the economic sector as much as the agricultural and the environmental sectors, since optimal water management supports agricultural yields, and agricultural costs contribute to water and resource security. Finally, alignment with the WEFE Nexus concept, multi-sectoral collaboration, and well-targeted policy measures are required for the IWRM implementation.

3.2.5. *Environmental flow compliance*

The indicator that is less cited in the selected articles is “Environmental flow compliance”, mentioned in 57 articles (47%). Although this indicator is of major importance for the promotion of sustainability and water conservation, it is demonstrated that ecological consciousness receives less attention compared to challenges regarding agricultural water management, human consumption and policy stewardship issues. More specifically, according to Araujo et al. (2021), the incorporation of environmental flow compliance into water policy systems contributes to the attainment of sustainable goals and ensures long-term resource safety. In addition, another relevant study underscores the importance

Table 2
Brief description of the criteria examined through the SLR implementation.

Thematic category	Criteria	Short description
1. General information	Source type	Scopus or WoS database.
	Publication year	The publication year of the article.
	Type of study	Empirical or theoretical study.
2. Water Pillar	Water availability & Supply	Physical presence of water resources.
	Integrated Water Resource Management (IWRM)	Manage water, land, and related resources to maximize sustainable related benefits.
	Water security	Quality of safe and affordable water to sustain human health, livelihoods, and ecosystems.
	Environmental flow compliance	The extent to which water use and management meet required flow levels to sustain ecosystems and river health.
	Total withdrawal in the agricultural sector	Total amount of water taken from natural resources (river, lakes, reservoirs, or underground) for agricultural activities like farming, irrigation etc.
3. Energy Pillar	Access to energy services	The availability and utilization of secure, cheap, and modern energy for households, enterprises, and societies.
	Renewable energy consumption	The share of total energy use derived from renewable sources such as solar, wind, hydro, and biomass.
	CO2 emissions from energy use	The total carbon dioxide released from burning fossil fuels for energy production and consumption.
4. Food Pillar	Food availability	Sufficient quantities of adequate quality of foods.
	Food access	Affordability,physical accessibility, and sociocultural access to food (e.g. common resources, gender etc.).
	Food utilization	Safe and nutritious food including drinking water to meet dietary and physiological needs including safe storage and preparation of food/ conflict in utilization e.g. with biofuels.
	Crop yield	The amount of produced agricultural products.
	Prevalence of undernourishment/food security index	The share of the population lacking sufficient food for an active and healthy life.
5. Ecosystem Pillar	Terrestrial & Freshwater protected areas	The share of land and inland water designated for biodiversity and ecosystem conservation.
	Biodiversity index/Red list index	A measure of species survival, tracking the risk of extinction over time.
	Clean air	The quality of air that is safe to breathe, with low levels of pollutants and harmful particles.
	Ecosystems services values (e.g., pollination, carbon sequestration, nutrient cycling)	The economic and ecological benefits provided by nature, such as pollination, carbon storage, and nutrient cycling.
6. Governance Pillar	Integrated decision-making processes	Coordinated approaches that include social, economic, and environmental factors for sustainable outcomes.
	Policy tools/multi-sectoral collaboration	Strategies and partnerships across sectors to achieve coordinated and effective policy outcomes.
7. Socioeconomic Pillar	Economic growth	Economy as factor to face challenges regarding the WEFE Nexus.
	Employment	Employment as a factor is analyzed.
	Access to resources for vulnerable groups (women, smallholders, low-income households)	Provision of support to vulnerable groups.
	Income distribution	Income distribution is taken into consideration.

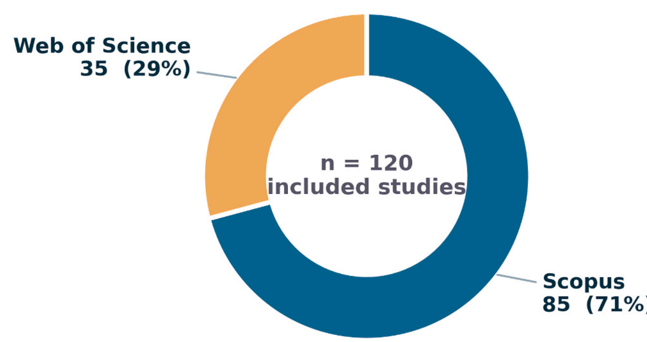

Fig. 4. Articles classified by their source type.

of environmental flow in supporting biodiversity, preserving the resilience of aquatic ecosystems, and enhancing ecological balance (Cook and Webber, 2016). Through the maintenance of baseline flow levels food productivity, energy generation, and long-term water availability and security are facilitated. Lastly, Malamataris et al. (2023), in a case study on the Pinios River Basin in Greece, highlight the challenges posed by adverse temperature levels to preserve ecological flow in Greece, as well as in regions with similar weather profiles. Therefore, fostering the integration of environmental flow compliance into policy and management frameworks is essential to preserve biodiversity, secure resource availability, and ensure long-term sustainability of the WEFE Nexus.

The comparatively low coverage of “Environmental flow compliance”, present in fewer than half of the studies, is unlikely to reflect a lack of ecological relevance; three interacting explanations emerge. First, environmental flow requirements demand continuous, spatially resolved hydrological and ecological data (naturalized discharge, ecological flow thresholds, habitat response) that are frequently unavailable or proprietary, particularly in the data-scarce Mediterranean and semi-arid basins that dominate the sample. Second, the indicator sits at the interface of the ecological and regulatory domains, so its uptake depends on binding policy incentives; where abstraction licensing does not enforce ecological flows, researchers have little applied reason to quantify compliance. Third, the prevailing modelling paradigm optimizes allocation for productive uses (irrigation supply, hydropower, crop yield) and treats ecological flow as an exogenous constraint rather

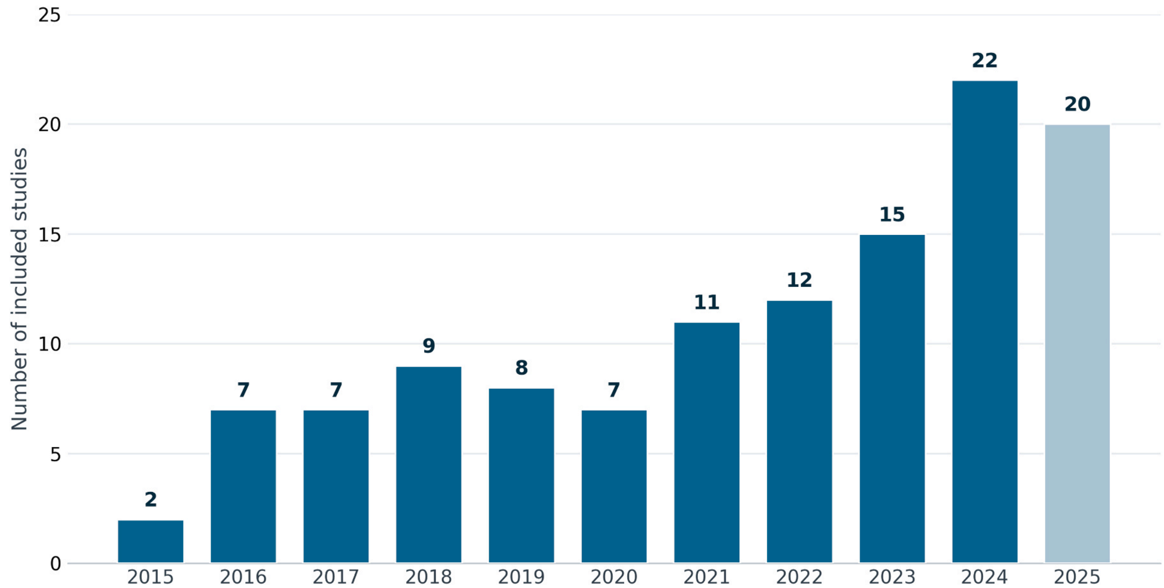

Fig. 5. Number of publications per year regarding the three terms in the final query (2015–2025). Data for 2025 are partial, covering January to August 2025, the data the search was closed.

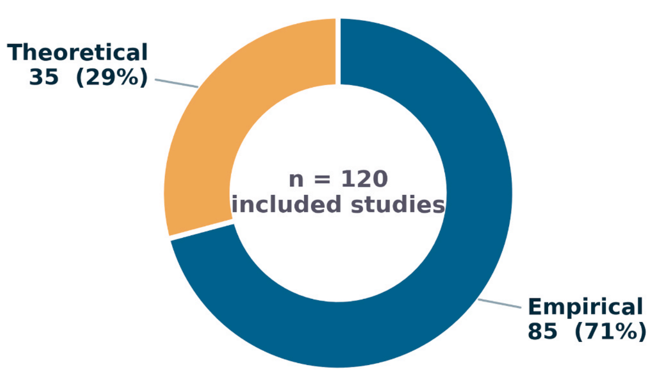

Fig. 6. Articles classified by their respective type.

than an endogenous objective, which structurally marginalizes the indicator. The case of the Pinios River Basin in Greece (Malamataris et al., 2023), where elevated temperatures and abstraction pressure jeopardize the maintenance of ecological flow, illustrates how these data, policy, and modelling constraints coincide in practice.

3.3. *Energy pillar*

Fig. 8 visualizes three energy-related indicators and their citation in the selected articles. Each bar reflects one of the three indicators, followed by the number of articles in which they are mentioned, along with their representative percentage.

3.3.1. *Energy production*

"Energy production" is the most referenced energy indicator, cited in 110 articles with a proportion of 92% out of the total selected articles. This proportion highlights the central role of energy production in social

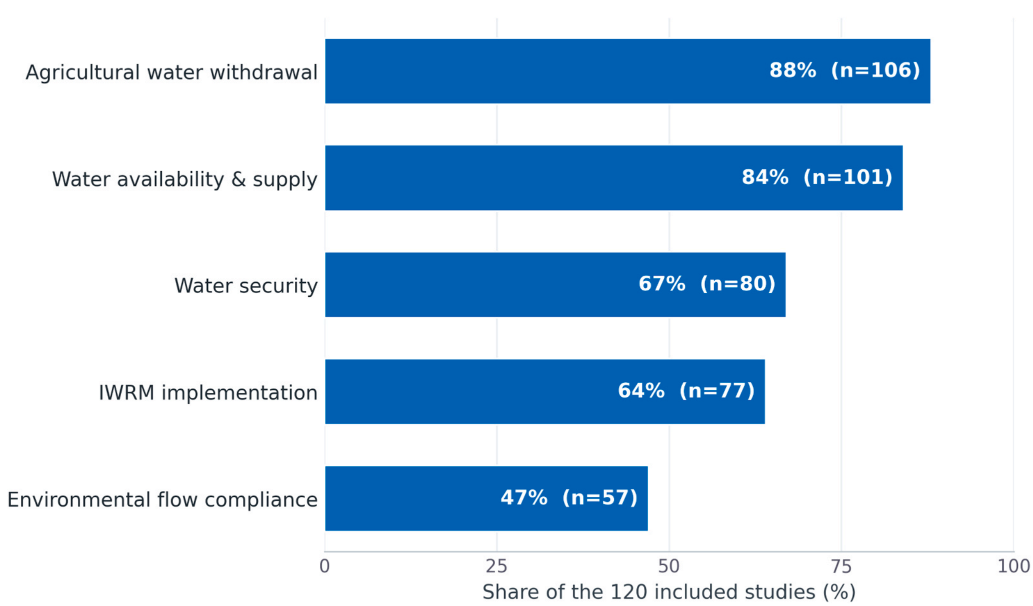

Fig. 7. Quantity of articles referring to water indicators.

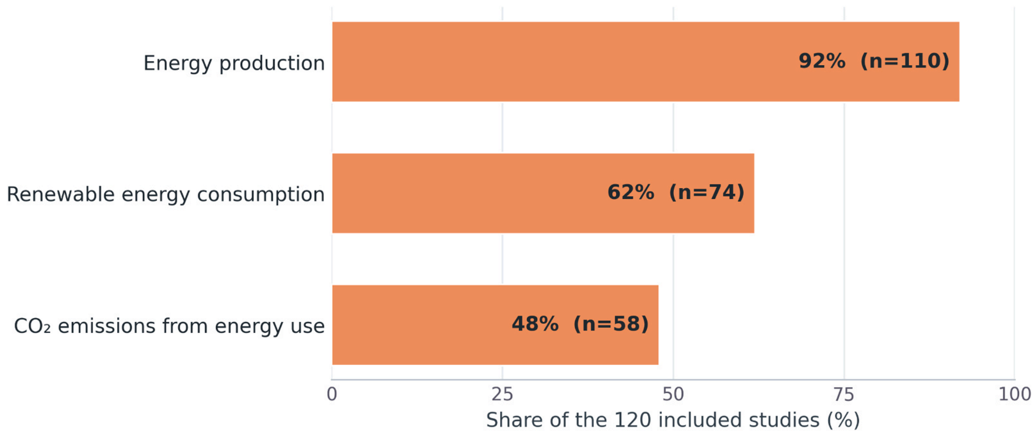

Fig. 8. Quantity of articles referring to energy indicators.

stability and economic growth, which are basic components of sustainable development.

Energy production is a major variable in the WEFE Nexus framework and is highly dependent on water, food, and ecosystem variables and vice versa (Probst et al., 2024). Inductively, a study by Hanes et al. (2018) demonstrates that integrating co-production systems of energy and food enables sustainable management of food-energy-water at a regional scale. The same researchers underline the need for efficient energy use to extend sustainability across ecosystem elements as well. Similarly, Liu et al. (2021), in their study, assess the water-energy system at an urban level and concluded that concurrent optimization of these two correlative parameters will contribute to sustainability across cities.

3.3.2. Renewable energy consumption

The "Renewable energy consumption" indicator also has a prominent position, as it is referenced in 74 articles (62%). This increase indicates the pivotal need for transition to cleaner energy sources (solar, wind, hydropower, etc.), minimizing dependence on petroleum and coal, and meeting environmental goals and sustainability. This progress contributes to the mitigation of the detrimental effects of climate change, as well as the protection of the natural resources.

As indicated in their study, Papadopoulou et al. (2022) highlight the urgent need to transition to alternative energy sources, as excessive consumption of conventional energy sources leads to carbon emissions. In the same study, a few policy measures are suggested regarding Greece to enhance clean energy usage, including replacement of oil with natural gas, energy pricing systems, abatement of coal, and energy-saving practices. Another study conducted by He et al. (2019) point out the importance of adopting the use of solar and wind energy (SWE) sources as a means of fostering Water-Food-Energy (WFE) safety, emphasizing the critical interconnection between clean energy sources, groundwater sustainability and food productivity. Lastly, the renewable and efficient energy use enhances sustainability, while non-renewable energy sources have severe side effects on the sustainability of water, energy, food, and ecosystem services, as well as harm economic viability (Sánchez-Zarco and Ponce-Ortega, 2023).

3.3.3. CO2 emissions from energy use

Lastly in this category, the "CO_2 emissions from energy use" indicator is mentioned in 58 articles (48%), indicating the underrated attention that it has gained, given its significance. Intense agricultural activities and resource exploitation lead to the pollution of the ecosystem and the release of harmful gas in the atmosphere, which contribute to climate change-induced impacts. In particular, the CO_2 emissions directly harm the social, environmental, and economic sectors; thus, it is a multidimensional topic that needs to be addressed, and a limited number of the selected articles focus on this major challenge.

Out of the 58 articles referring to CO_2 emissions, Lamalice et al. (2018) highlight the necessity of mitigating CO_2 emissions to optimize food productivity, water and energy security, and ecosystem maintenance. In addition, Laspidou et al. (2020) not only recognize the detrimental role of non-renewable energy sources in intensifying CO_2 emissions (with oil at the top of fossil fuel consumption in Greece) but also provide recommendations for ensuring long-term sustainability through optimal resource use. In the same study, the negative role of agricultural and livestock activities in increasing CO_2 emissions is pointed out; thus, transition to clean energy sources requires immediate attention. To end up with, CO_2 emissions have a contributory role in deteriorating climate change-induced impacts, including global warming and food insecurity among all the severe outcomes (Chen et al., 2025).

3.4. Food pillar

Fig. 9 illustrates the frequency with which the five food-related indicators are referenced in the selected articles. Each bar depicts a food indicator, accompanied by the corresponding number of articles and the percentage of each. According to the Policy Brief Changing Policy Concepts of Food Security (2006) & WEF NEXUS Indicator Framework Content (2020), food security is defined as the concurrent implementation of food availability, food access, and food utilization. The assessment of each indicator, described below, contributes to the better comprehension of the food pillar.

3.4.1. Food availability

"Food availability" is the most mentioned food indicator among the selected articles, cited in 107 of them (89%). The vast majority of the reviewed articles, which include this indicator, point out that the literature defines food security closely to the overall availability of food and devotes more attention to food availability compared to the rest of the food indicators.

Beyond ensuring safety and authenticity, the strategic deployment of emerging technologies is fundamental to reinforcing the resilience and stability of global food systems (Brooks et al., 2021). By leveraging Blockchain and Internet of Things (IoT) for reliable traceability alongside Artificial Intelligence (AI) and Big Data for predictive analytics, food supply chains can significantly bolster food security through improved authenticity and waste reduction. These integrated technologies streamline distribution and decision-making, ultimately ensuring more consistent food availability across global markets (Kyrgiakos et al., 2024). On the other hand, water supply, energy inputs, ecosystem maintenance, and land allocation are prerequisites to food availability, which has recently become a matter of importance (Panjehpour and

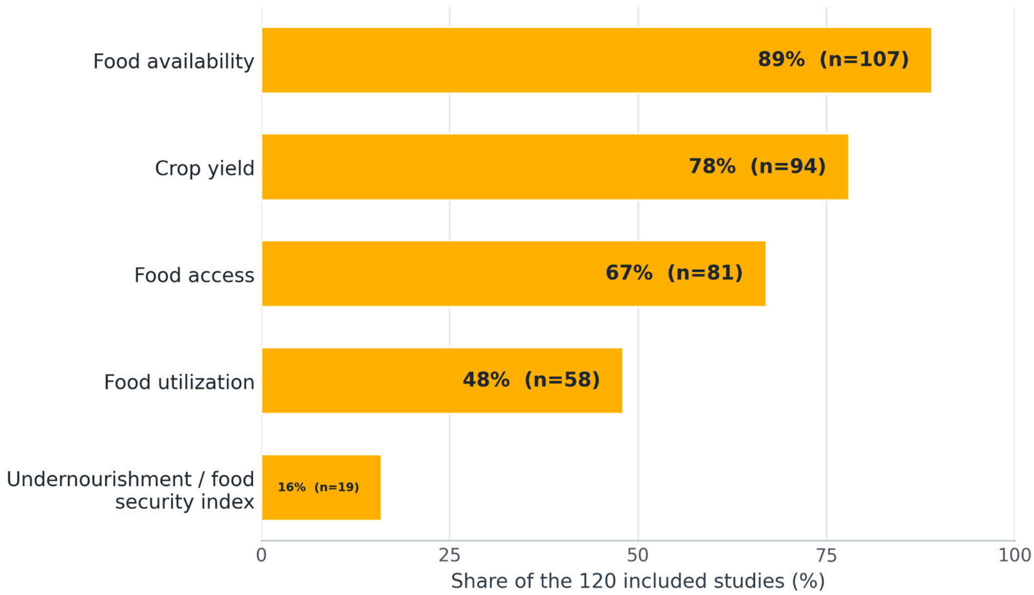

Fig. 9. Quantity of articles referring to food indicators.

Zarrinpoor, 2025). The assessment of food production has been studied thoroughly and imbalance in each of the water, energy, and ecosystem elements can lead to a long-term undermining of food production (Serrano-Tovar et al., 2019). Meanwhile, the expansion of food availability frequently results in trade-offs, including excessive energy consumption and water shortage that can threaten sustainability (Caputo et al., 2021). Concluding, food availability is a core element of food security, and assessing it at a Nexus scale indicates its direct dependence on all three elements of the context and the need for sustainable resource management.

3.4.2. Crop yield

The "Crop yield" indicator is the second most referenced food indicator in this category and is cited in 94 articles (78%). Crop productivity is a fundamental topic concerning the agricultural field, as it is directly related to economic and social effects and strongly affected by climate change impacts. In addition, crop yield is closely linked to maintenance of sustainability, since it influences economic, environmental, and social stability.

Yue et al. (2021) conducted a study in which they implement a comprehensive modelling approach to maximize crop yield, social stability, ecosystem services, water allocation, hydroelectricity generation, etc., and confirm that crop yield is directly dependent on water and energy sources. Furthermore, Correa-Cano et al. (2022) recommend that further research should be focused on crop yield data to estimate economic values, as well as to assess environmental effects. Crop yields are closely connected to WEFE Nexus, since agricultural productivity is strongly determined by the balanced and efficient management of water, energy, and ecosystem services. This is also indicated through the study of Do et al. (2020), in which they demonstrate the close correlation between crop yields and WEFE resources. More precisely, a 49% increase in irrigated crop yields has been observed when reservoirs are used in the Lancang-Mekong River basin, while crop loss decreases by up to 30% when droughts occur. Lastly, food availability is dependent on crop yields and productivity, as well as the intensification of irrigated crops, which in turn are closely connected to the amount of irrigation water (Laspidou et al., 2020). Viewing the crop yields through the WEFE Nexus scope, a need for integrated resource management to augment the agricultural productivity emerges.

3.4.3. Food access

"Food access" is cited in 81 articles (67%), which leads to a smaller number of citations compared to "food availability" and "crop yield" indicators. Food access is a central element of food security since it refers to food affordability and access to food by various social and cultural groups (Policy Brief Changing Policy Concepts of Food Security, 2006; WEF NEXUS Indicator Framework Content, 2020).

Recanati et al. (2017) found that many of the selected farmers experienced food insecurity due to limited access to both natural and economic resources, indicating its multidimensional nature; therefore, holistic management of Nexus resources is necessary to address the trade-offs between limited food access and resource inadequacy. In the same study, it is highlighted that food access is strongly affected by income distribution, expenditures on food, and rate of unemployment, which emphasizes the strong dependence of food access on economic factors. On the other hand, Pourfallah Asadabadi et al. (2025), point out that sustainable water management contributes to food access insurance, thereby indicating the natural dimension of this indicator. Guaranteeing food access is of major importance to social welfare and economic feasibility, and resource availability is required.

3.4.4. Food utilization

"Food utilization" is mentioned in 58 articles (48%), which is a vertical reduction in comparison to the aforementioned food indicators, indicating the need to include this subject in further research. Food utilization, as a food security element, is the process by which food is utilized to satisfy nutritional requirements, which consist of diet quality, wellness, and safe food production (WEF NEXUS Indicator Framework Content, 2020).

Elaborating on the food utilization from a Nexus viewpoint, it is highly dependent on safe water conditions for sanitation, adequate energy generation, and ecosystem stability for ensuring nutritious commodities. More specifically, Tidwell (2016) underscores the role of water in food utilization, whereas water shortage harms food utilization as well as its availability and access. Furthermore, food utilization, as a crucial element of food security, contributes to economic growth and stability. Ecosystem maintenance and energy security also foster the accomplishment of nutritional needs, therefore leading to food security insurance (Vanham, 2016). Therefore, strengthening the food utilization indicator requires the holistic management of water, energy, and ecosystem services and the elimination of trade-offs among the Nexus pillars (Bell et al., 2016).

3.4.5. Prevalence of undernourishment/food security index

The indicator "Prevalence of undernourishment/food security index" has the lowest proportion of citations out of the food indicators, appearing in only 19 articles (16%). This indicates that researchers rarely concentrate on urgent issues regarding people's well-being and nutritional status (e.g. levels of undernourishment) and pay more attention to the quantity of the produced food, which is not distributed equally.

The literature prioritizes the quantification of the produced food indicator instead of focusing on the food security indexes, which are more representative of the nutritional conditions of the population and also depict the prevalence of undernourishment. Considering the few articles including this indicator, one of the most devastating challenges the world is currently facing is food insecurity and poverty (Papadopoulou et al., 2022). The prevalence of undernourishment is illustrative of ongoing barriers to accomplishing food security and underlines the mutual dependence encapsulated by the WEFE Nexus system. Further measures need to be implemented to decrease the proportion of undernourishment and to accomplish the target of SDG 2 (Falchetta et al., 2023).

The marginal coverage of the undernourishment and food-security-index indicator (16%), the lowest within the food pillar, reveals a persistent productivity bias in Nexus scholarship. Studies overwhelmingly quantify the supply side of food security (availability and crop yield, present in 89% and 78% of the corpus respectively) while under-representing the outcome side, that is, whether people are adequately nourished. This asymmetry arises partly because production and yield are readily modelled from biophysical inputs, whereas undernourishment prevalence requires household-level consumption, access, and health data that fall outside the biophysical scope of most Nexus assessments. The consequence is a framework that measures how much food a system can produce far more often than whether that food reaches and nourishes vulnerable populations, weakening the equity dimension that the food pillar is intended to safeguard.

3.5. Ecosystem pillar

Fig. 10 illustrates the citations of the four ecosystem indicators in the selected articles. Each bar represents an ecosystem indicator, accompanied by the corresponding number of articles and the percentage of each. The examination of each indicator provides a more holistic description of the ecosystem pillar. Notably, while ecosystem services are almost universally represented, the biodiversity, protected-area, and clean-air indicators are addressed far less often; the reasons for this selective inclusion, together with the data, policy, and modelling investments that future research would need to redress it, are examined for each indicator below and synthesized in Subsections 4.2 and 4.3.

3.5.1. Ecosystem services value

The primary ecosystem indicator identified in the reviewed articles is the "Ecosystem services value", which is mentioned in 106 articles (88%) and encompasses practices such as pollination carbon sequestration, and nutrient cycling.

Shifflett et al. (2016) highlights that the enhancement of ecosystem services through fertilization, water reuse, carbon storage, and bioenergy leads to water, energy, and food resilience. In the same study, the researchers find that coupling aquaculture activities with managed forest plantation can augment various ecosystem services. Ecosystem services are closely related to the agricultural sector and highly connected to the WEFE Nexus. Robust ecosystems enhance soil fertility, pollination, and water supply and ensure climate resilience, each of which is necessary for agricultural outputs. Simultaneously, agricultural activities consume large amounts of water and energy sources, resulting in mutual synergies and trade-offs within the Nexus framework (Mortensen et al., 2016). For instance, irrigation increases food productivity and may result in water shortage, whereas intensive agricultural activities can boost yields yet deteriorate soil wellness and degrade biodiversity. According to Schwanitz et al. (2017), ecosystem services are gaining increasing attention lately, considering that they ensure long-term sustainability and resilience across the WEFE resources. Since the future global population is rising, along with their increasing demands for food and energy, strengthening the ecosystem services becomes crucial for water security and WEFE Nexus adaptability both in rural and urban areas (Shifflett et al., 2016).

3.5.2. Terrestrial & freshwater protected areas

"Terrestrial and freshwater protected areas" are mentioned in 49 articles (41%). This indicator is directly connected to ecosystem protection and sustainable development. It is noted that this criterion is referenced in half the number of articles compared to the aforementioned indicator.

Terrestrial and freshwater protected areas play a pivotal role in preserving biodiversity and promoting ecosystem sustainability. According to Schwanitz et al. (2017), the establishment of protected areas is strongly linked to economic activities. In addition, Hong et al. (2022) highlight the direct interdependence of human well-being and

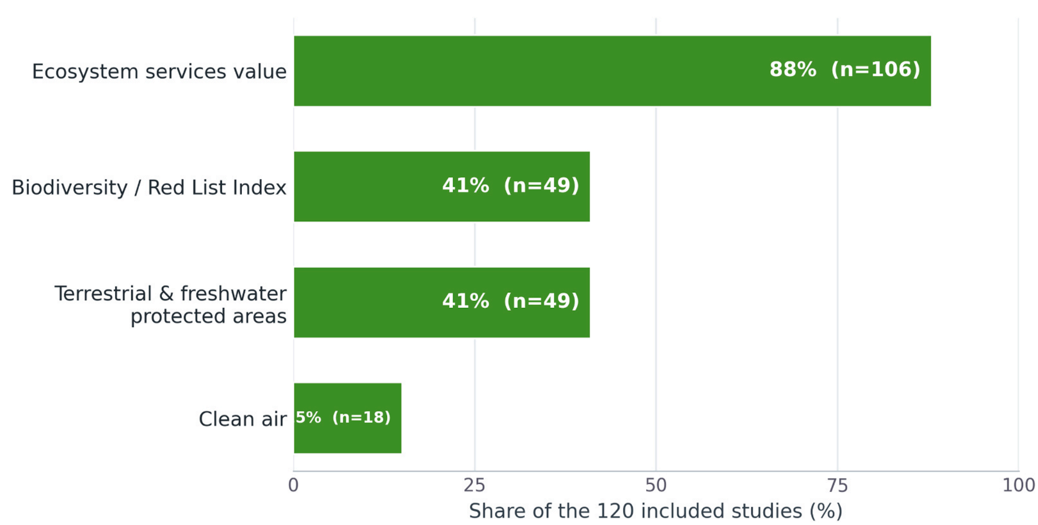

Fig. 10. Quantity of articles referring to ecosystem indicators.

livelihood with protected territories. Freshwater areas are becoming the center of attention as their protection is closely related to water conservation and directly influenced by the WEFE resources management. Protected areas require further attention to ensure ecological preservation (Ding et al., 2024).

3.5.3. Biodiversity index/red list index

Similarly, with the “Terrestrial and freshwater protected areas indicator”, moderate representation appears in the “biodiversity index” with 49 articles (41%), which functions as a fundamental element of the ecosystem pillar, and particularly on ecosystem preservation efforts.

Firstly, Galani et al. (2025), in their study relevant to nature-based solutions, emphasize the biodiversity loss that is obvious on Tinos Island, Greece. They also mention that the implementation of mitigating measures to ensure biodiversity maintenance and ecological balance is of important value. An important point Hurtado et al. (2024) mention in their study is that biodiversity conservation is directly affected by climate change mitigation solutions, water availability, food security and resource management. Furthermore, to prevent further harm to biodiversity maintenance, agricultural practices must prioritize sustainability and efficacy (Avgoustaki and Xydis, 2020). The development of SDGs contributes to ecosystem health and biodiversity protection globally, ensuring long-term resilience (Muhirwa et al., 2025). Preserving biodiversity is essential not only for ecological protection but also as a prerequisite for enhancing sustainable development and adaptability against worldwide environmental changes, such as climate change.

3.5.4. Clean air

The least mentioned indicator among all the examined indicators is “Clean air”, with a proportion of 15% (18 articles), indicating that clean air is rarely incorporated into ecosystem assessment methods, regardless of its particular significance to environmental protection and human livelihoods.

The main cause of air pollution regarding the agricultural sector is fertilizer application, resulting in the increasing levels of the global warming phenomenon (Del Borghi et al., 2022). In some articles, including one by Avgoustaki and Xydis (2020), air temperature, air humidity, and CO_2 concentrations in the atmosphere are calculated to assess air quality and, therefore, the level of environmental devastation. The aforementioned research highlights that air management is a crucial issue regarding ecosystem preservation and directly affects agricultural yields, since greenhouse crops are strongly dependent on atmospheric conditions. As a result, air quality plays a significant role in sustainability concerns, affecting social, environmental, and economic parameters (leading to an increase or decrease in yield and productivity and, thus, cost market fluctuation). The very low coverage of the clean-air indicator (15%) is best understood as an artefact of disciplinary framing rather than of ecological insignificance. Air quality is conventionally treated as an atmospheric or public-health variable and is seldom operationalised within resource-allocation Nexus models, which are organised around water and energy flows. Where it does appear, it is proxied indirectly through CO2 concentration or greenhouse-gas emissions (Avgoustaki and Xydis, 2020; Del Borghi et al., 2022) rather than measured as a distinct ecosystem-regulating service. This indirect treatment, together with the absence of air-quality data in most agro-hydrological datasets, explains why clean air is the least represented indicator across the entire review despite its documented links to fertiliser use, greenhouse cultivation, and crop productivity.

3.6. Governance pillar

Fig. 11 represents the two criteria related to governance pillar, which are policy tools/multi-sectoral collaboration, cited in 70 articles (58%), and integrated decision-making processes, mentioned in 72 articles (60%). Their frequency of occurrence demonstrates the need for institutional mechanisms that enhance coordination across sectors and stakeholders. The close correlation between these two indicators indicates that the reviewed articles highlight the importance of systematic governance structures as essential for promoting WEFE-related initiatives (Garau et al.,2025a).

3.6.1. Policy tools/multi-sectoral collaboration & integrated decision-making processes

Governance is the core component that makes the WEFE Nexus functional. Elaborating on the examined articles, the need for adopting the governance pillar into the WEFE Nexus framework is vital. Do et al. (2020) emphasize the integration of policy tools in decision-making processes and the enhancement of policy dialogue for WEFE Nexus issues to subsequently establish a comprehensive approach that prioritizes sectors. At the same time, Laspidou et al. (2020) underline the efficacy of governance in coordinating interactions and collective commitments among different types of stakeholders to guarantee the sustainability of interdependent resources. In accordance with the aforementioned, the inclusion of multi-criteria decision-making creates synergistic approaches that, by engaging diverse stakeholders to ensure objectiveness, compliance, and impartiality, lead to the advancement of WEFE Nexus management (Vasović et al., 2025). Sievers et al. (2025) underline the initiative of establishing institutional capability and introducing cross-sectoral collaborative actions as a means of orienting the direction towards a governance-oriented operational WEFE Nexus framework. Through this incentive, key institutional stakeholders (e.g. ministries of water, energy, agriculture, and environment) are engaged in WEFE Nexus-related issues and consist of active entities in jointly managing WEFE challenges. A relevant study conducted by Mooren et al. (2025), prioritizes policy coherence and stakeholders' insights at the center of its methodological approaches, emphasizing on the need of WEFE Nexus governance perspective. Transitioning to a governance-oriented WEFE Nexus secures the engagement of high-level sectoral institutions. This involvement is critical for fostering cross-sectoral coordination,

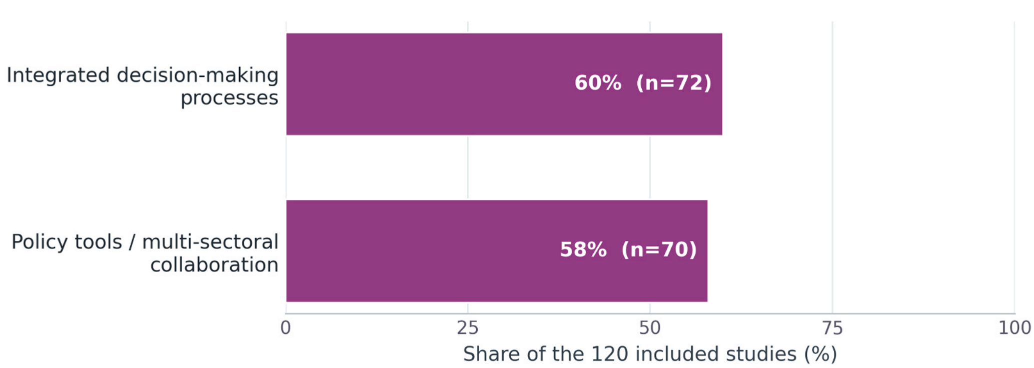

Fig. 11. Quantity of articles referring to governance indicators.

facilitating the translation of research results into policy-making actions, and ultimately providing institutional support and legitimacy (Garau et al., 2025a). This is in total alignment with the study of Sofiyah et al. (2025), in which they highlight the central role of adaptive governance in guiding policy directions for WEFE Nexus consultation topics and guaranteeing social resilience. Furthermore, more recent findings suggest the necessity of policymakers to better comprehend the interconnections among WEFE pillars in order to facilitate decisions for integrating management of the WEFE Nexus system (Ma et al., 2024). Correspondingly, Y. Zhang et al. (2024) conclude that adopting decision-making processes in irrigation regions, as well as the integration of coupled models with quantitative indicators, leads to necessary data for agricultural irrigation managers to implement both supply and demand management. Simultaneously, they highlight that decision-makers should align with multisectoral resource management. In the same line, Caputo et al. (2021) underscore the major role of policymakers in expanding urban agriculture using geographical land use data. Last but not least, Kleftodimos et al. (2024) underline the necessity of farmers' decision-making processes in adopting Precision Agriculture Technologies (PAT), emphasizing that these individual choices are the linchpin of a comprehensive WEFE approach. By fostering a holistic perspective on crop production, this research underscores the importance of data-driven decision-making to mitigate risks and ensure the practical feasibility of proposed interventions.

Integrated Nexus solutions augment the efficacy of decision-making and policy, resulting in optimal resource management and profitable strategic visions (Kaddoura and El Khatib, 2017). There is high alignment between decision-making processes and policy tools/multi-sectoral collaboration as illustrated by the outcomes of examined articles, and the need to incorporate the governance pillar into the WEFE Nexus framework is of major importance considering the large number of the reviewed articles, including these two indicators. Finally, the governance pillar, attended by its two pillars, is a fundamental mechanism that drives the WEFE Nexus from a theoretical framework to a practical reality, while balancing competing sectoral demands, ensuring equity and long-term resilience. A critical reading of these two governance functions indicates that their effectiveness is conditional rather than universal. Adaptive, participatory, and multi-criteria decision-making is most valuable under deep uncertainty and contested allocation, where climatic volatility and competing stakeholder claims make rigid plans brittle (Sofiyah et al., 2025; Vasović et al., 2025). Formal regulatory and licensing instruments, such as abstraction caps and enforceable ecological-flow standards, are decisive where over-abstraction and weak enforcement dominate, because voluntary coordination alone rarely restrains resource use. Multi-sectoral coordinating bodies that convene the water, energy, agriculture, and environment ministries are most effective where institutional fragmentation splits competence across agencies (Sievers et al., 2025). The reviewed evidence therefore suggests that no single governance form is sufficient on its own: the appropriate mix depends on the dominant constraint in a given setting, whether uncertainty, enforcement failure, or institutional fragmentation.

3.7. Socioeconomic pillar

Fig. 12 illustrates the four criteria regarding the socioeconomic category, (*i*) economic growth, (*ii*) income distribution, (*iii*) access to resources for vulnerable groups (women, smallholders, low-income households, etc.), and (*iv*) employment. Each bar represents a socioeconomic-related indicator, accompanied by the corresponding number of articles and the percentage of each. The integration of the socio-economic pillar in the WEFE Nexus framework contributes to sustainable resource management, as well as provides access to various types of stakeholders' groups for these resources (Shokri et al., 2025). The examination of each criterion provides a more holistic description of the socioeconomic category.

3.7.1. Economic growth

"Economic growth" is the most commonly referred criterion, appearing in 60 articles (50%), indicating its pivotal role in sustainability issues, in WEFE Nexus challenges, and in the agricultural sector. Viewing the WEFE nexus from an economic perspective is a recent topic of interest, aiming to provide significant insights regarding water saving, energy generation, food security, and ecosystem preservation (Recanati et al., 2017). "Economic growth" is not just an outcome of the WEFE Nexus but a crucial enabler of its optimal management, as indicated in the examined articles.

Focusing on the connection of growth to capital is of major importance when it comes to integrated WEFE resource management. Important financial capital is a prerequisite of synergies regarding the integrated WEFE Nexus management, such as investing in solar-powered irrigation, building water treatment plants, or funding environmental protection (Abdelhamid et al., 2025; Abera et al., 2024). In line with this, rapid economic growth results in private capital, and public incomes increase (such as taxes), which in turn funds the development of operational infrastructures and technological innovations, including precision agriculture systems, as well as the appropriate expertise for comprehensive resource management (KC et al., 2025). In

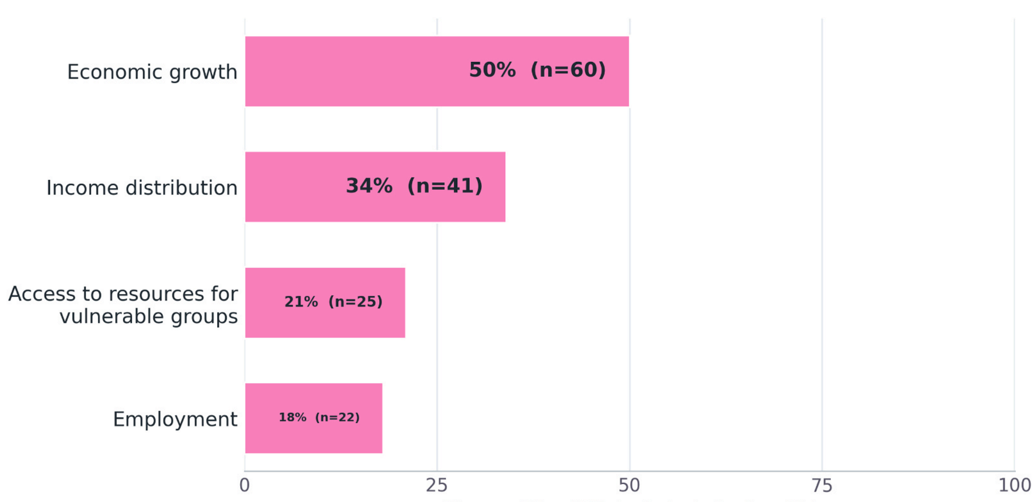

Fig. 12. Quantity of articles referring to society and economy indicators.

particular, economic viability is strongly connected to agricultural sustainability and resilience, including the efficient use of fertilizers and water-saving methods, which leads to a decrease in operational costs for fertilizers and water (Karnib et al., 2025). Additionally, the enhancement of sustainable economic development can facilitate the adoption of renewable energy practices, thus contributing to energy cost savings (Kertolli et al., 2024). In the same study it was highlighted the strong interconnection between WEFE resources and economic development, the coordination of which results in future resilience. Bateni et al. (2025) concur with the concept that the inclusion of multidisciplinary fields, including the economic sector, should be considered to address challenges regarding the biophysical resources, and the socio-economic effects of the WEFE management should be likewise assessed. Among the others, economic viability serves as an essential driver of the holistic assessment of the synergies and trade-offs among the WEFE Nexus elements (Demir and Alp, 2025). The establishment of sustainable economic growth requires optimal management of environmental resources, as well as social stability (Pourfallah Asadabadi et al., 2025). Ultimately, WEFE components and resource management are strongly affected by economic growth, and their combined consideration leads to future sustainability enhancement (Hurtado et al., 2024).

3.7.2. Income distribution

"Income distribution" is the second most commonly referred criterion, appearing in 41 articles (34%), underscoring its fundamental role in issues of social stability and equity, as well as economic viability (Rhouma et al., 2025). Delving into the WEFE Nexus framework, "Income distribution" serves as an indispensable, overarching variable that determines resource governance, access, and systemic susceptibility. As indicated by Lu et al. (2025), income distribution directly affects the WEFE Nexus management, and its integration into the comprehensive evaluation of the WEFE system leads to an increase in equity as well as a reduction in unsteadiness and inequality in multiple sectors. "Income distribution" serves as a pivotal indicator in the socioeconomic pillar and also contributes to coherent policy structure (Pourfallah Asadabadi et al., 2025). An equal income distribution combined with high levels of income indicates social coherence, economic development, and augmentation of demand. On the other hand, unequal income distribution in relation to low-income rates impacts the whole economic system and deteriorates social instability. This results in limited access to WEFE resources by vulnerable and marginalized populations, demonstrating the robust influence of income distribution imbalances on the WEFE Nexus shaping policy (Cotella et al., 2025). It is also mentioned that the agricultural income derives mainly from crop yields, food production, and crop prices; thus, agricultural household income strongly depends on crop and food productivity (Li et al., 2024). When various damaging physical phenomena occur that impact crop productivity, hydropower, and energy prices, low-income populations suffer the consequences, as they lack the financial reserve to adjust to these vulnerabilities (McCoshan, 2020). In addition, low-income regions, where scientific knowledge and data availability are limited, hinder integrated water, energy, food, and ecosystem management and result in various deficiencies (Fleischmann et al., 2024). Conversely, the study of Henseler (2025) underscore that sustainable water management, as well as proper use of governmental water practices, could lead to limited water wastefulness while maintaining affordability for lower-income households. Therefore, neglecting the pivotal role of "Income distribution" in WEFE Nexus management issues, while simultaneously aggravating social tensions and economic disparities, undermines the comprehensive and sustainable dimension of the WEFE Nexus framework.

3.7.3. Access to resources for vulnerable groups

Subsequently**, "**Access to resources for vulnerable groups", including women, smallholders, and low-income households, follows with 25 citations (21%), emphasizing the recognition of inclusivity and fairness in resource allocation. Equitable access to the WEFE Nexus services is both an issue of social and economic equity and growth, as well as an essential element of sustainability promotion.

Currently, vulnerable and marginalized populations suffer from inadequate nutrition and limited access to basic resources, including clean water supplies, reliable energy sources, healthy livelihood conditions, and education (Rosenheim et al., 2024). Through these insufficiencies, the entire system's structure is characterized as fragile, revealing its social weaknesses. To address the aforementioned, Raffo-Babici et al. (2025) emphasize the need to implement multiple correspondence analysis (MCA) for a comprehensive understanding of the interconnections among the factors that negatively impact the access to resources for various population groups. At the same time, it was suggested that the inclusion of the indicator "access to resources for vulnerable groups" in the WEFE Nexus management ensures sustainability solutions, long-term efficacy, and transparency in socioeconomic aspects. According to Falchetta et al. (2023), vulnerable groups, such as smallholders, in the region of Sab-Saharan Africa are favored by solar irrigation systems, which increase crop yields and food productivity and finally enhance economic feasibility. These innovative infrastructures allow smallholders to have access to clean energy sources, as well as enhance sustainability. In addition, Pastori et al. (2021) assess the implementation of sustainable strategies in rural regions that support energy generation by enhancing food productivity and ecosystem maintenance. These initiatives provide smallholders and low-income farmers with stable and affordable energy access, which in other circumstances comes with various energy cost challenges. Moving on, in their study, Caputo et al. (2021) and Recanati et al. (2017) underline the necessity of increasing food availability and agricultural productivity among various vulnerable stakeholders, including small-scale farms and low-income households, as a means of augmenting sustainable livelihoods consciousness. By ensuring access to resources for vulnerable groups, social equity and justice are achieved, as well as holistic incorporation of all population groups in WEFE Nexus-related issues (Sanchez et al., 2023). Concluding, considering the examined articles, vulnerable groups are most likely to experience resource scarcity and environmental deterioration, yet they exhibit inadequate resilience to respond to disturbances such as climate change and price fluctuations. Mitigating these challenges necessitates the inclusion of vulnerable groups in decision-making processes and the promotion of policies that diminish structural disparities. Hence, in this way, the WEFE Nexus acquires a more holistic and resilient dimension and empowers its sustainability dimension.

3.7.4. Employment

Lastly, the indicator "Employment" has the lowest proportion of citations out of the socioeconomic category, appearing in only 22 articles (18%), demonstrating its relatively lesser importance in comparison to economic growth, income distribution, and access for vulnerable groups. Job creation is a key aspect of the economic stability of a region, so research endeavors should further focus on direct employment effects rather than implicit aspects of socio-economic objectives. The "employment" indicator has been introduced in the WEFE Nexus framework as an important variable, among all, for dynamically assessing the interconnections among its pillars, as well as addressing various social Mediterranean threats (Hussein and Ezbakhe, 2023).

Employment is a prerequisite to economic growth, and economic growth, as a part of the socioeconomic pillar, entails high employment rates, indicating the crucial role of the "employment" indicator (Mitić et al., 2022). According to Panjehpour and Zarrinpoor (2025), agricultural sector plays a crucial role in job creation and contributes to the decrease of rural unemployment. They found that rural regions with rising unemployment levels are more suitable for canola cultivation to eliminate this plague. Furthermore, De Strasser et al. (2016) highlight that high rates of employment are mostly noticed in areas where agricultural and industrial sectors are thrived. These two studies are in complete alignment with the study of Gkatsikos et al. (2022) and Chen et al. (2023), in which it was demonstrated that high employment rates evidence the existence of adequate WEFE sector development (e.g. farming, power generation labor, and water infrastructure construction). In addition, the "employment" indicator serves as a means of accessing WEFE resources, as earned income leads to affordability for electricity bills, diverse and plentiful nutritious food, and a clean water supply (Khan et al., 2023). A WEFE framework that neglects the "employment" indicator risks designing solutions that are resource-efficient bit socially devastating, failing to ensure that the benefits of integrated management are equitably distributed. Therefore, there is a robust interconnection among employment rates, socioeconomic effects, and ultimately, sustainable WEFE Nexus management.

3.8. Cross-cutting interactions among indicators

The defining premise of Nexus research is that resources are interdependent; a frequency-based reading of individual indicators therefore has to be complemented by an analysis of how the indicators co-occur across the corpus. The analysis that follows moves beyond frequency counts to expose not only where studies converge but also where they diverge in how they conceptualize the same pillar, for instance whether water is framed as a productive input or as a regulating, ecological constraint, a divergence that the co-occurrence structure renders visible. To this end, pairwise co-occurrence was examined for the indicator combinations most relevant to the synergies and trade-offs emphasized in the reviewed studies, using both the proportion of joint mentions and the phi coefficient of association (Tamura et al., 2026). The phi coefficient is interpreted alongside the raw co-occurrence proportion for each pair, since its maximum attainable value is constrained when two indicators differ markedly in prevalence. Several patterns stand out, both within individual pillars and across them; the complete matrix of pairwise phi coefficients is shown in Fig. 13, and the most salient patterns are discussed in turn below.

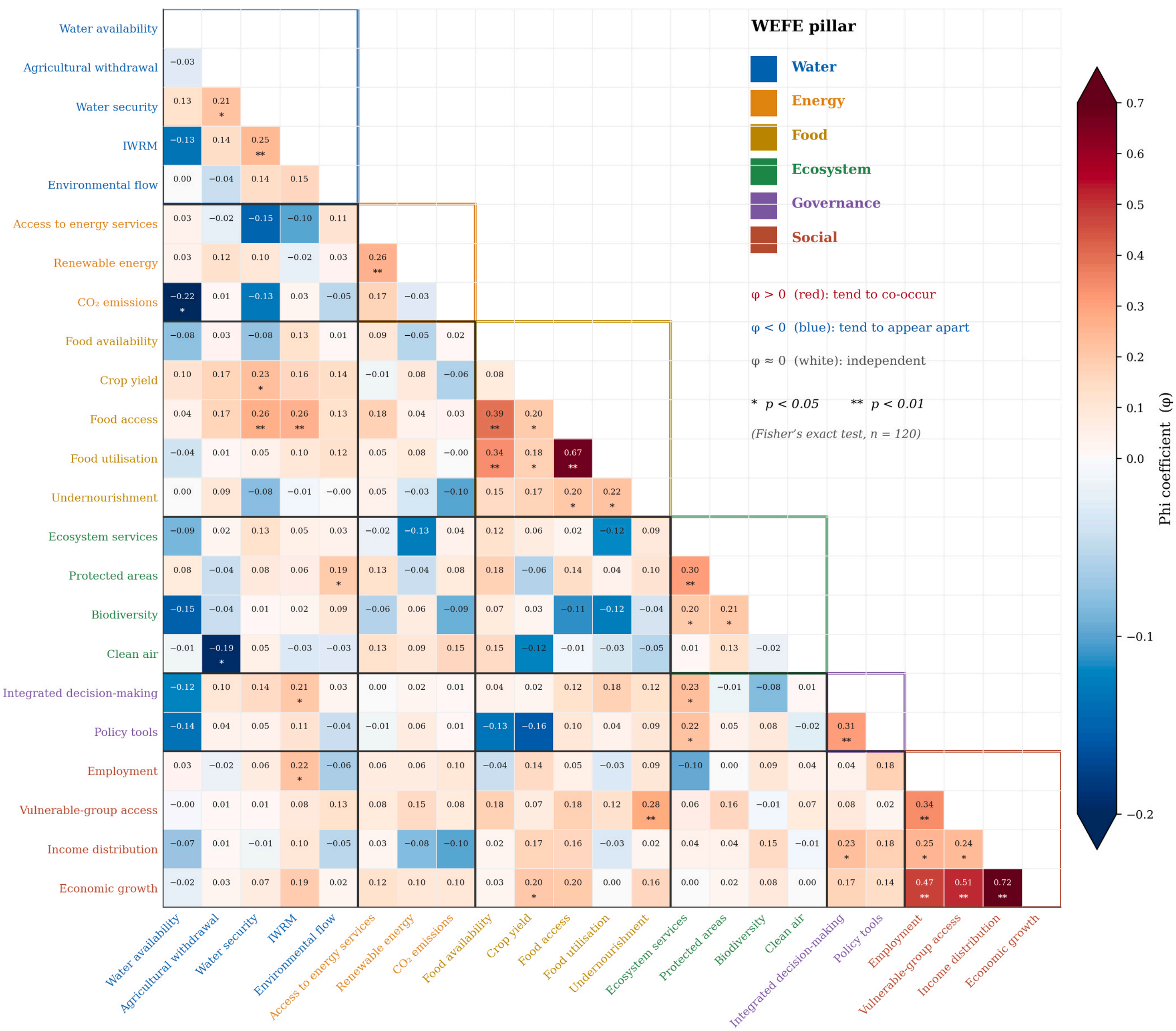

Fig. 13. Matrix of pairwise phi coefficients (φ) among the substantive WEFE indicators across the 120 reviewed studies. Each lower-triangle cell reports the φ association between two indicators, computed from their 2 × 2 co-occurrence table across the corpus; positive values (red) identify indicators that tend to be addressed together, negative values (blue) indicators that tend to be addressed separately, and values near zero (white) indicators that appear independently of one another. Indicators are grouped and colour-coded by pillar, with heavier lines separating the pillar blocks. Asterisks denote statistical significance assessed with Fisher's exact test (* $p < 0.05$, ** $p < 0.01$).

Within the water pillar, the strongest internal coupling links water security to IWRM implementation (phi = 0.25). Water security is treated predominantly as a management outcome, so 72% of water security studies also address integrated water resources management. Physical water availability and agricultural water withdrawal, the two most frequent water indicators (84% and 88% of studies), are effectively near-universal and therefore co-occur with most other indicators without discriminating between them; water availability is, if anything, marginally negatively associated with IWRM (phi = −0.13), which reflects a mild separation between studies centred on the biophysical resource and those centred on its governance. Most striking is that environmental flow compliance is statistically decoupled from water availability. The number of studies addressing both (48) is essentially identical to the 48 expected by chance (phi = 0.00), and it associates only weakly with the management-oriented indicators (IWRM, phi = 0.15; water security, phi = 0.14). Environmental flow therefore enters the literature, to the limited extent that it does at all, through a governance and security framing rather than through resource accounting, indicating at the water-pillar level the marginalization of regulating services already observed for the ecosystem pillar.

Within the energy pillar, energy production is near-universal (92% of studies) and anchors the pillar, with renewable energy consumption and CO_2 emissions each almost entirely nested within it, since 97% of the studies that address either indicator also address production. The more revealing result concerns the relationship between the two remaining indicators; renewable energy consumption and CO2 emissions are themselves statistically decoupled (phi = −0.03; their joint coverage of 35 studies matches the 36 expected by chance), so studies that examine renewable energy are no more likely than any other to quantify the associated emissions. The decarbonization linkage that connects renewable deployment to emission reductions, and that underpins much of the rationale for the energy transition, is thus seldom made explicit within the reviewed corpus, an omission that weakens the climate argument these studies frequently invoke.

Within the food pillar, the food-security dimensions form a nested hierarchy of increasing specificity rather than an unstructured set. Food utilization is effectively contained within food access (phi = 0.67; every study that addresses utilization also addresses access), and both are strongly tied to food availability (availability and access, phi = 0.39; availability and utilization, phi = 0.34), which indicates that studies add the deeper access and utilization dimensions cumulatively on top of a baseline concern with availability. Crop yield, although also a supply-side indicator, is only weakly associated with food availability (phi = 0.08) despite co-occurring with it in 71% of studies, because both indicators are so common that their joint appearance is close to what their individual frequencies alone would predict. The prevalence-of-undernourishment indicator behaves as a small, fully nested subset: every study that measures undernourishment also measures food availability (100%), and almost all also measure crop yield (95%) and food access (89%), yet only 18% of availability studies address undernourishment in return. This asymmetry quantifies the supply-side bias noted earlier for the food pillar, since the outcome dimension of food security appears only as an addition to production-oriented studies and is almost never examined in its own right.

Within the ecosystem pillar, the associations are strongly uneven, and they trace the same selective inclusion that the frequency counts suggest. Ecosystem services, present in 88% of studies, anchors the pillar, and the two conservation-oriented indicators are largely nested within it: every study that addresses terrestrial and freshwater protected areas also addresses ecosystem services (phi = 0.30), as do 96% of the studies addressing the biodiversity index (phi = 0.20). Protected areas and biodiversity are in turn moderately associated with one another (phi = 0.21), so the studies that engage conservation tend to treat spatial protection and species diversity together. Clean air is the conspicuous exception; it is effectively decoupled from ecosystem services (phi = 0.01), appearing in only 15% of ecosystem-services studies, which is exactly its overall rate, and it is unrelated to biodiversity (phi = −0.02). The pillar is therefore coherent around the instrumental, production-supporting and spatially delimited facets of ecosystems, while the regulating air-quality service sits outside the cluster, confirming at the level of association the imbalance that leaves regulating and intrinsic ecosystem attributes under-represented.

Within the governance pillar, which comprises only two indicators, the single available pair is strongly and significantly associated; integrated decision-making appears in 73% of the studies that address policy tools/multi-sectoral collaboration, and policy tools appear in 71% of the studies that address integrated decision-making (phi = 0.31, both present in 51 of the 120 studies). The relationship is nearly symmetric, indicating that the literature does not separate coordinated decision processes from the cross-sectoral instruments that enact them, but treats them as a single, mutually reinforcing governance capability. This internal cohesion does not extend outward, however: the governance indicators connect only weakly to the other pillars, their strongest cross-pillar links being with ecosystem services and with income distribution (phi = 0.23 in both cases). Coordinated governance is therefore conceived as a largely self-contained competence, rather than one whose reach into the biophysical and social domains is explicitly represented.

Within the socio-economic pillar, a single indicator organizes the entire block. Economic growth, present in half of the studies, is the hub around which the narrower equity indicators are arranged, and the arrangement is one of complete nesting; every study that addresses income distribution, access to resources for vulnerable groups, or employment also addresses economic growth. The associations are correspondingly strong, with economic growth co-occurring with income distribution at phi = 0.72, the strongest single association in the entire matrix, with access for vulnerable groups at phi = 0.51, and with employment at phi = 0.47, all significant at the 1% level. The three equity indicators are additionally linked among themselves, most clearly employment with access for vulnerable groups (phi = 0.34) and, more weakly, income distribution with employment and with vulnerable-group access (phi = 0.25 and 0.24). This makes the socio-economic pillar the most internally coherent grouping in the review; the coherence is nonetheless confined to a small share of the corpus, since the equity indicators are among the least frequently reported overall, so the pillar represents a compact but marginal distributional-and-development strand whose extension across a larger portion of the literature would materially strengthen the equity dimension of the Nexus.

At a pillar level, Fig. 13 shows that association in the dataset is concentrated within pillars rather than across them. Averaging the phi coefficients over all indicator pairs inside each pillar, the socio-economic pillar is by far the most internally coupled (mean phi = 0.42), driven by a tight cluster around economic growth that co-occurs strongly with income distribution (phi = 0.72), access to resources for vulnerable groups (phi = 0.51), and employment (phi = 0.47). The food pillar is the next most coherent (mean phi = 0.26), resting on the nested food-security dimensions, above all food access with food utilization (phi = 0.67), while governance records a comparable value (mean phi = 0.31) that stands on its single indicator pair, integrated decision-making with policy tools. The ecosystem and energy pillars are considerably looser (mean phi = 0.14 and 0.13), and the water pillar is the least coupled of all (mean phi = 0.08); water is moreover internally heterogeneous, since physical availability is slightly negatively associated with IWRM (phi = −0.13), separating studies centred on the biophysical resource from those centred on its governance. Coupling across pillar boundaries is uniformly weaker still: no pillar-to-pillar average exceeds phi = 0.13, the highest being the governance-social and food-social links, and the strongest individual cross-pillar associations, such as undernourishment with access for vulnerable groups (phi = 0.28) and water security or IWRM with food access (phi = 0.26), remain well below the leading within-pillar values. Most tellingly, the water-energy interface is the weakest coupling in the entire matrix (mean phi =

−0.016); once the high co-occurrence produced by the ubiquity of the water indicators is discounted, the frequently invoked water-energy nexus shows no association beyond chance. The matrix therefore depicts pillars that are each internally coherent, most strongly in the socio-economic and food domains and most weakly in the water domain, yet only loosely connected to one another, which is precisely the cross-pillar fragmentation that an integrated WEFE assessment is intended to overcome.

Taken together, these patterns reveal a consistent architecture beneath the WEFE literature. Each pillar is organized around one or two near-universal indicators onto which the narrower dimensions are added cumulatively, and the associations that would most fully express the Nexus logic, namely the links between renewable energy and emissions, between water use and ecological flow, between food production and nourishment, and between the biophysical pillars and their governance and equity context, are precisely the ones that remain weak or statistically absent. This study is thus internally coherent within each pillar, most tightly within the socio-economic and food domains, yet only loosely connected across pillar boundaries. The analysis therefore exposes not an absence of interdependence but its selective representation, since the field couples the indicators that are easiest to measure together while leaving the regulating, outcome, and cross-sectoral linkages implicit. Rendering these latent connections explicit, rather than adding further indicators, is the step most likely to move WEFE research from a set of pillar-specific literatures toward the integrated assessment that the framework envisions.

3.9. Empirical versus theoretical studies

Empirical studies dominate across this study (85 of 120, 71%), with theoretical and conceptual contributions accounting for the remaining 35 (29%). Beyond this numerical split, the two categories differ

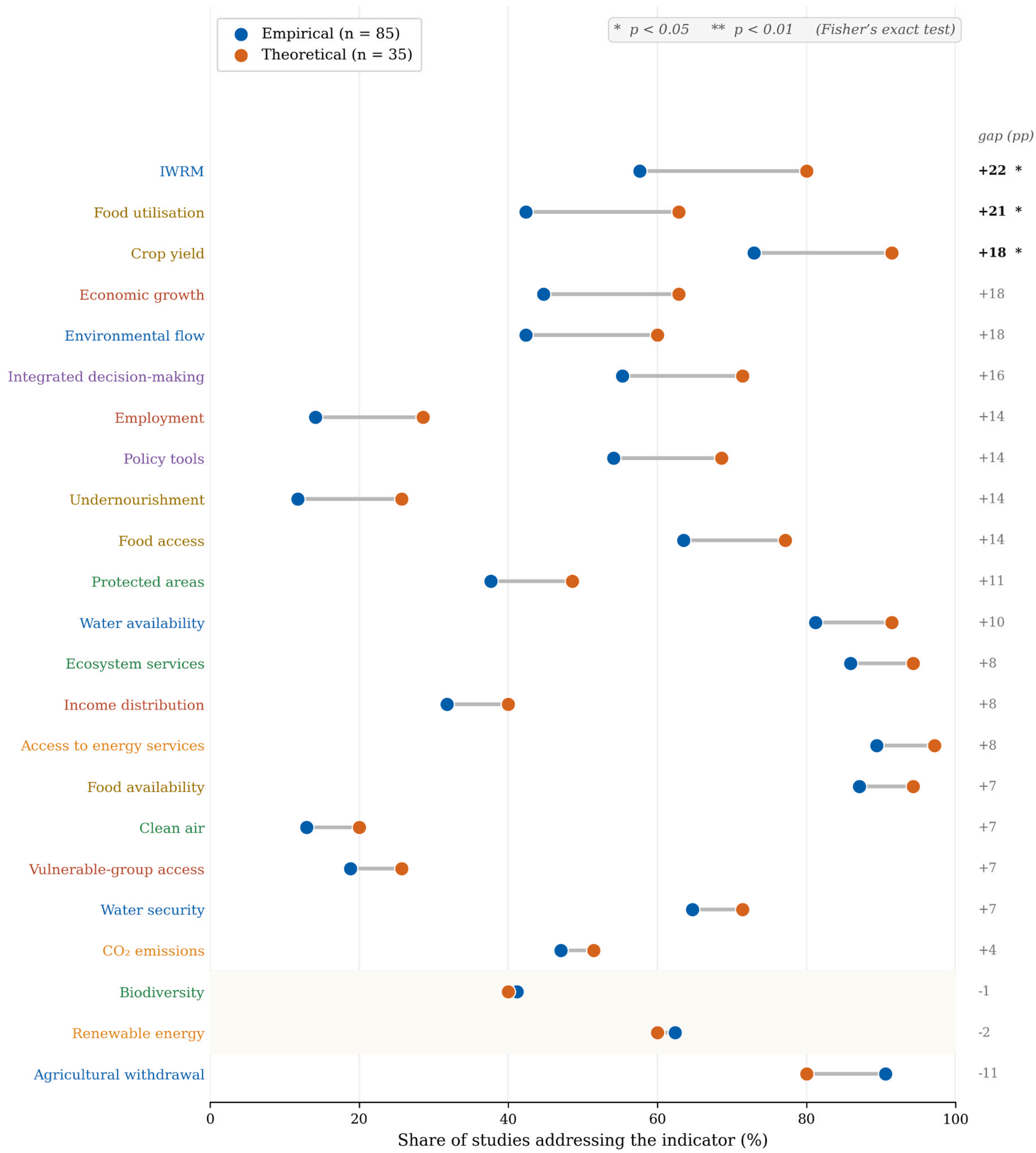

Fig. 14. Indicator coverage in theoretical (n = 35) versus empirical (n = 85) studies.

systematically in scope. Theoretical studies report a broader set of indicators per study, on average approximately 14 of the 23 substantive indicators, than empirical studies, which report approximately 12. This breadth is visible indicator by indicator in Fig. 14; in which each indicator is represented by two connected dots, one for the share of theoretical and one for the share of empirical studies that address it, with the indicators ordered from the widest theoretical-over-empirical gap at the top to the widest empirical-over-theoretical gap at the bottom and colored by pillar. Theoretical coverage is higher for the large majority of indicators, and the difference is most pronounced for IWRM implementation (80% versus 58%), crop yield (91% versus 73%), food utilization (63% versus 42%), food access (77% versus 64%), integrated decision-making (71% versus 55%), policy tools (69% versus 54%), the prevalence of undernourishment (26% versus 12%), and economic growth (63% versus 45%). Of these, only the gaps for IWRM implementation, food utilization, and crop yield are statistically significant under Fisher's exact test ($p < 0.05$); the remaining differences are consistent in direction but, given the smaller theoretical sample, individually inconclusive. Renewable energy consumption and the biodiversity index are the only indicators for which the two categories converge, while agricultural water withdrawal is the single indicator more common in empirical work (91% versus 80%), consistent with its measurement in field-based case studies.

The pattern reveals a structural theory-practice gap. Conceptual and framework-building studies aspire to holistic, multi-indicator coverage, including the governance, equity, and ecosystem-regulating dimensions that this study advocates, whereas empirical studies, constrained by data availability and by the tractability of coupled models, concentrate on a narrower biophysical-productive core (water availability, energy production, food availability, crop yield) and tend to omit precisely the socio-economic and ecological-integrity indicators that are hardest to measure. The divergence is therefore not merely descriptive; what the field can conceptualize it often cannot yet operationalize, and the governance and equity ambitions articulated in theoretical work outrun the empirical evidence base that would validate them. Closing this gap requires investment in the data infrastructure and in the coupled socio-hydrological-economic methods needed to render the peripheral dimensions empirically measurable, a point developed in the Discussion and Conclusion sections.

3.10. *Methodological quality of the included studies*

A design-specific critical appraisal of the 120 included studies, using the JBI checklists matched to each study design and the Mixed Methods Appraisal Tool for studies that combine designs, indicates a predominantly moderate evidence base. Thirty studies (25%) were rated high quality, sixty-one (51%) moderate, and twenty-nine (24%) low quality. Stratifying indicator coverage by quality tier shows that the concentration documented above is not an artefact of weaker studies: the most frequently reported indicators remain near-universal within the high-quality subset, namely energy production (87%), food availability (83%), ecosystem services (83%), and water availability (83%), whereas the least reported indicators stay marginal across every stratum, namely clean air (7% among high-quality studies), the prevalence of undernourishment (10%), and employment (10%). The core-and-periphery imbalance that characterizes the corpus as a whole therefore persists among the most methodologically robust studies, indicating that the headline findings of this review are not driven by the quality of the underlying evidence.

4. Discussion

In light of current challenges and inefficient resource management, the assessment of the WEFE Nexus framework and the elucidation of its pillars' interconnections are of major value. Furthermore, the enhancement of the Nexus context, by incorporating economic, societal, and governance dimensions, is presented in this review. The assessment of the selected articles demonstrates that research on the WEFE Nexus in agriculture has increased significantly in recent years, with a peak of publications in 2024–2025. This trend is reflecting the growing acceptance of the Nexus as a theoretical framework and a practical approach for confronting issues related to sustainability. The findings indicate both strengths and limitations in the conceptualization and operationalization of the various elements of the WEFE Nexus, which require additional discussion. To enhance the efficacy of the WEFE Nexus operationalization in the Mediterranean, it is suggested that the design goals for sustainable technology and natural resources are aligned more consistently. This would facilitate a more consistent approach for environmental protection while ensuring adequate food, water, and energy supply.

4.1. *Contribution and novelty relative to prior reviews*

Positioning these findings against the most recent systematic reviews summarized in Table 1 clarifies the specific contribution of the present work. The reviews by Meng et al. (2023), Shrimpton and Balta-Ozkan (2024), Morales-Garcia and Rubio (2023), and Solano-Pereira et al. (2025) each confine their analysis to the water-energy-food triad and explicitly omit the ecosystem pillar, while Chapagain et al. (2024) draw on a single database (Scopus) and adopt a water-centred perspective. Two of these reviews (Solano-Pereira et al., 2025; Morales-Garcia and Rubio, 2023) further restrict their evidence base to empirical case studies, thereby excluding the conceptual modelling that the present analysis shows to carry much of the field's governance and equity ambition. Against this backdrop, the present study makes three distinguishing moves: (*i*) it retains the ecosystem pillar as a full member of the core Nexus and evaluates it through four dedicated indicators; (*ii*) it integrates empirical and theoretical studies within a single corpus and contrasts them directly (Subsection 3.9); and (*iii*) it operationalizes the socio-economic and governance dimensions as coded indicators rather than treating them as background context. This indicator-level coding also distinguishes the present review from the mainly narrative Mediterranean and regional synthesis of Lucca et al. (2023) and Jain et al. (2023), which characterize the field and its policy gaps qualitative but do not quantify indicator coverage across a common corpus. The resulting core-and-periphery reading is not a restatement of prior reviews but an extension that quantifies, rather than merely asserts, the under-representation of ecosystem-integrity and equity concerns in agricultural WEFE research. This integration also reveals a structural theory-practice gap; the conceptual literature articulates the governance, equity, and ecosystem-integrity dimensions more fully than the empirical literature can yet measure them (Subsection 3.9), so what the field can conceptualize currently outruns what it can operationalize.

4.2. *Coverage and imbalance across the WEFE pillars*

Regarding the assessment of both the WEFE Nexus pillars and their indicators in the current paper, it illustrates the prioritization of efficiency and productivity in water, energy, and food elements, while giving less importance to ecological integrity. Concerning the “Water Pillar”, it dominates the reviewed literature, with a particular focus on “agricultural water withdrawal” and “water availability” indicators. This increased interest highlights agriculture’s critical role as the largest consumer of freshwater, particularly in the Mediterranean and arid regions. Substantial emphasis is also given to “water security” and “IWRM” in indicators, which is a sign of the necessity for systemic solutions that combine water with food production, energy generation, and ecosystem maintenance. Nevertheless, the depiction of environmental flow compliance is limited, indicating that ecological integrity is frequently neglected in favor of human needs and production demands. A plausible reason is that environmental flow is a regulating, non-productive service whose benefits are diffuse and long-term, so it is readily displaced by the immediately measurable withdrawal and availability indicators that dominate irrigation-oriented studies. Regarding the "Energy Pillar", the vast majority of the selected articles included "energy production" and "renewable energy consumption" indicators, emphasizing the necessity of transition toward clean energy sources. These outcomes reflect a high correlation with climate change mitigation strategies and the accomplishment of sustainable energy systems. However, the indicator "CO_2 emissions from energy use" has not yet received the required importance, given its strong impact on the environment, economy, and society. The limited assessment of this indicator leads to insufficient and imprecise research findings, which exclude both the basic factor of climate change and the cascading repercussions on WEFE elements. Subsequently, the "Food Pillar" is widely analyzed through the lenses of "food availability" and "crop yield" indicators within the selected articles, confirming their great importance in food security issues. Conversely, the criteria for "food access", "food utilization", and "undernourishment" are often underestimated, leading to an inadequate and non-holistic depiction of food security because nutrition, distribution, and equity are neglected against productivity. Lastly, the "Ecosystem Pillar" is the least incorporated in the selected articles, with the indicators related to "biodiversity", "protected areas", and "clean air" to being highly neglected. Nonetheless, "ecosystem services" indicator is included as a major topic in the reviewed articles, as it is acknowledged for its significant impact on resource sustainability and agricultural productivity. The inadequate inclusion of the three criteria into the "Ecosystem Pillar" indicates the insufficient incorporation of the "Ecosystem Pillar" into the WEFE Nexus framework. Fostering biodiversity protection and air quality consciousness would strengthen the Nexus perspectives and balance the conflicts between productivity and ecological stability.

4.3. The ecosystem pillar as the foundation of the core Nexus

The results expose a paradox at the heart of the ecosystem pillar: ecosystem services are among the most frequently cited indicators in the entire review (88%), yet the biodiversity index and protected areas appear in only 41% of studies, and clean air in 15%. This is not a minor inconsistency but an indication of how ecosystems are conceptualized in Nexus research. Ecosystem services are typically invoked in their instrumental, provisioning form, such as pollination, carbon sequestration, and nutrient cycling that directly support crop production, and are therefore easy to fold into a productivity narrative (Petsch et al., 2023). Biodiversity, protected areas, and air quality, by contrast, are intrinsic or regulating attributes whose value is diffuse, long-term, and not immediately monetizable in yield terms (Pulido-Chadid et al., 2023); they require dedicated ecological data and offer no short-run productive payoff, so they are quietly dropped from allocation-oriented models. The near-zero association between ecosystem services and clean air reported in Subsection 3.8 confirms that the pillar is being represented through its production-supporting facets while its regulating and biodiversity-conservation facets are neglected.

Correcting this selective inclusion matters because the ecosystem pillar is not one sector among four but the biophysical substrate on which the other three depend. Water availability and quality are regulated by catchment vegetation, wetlands, and soil structure; agricultural productivity rests on pollination, pest regulation, and nutrient cycling; and the renewable-energy transition, through hydropower and bioenergy, is itself constrained by ecological flow and land-use limits. Treating ecosystem integrity as the foundation rather than a peripheral co-benefit reframes the Nexus; degradation of regulating services does not merely reduce an environmental score, it undermines the water, energy, and food pillars simultaneously and non-linearly. A framework that measures ecosystems only through their provisioning services therefore systematically overstates the resilience of the whole system. Restoring the biodiversity, protected-area, and air-quality indicators to the core assessment, and coupling them to the water, energy, and food indicators as in Subsection 3.8, is necessary for the Nexus to represent the biophysical limits that ultimately bound long-term productivity.

4.4. The socio-economic and governance dimensions and the Core-Peripheral structure

The findings of this study highlight the need to encompass the economy, society, and government as main elements of the WEFE Nexus perspective. After the examination of these three elements as additional pillars of the Nexus framework, it was indicated their crucial role in efficient Nexus management. Abera et al. (2024) underline the necessity of including the economic element into the WEFE Nexus framework, as its absence results in many scientific gaps regarding the holistic evaluation of the Nexus performance. In addition, understanding and assessing the economic factors involved in addressing WEFE challenges contributes to balancing the conflicts that threaten sustainable development. Another study conducted by Garau et al. (2025a) revealed that the WEFE Nexus is directly affected by socio-economic factors, and all four elements of the Nexus are defined by the economic viability of the agricultural sector. In the same study, it is underscored that the introduction of society and economy into the Nexus context directly affects sustainability issues, as well as resource management. An important insight from Besser et al. (2025) highlights the central role of the social aspect and community-based approaches as innovative methods of expanding the Nexus framework by considering flexible and adaptive strategies. According to Sood et al. (2019) research, the utilization and administration of resources, as well as the synergies and trade-offs that exist among the systems, are the outcomes of socio-economic and governance aspects. The demand for resources among various sectors is an example of a socio-economic component. Governance factors, on the other hand, include the laws and regulations that are in place for the distribution and use of resources, as well as the formal and informal institutions that have an impact on the management of natural resources. It is vital to develop a holistic approach that can integrate these biophysical, socio-economic, and governance components of the WEFE Nexus to comprehend the complex interconnections within the WEFE systems. These systems are examples of both natural events and a social and economic structure (Fürst et al., 2017; Laspidou et al., 2020). As mentioned above, Mooren et al. (2025) concurs with the emphasis on Nexus governance by highlighting the interconnectedness of these domains and the necessity for an integrated governance structure. Their paper focused on the ecosystem-centered WEFE Nexus governance approach, which puts ecosystems at the center of resource management to assure that practices are sustainable. This method deals with problems in governance, like making sure policies are consistent, getting stakeholders to work together, and deciding how to use resources. The goal of the approach is to promote policy consistency, stakeholder co-creation, and long-term resource management across all levels and disciplinaries.

With a view to the aforementioned, to establish a holistic WEFE Nexus framework, it is necessary to expand beyond the biophysical interdependencies of the "Core Nexus" (which include water, energy, food, and ecosystem elements) and integrate the wider socioeconomic and governance-related pillars that define the peripheral Nexus. The "Core Nexus" approach emphasizes that water, energy, food, and ecosystems are not separate entities but are highly interconnected and interdependent systems (Vrachioli et al., 2025). Their complex associations indicate that actions or pressures on one system inevitably affect the others, resulting in both synergies and trade-offs. These four resource systems are interdependent, interact, and compete for resources (Li et al., 2019). While the "Core Nexus" focuses on the direct and indirect interdependencies between water, energy, food, and ecosystems, the concept of a "peripheral WEFE Nexus" extends this understanding to include the broader external drivers, influences, and outcomes that interact with and shape the "Core Nexus" pillars (Garau et al., 2025b). As illustrated in Fig. 15, this can be represented as an

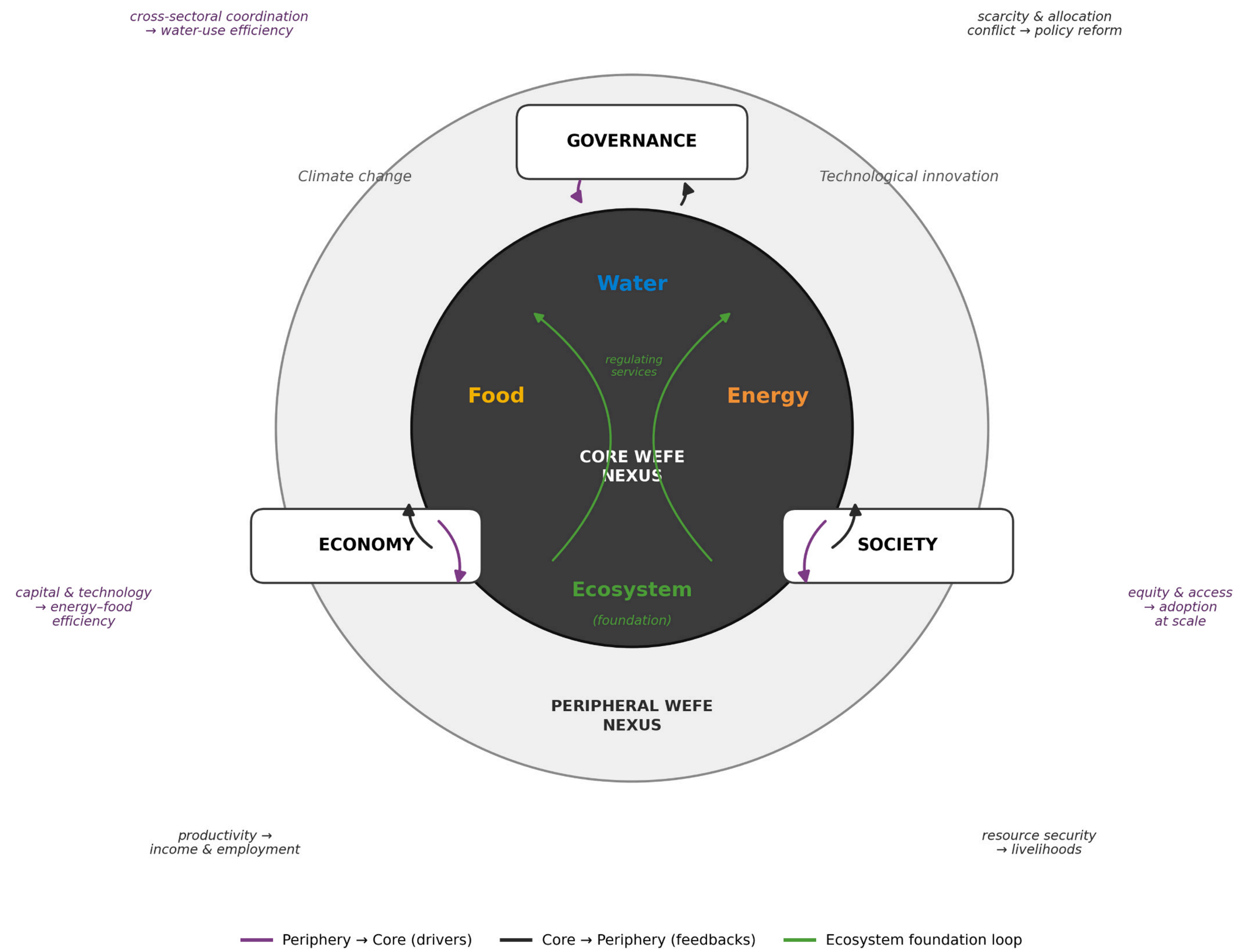

Fig. 15. Interaction mechanisms and feedback loops between the Core WEFE Nexus and the Peripheral WEFE Nexus (WEFE+). Arrows denote the direction of influence: periphery-to-core drivers (governance coordination, capital and technology, equity and access), core-to-periphery feedback (productivity, incomes and employment, resource-security and allocation conflict), and the ecosystem foundation loop through which regulating services underpin the water, energy, and food pillars.

inner circle (Core Nexus), which depicts the direct interactions, synergies, and trade-offs between water, energy, food, and ecosystems, and an outer Circle (Peripheral Nexus), which illustrates the surrounding factors and sectors that significantly impact the "Core Nexus" and are, in turn, affected by its dynamics. These external factors could be social and economic aspects, governance and institutional factors, climate change impacts, technological innovations, and the agricultural sector. In essence, the peripheral WEFE Nexus emphasizes that addressing resource security and sustainability issues requires concentrating beyond the immediate interactions of water, energy, food, and ecosystems. It necessitates understanding the broader societal, economic, and political context in which these interactions occur and developing integrated solutions that account for these external influences. Particularly, the strategic implementation and assessment of the "Peripheral WEFE Nexus", emphasizing social components, policy processes, and the incorporation of metrics, significantly influences both the impetus Nexus and Nexus thinking (Covarrubias, 2019; Moss and Hüesker, 2019; Voelker et al., 2022). Huang et al. (2023) concluded that the external elements of the "Peripheral WEFE Nexus" impact the "Core Nexus" pillars evaluation, resulting in the fact that these two dynamic systems are interdependent and interconnected. Furthermore, the "Peripheral WEFE Nexus" is regarded as a key factor in regional and local fluctuations; therefore, most studies have concentrated on its contribution to region-specific differences (Huang et al., 2021). The aforementioned studies depict the robust contribution of the "Peripheral WEFE Nexus" to both "Core Nexus" management and improving agricultural sector productivity as well as accelerating its transition to sustainable development (Cui et al., 2024). The present study focuses solely on the social, economic, and governance pillars within the "peripheral WEFE nexus" components, in conjunction with water, energy, food, and ecosystem elements, while acknowledging the importance of the remaining peripheral elements as future objectives for reinforcing the efficacy of the WEFE Nexus framework.

4.5. Interaction mechanisms and feedback loops between the core and the periphery

The cross-cutting analysis in Subsection 3.8 provides an empirical vantage point on how the reviewed literature currently treats these interactions, and the picture is uneven. Associations between indicators are concentrated within pillars rather than across them; the socio-economic pillar is the most tightly coupled internally (mean phi = 0.42), driven by the strong co-occurrence of economic growth with income distribution (phi = 0.72), yet coupling across pillars boundaries is consistently weak, and the ecosystem regulating and equity indicators in particular remain largely decoupled from the biophysical-productive core. This study therefore encodes the interdependence that defines the Nexus only selectively, expressing it clearly among the biophysical-productive indicators while leaving the links to regulating services and social equity largely implicit. This selective encoding is itself the gap that a Nexus approach is meant to close, since interactions that are strong in reality but rarely examined together in the literature cannot be deliberately managed until the channels linking the core and the periphery are made explicit.

Beyond identifying which dimensions belong to the core and which to the periphery, an integrated framework has to specify how they interact, and the relationship is bidirectional. In the periphery-to-core direction, governance arrangements condition the efficiency of the core; cross-sectoral collaboration and integrated decision-making align the abstraction, energy-pricing, and land-use rules that are otherwise set by separate ministries, and this coordination is what allows, for instance, the joint scheduling of irrigation supply and energy demand that raises agricultural water-use efficiency (de Vito et al., 2017; Do et al., 2020). Economic growth acts on the core through a technology channel: rising public and private capital finances the precision-irrigation, solar--pumping, and water-treatment infrastructure that reshapes the energy-food linkage, substituting capital and information for water and conventional energy (Abdelhamid et al., 2025; KC et al., 2025). Social conditions, in particular income distribution and vulnerable-group access, determine whether these efficiency gains are adopted at scale or captured only by better-resourced producers, thereby feeding back on the productive performance of the core. In the core-to-periphery direction, the state of the core reshapes its periphery: water scarcity and crop failure depress agricultural incomes and employment, widen distributional gaps, and raise the political salience of allocation rules, which in turn drives governance reform; ecosystem degradation erodes the regulating services, such as pollination, water purification, and flow regulation, on which the productivity of the other three core pillars ultimately depends, closing a reinforcing loop between ecological decline and resource insecurity. These causal directions and feedback loops are summarized in Fig. 15, which depicts the static core-periphery representation with the dynamic interactions that link the two layers.

4.6. Widening the governance and social lens

The governance and social pillars in this study were operationalized through a compact set of indicators, and the analysis makes clear that they should be widened. On the governance side, the two coded indicators, integrated decision-making and policy tools/multi-sectoral collaboration, subsume functions that merit separate treatment: policy implementation and enforcement as distinct from policy design, regulatory and licensing mechanisms for abstraction, emissions, and land use, and structured stakeholder engagement. The reviewed articles repeatedly point out these functions, for example the engagement of water, energy, agriculture, and environment ministries as active entities (Sievers et al., 2025), the translation of research results into policy action (Garau et al., 2025a), and adaptive governance for social resilience (Sofiyah et al., 2025), yet the field seldom measures whether policies are implemented and enforced rather than merely adopted. On the social side, the vulnerable-groups indicator explicitly encompasses women and, in several studies, education and livelihood conditions (Rosenheim et al., 2024), yet gender and educational attainment are not analysed as standalone dimensions despite their well-established mediating role in resource access and technology adoption. Disaggregating governance into design, implementation, and enforcement, and social equity into gender, education, and income, would convert these currently latent concerns into measurable components of the peripheral Nexus and is identified among the future research priorities.

4.7. Regional specificity and cross-scale governance in the Mediterranean

The generalizability of Nexus conclusions is bounded by scale and by region, two dimensions that the reviewed studies rarely address explicitly. The Mediterranean concentrates the tensions the framework is meant to resolve: a semi-arid, warming climate with high interannual rainfall variability; agriculture as the dominant water user; energy-intensive conveyance, pumping, and, increasingly, desalination; and fragmented, multi-level institutions that split competence over water, energy, and agriculture across ministries and administrative tiers (Soares and Lima, 2022). Case studies from the region make these pressures concrete: the over-abstraction of groundwater and shrinking of the Urmia Lake basin (Bakhshianlamouki et al., 2020), the difficulty of sustaining ecological flow in the Pinios River Basin under rising temperatures (Malamataris et al., 2023), and biodiversity loss and water stress on Tinos Island addressed through nature-based solutions (Galani et al., 2025). These are not incidental settings but illustrations of a distinctively Mediterranean coupling of climatic volatility, agricultural water dependence, and institutional fragmentation that differs markedly from the humid, industrial, or transboundary-river contexts studied elsewhere.

These same cases show that WEFE interactions are inherently cross-scale yet are typically analyzed at a single scale, a structure summarized in Fig. 16. Field- and farm-level decisions on crop choice, irrigation technology, and energy source aggregate into basin-level water balances and national energy and food policy, while climate signals operate at regional scale; this upward aggregation of local decisions into basin and national outcomes is matched by downward governance instruments (licensing, ecological-flow standards, and incentives) that constrain local action. A measure that improves efficiency at one scale can shift burdens to another, represented by the lateral burden-shift arrow, as when farm-level groundwater pumping secures local yields while depleting a shared aquifer; Mediterranean climate volatility, in turn, acts as an external driver on all scales, and the three representative cases are positioned at the scale where each pressure is most acute. Governing this vertical interdependence requires nesting local abstraction and licensing rules within basin-scale allocation plans and national Nexus strategies, embedding ecological-flow standards directly in irrigation-licensing regimes, and creating coordinating bodies that reconcile the ministries of water, energy, agriculture, and environment. Aligning consistent design goals for sustainable technology and natural-resource management across these scales, rather than optimizing each scale in isolation, is the central governance challenge for operationalizing the WEFE Nexus in the Mediterranean and comparable semi-arid regions.

4.8. Methodological limitations of the reviewed literature

A critical reading of the reviewed evidence also exposes recurrent methodological limitations in the WEFE literature itself, beyond the thematic gaps in indicator coverage. A large share of the empirical articles relies on static, equilibrium-based optimization that represents resource allocation at a single planning horizon and does not endogenize the interannual variability, extremes, and deep uncertainty that climate change imposes on Mediterranean and semi-arid agriculture. Where dynamic representations are adopted, such as the system-dynamics model of the Urmia Lake basin (Bakhshianlamouki et al., 2020) or the coupled WEAP-MODFLOW framework applied to irrigation districts (Zhang et al., 2024), they remain scenario-specific and calibrated to a single basin, so their parameters and conclusions do not transfer readily to other contexts. This reliance on single-site case studies, combined with heterogeneous system boundaries and indicator definitions, limits the external validity and comparability of findings across the field and helps explain why cumulative, generalizable conclusions about WEFE trade-offs remain scarce. Explicit treatment of uncertainty, multi-basin and cross-scale designs, and the reporting of transferable model parameters would materially strengthen the evidence base.

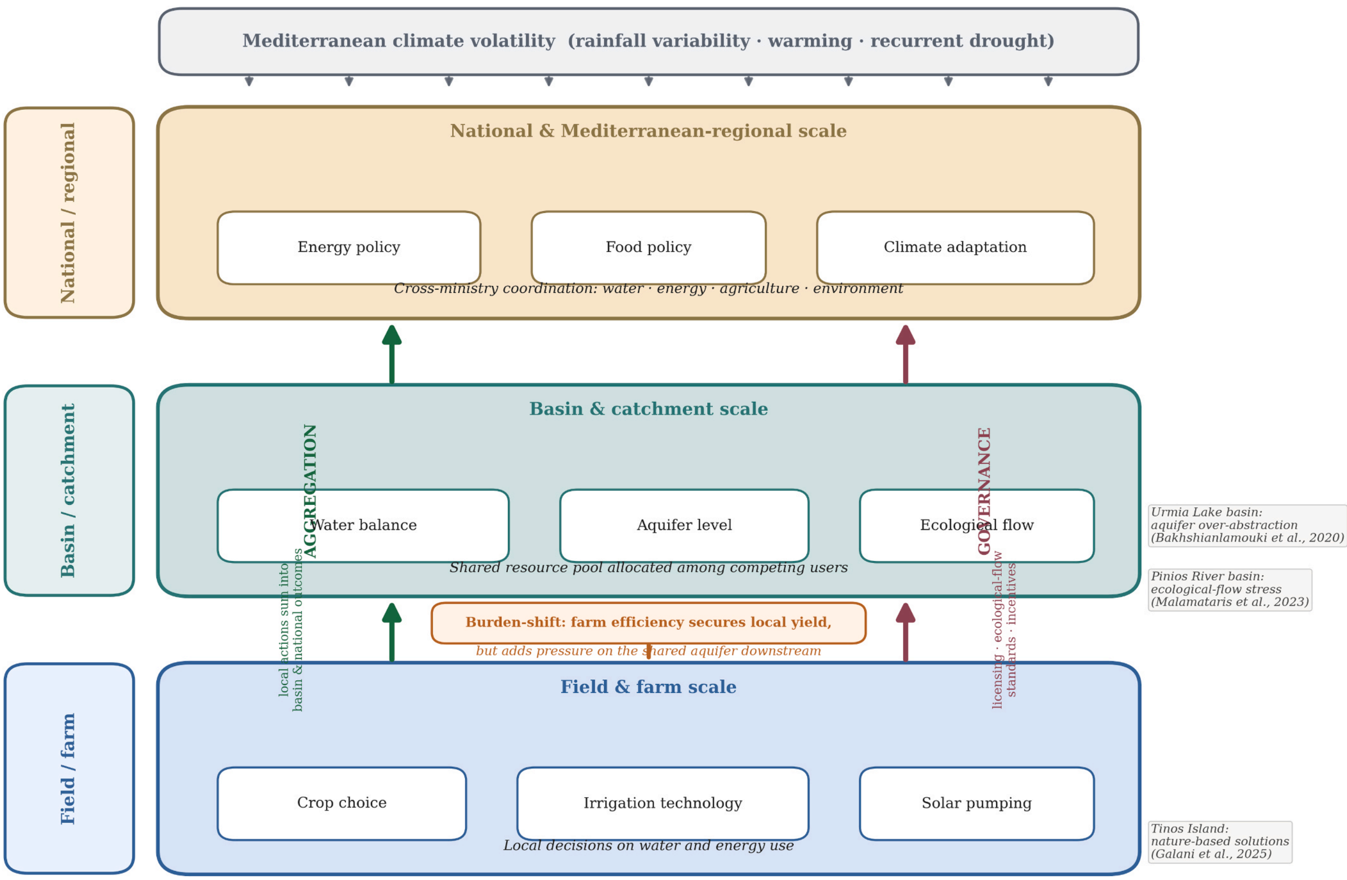

Fig. 16. A cross-scale governance of WEFE governance in the Mediterranean. WEFE interactions are nested at three scales: i) field and farm, ii) basin and catchment, and iii) national and Mediterranean-regional.

4.9. Practical implications for agricultural water management

A key point to consider it that this study yields several actionable implications for irrigation practitioners, water authorities, and policymakers. In an irrigated system, the most consequential Nexus trade-offs are between water and energy (cheaper pumping can induce additional abstraction) (Karri et al., 2026; Qian et al., 2026), between local and shared resources (farm-level groundwater pumping secures individual yields while depleting a common aquifer) (Haldar et al., 2026), between irrigation expansion and ecological-flow maintenance (Cheng et al., 2026), and between short-run productivity and equitable access for smallholders (Xu et al., 2026). The governance processes that the reviewed articles identifies as most effective for managing these trade-offs are integrated water-energy-agriculture decision-making bodies, irrigation-licensing regimes that embed enforceable ecological-flow thresholds and volumetric abstraction caps, and incentive structures tied to water- and energy-use efficiency rather than to volumetric consumption (Dhar, 2025; Soltani et al., 2023). Particularly, for practitioners, the strong water-energy coupling identified here argues for demand-side irrigation strategies that economize water and energy jointly: deficit and precision irrigation, soil-moisture- and sensor-based scheduling, and the pairing of solar-powered pumping with water-saving delivery so that cheaper energy does not simply induce additional abstraction (Abdelhamid et al., 2025; Kleftodimos et al., 2024). For water authorities, the under-representation of environmental flow compliance and the fragmentation of the ecosystem indicators point to concrete instruments: embedding enforceable ecological-flow thresholds and volumetric abstraction caps in irrigation-licensing regimes, metering and monitoring groundwater use, and integrating treated-wastewater reuse into basin water budgets to relieve pressure on freshwater while advancing circularity (Demir and Alp, 2025). For policymakers, the analysis supports coordinating water, energy, and agricultural policy through integrated decision-making bodies, directing incentives and subsidies towards water- and energy-efficient technologies rather than towards volumetric consumption, and designing support so that smallholders and low-income farmers can access efficient irrigation and clean-energy options on equitable terms (Falchetta et al., 2023; Pastori et al., 2021). Common to these recommendations is the principle that efficiency gains in one resource must be accompanied by safeguards that prevent burden-shifting to another resource, to a downstream user, or to the ecosystem, which is the operational essence of a Nexus approach to agricultural water management.

These observations motivate extending the framework beyond its four biophysical pillars. The reviewed articles shows that water, energy, food, and ecosystem systems do not operate in isolation but are conditioned by social, economic, and policy factors that the frequency and co-occurrence analyses repeatedly surface at the margins of the corpus (Besser et al., 2025). Retaining the tightly coupled “Core WEFE Nexus” while making these external influences explicit yields a peripheral WEFE Nexus, and their combination is formalized here as the “WEFE + Nexus”, in which the plus sign denotes the socioeconomic conditions, governance and institutional arrangements, climate-change pressures, and technological drivers that condition core dynamics (Fig. 15). Framing the Nexus in this way is not merely terminological: it aligns the analytical boundary of the framework with the drivers that the reviewed studies identify as decisive for sustainability, poverty alleviation, and cross-sectoral coherence, and it clarifies why governance and equity indicators, although peripheral in current coverage, are central to Nexus performance (Hashemi, 2025; MedECC, 2024).

In comparison with previous research findings, the Nexus approach is necessary but, as currently practiced, not yet sufficient. Advancing resource efficiency and sustainability requires coupling biophysical dynamics with the economic, social, and governance dimensions that the reviewed literature still treats unevenly (Sarbijan et al., 2025), and the persistence of within-pillar clustering in the co-occurrence structure indicates that genuine cross-sectoral integration, rather than the parallel reporting of indicators, is where the greatest analytical gains remain. The concepts of a peripheral WEFE Nexus and a WEFE + Nexus provide a structured way to incorporate these additional dimensions and external variables, and they set the agenda for the conclusions and future directions developed in the next section.

5. Conclusions and further directions

This study examined the WEFE Nexus framework by implementing a SLR, in order to clarify how interconnected resources are conceptualized and operationalized in agricultural research. The WEFE Nexus framework has emerged as a fundamental framework for confronting resource challenges, enhancing sustainability, and building resilience in vulnerable agricultural systems; its central premise is the explicit recognition and joint management of interdependencies among resources that are conventionally governed in isolation, which support policy coherence and holistic assessment. Two gaps motivated this study: the ecosystem pillar, although constitutive of the framework, is frequently absent from applied Nexus assessments, and no prior review has concurrently operationalized the economic, societal, and governance dimensions alongside the four biophysical pillars within a single coded corpus. Integrating biophysical dynamics with economic, governance, and societal elements is therefore the principal contribution of this study, providing the basis for a more complete reading of cross-sectoral interdependencies and for adaptation strategies oriented toward long-term resilience.

Methodologically, this review followed the PRISMA guidelines across the identification, screening, and selection stages, prioritizing the transparency, consistency, and reproducibility that distinguish a systematic review from a narrative one. The initial search returned 16,497 records (16,240 from Scopus and 257 from Web of Science), which a VOSviewer co-occurrence analysis resolved into three thematic clusters: agriculture and climate change; sustainable development, sustainability, and ecosystems; and water, energy, water management, and their economic and social effects. After deduplication and the sequential application of the eligibility criteria, 120 articles published between 2015 and 2025 were retained, spanning both empirical and theoretical work and covering the search window up to 25 August 2025. Seven thematic categories and twenty-six criteria were derived, of which twenty-three are substantive resource indicators used in the quantitative synthesis, while the remaining criteria describe general study attributes.

The synthesis confirmed a strong and uneven concentration of attention on the water, energy, and food pillars. A small set of indicators is near-universal, namely energy production (92%), food availability (89%), and agricultural water withdrawal (88%), whereas many others remain marginal. Within the water pillar, agricultural withdrawal, water availability, and water security dominate, while Integrated Water Resource Management and environmental-flow compliance receive markedly less attention; within the energy pillar, energy production leads, followed by renewable-energy consumption, with CO_2 emissions comparatively neglected despite their centrality to climate impacts; and within the food pillar, food availability and crop yield prevail over food access, food utilization, and the prevalence of undernourishment. A pairwise co-occurrence analysis based on phi coefficients showed that indicator associations concentrate within pillars rather than across them, and that several cross-pillar links, including the frequently invoked water-energy interface, are weak or statistically absent. This structural finding indicates that the integrative ambition of the Nexus is, in practice, only partially realized in the reviewed literature.

The ecosystem pillar remains comparatively underdeveloped, in part because it was incorporated into the framework more recently. Ecosystem services is the only ecosystem indicator that is broadly represented, appearing in 88% of the reviewed studies (106 of 120), whereas terrestrial and freshwater protected areas and the biodiversity index are each addressed in roughly two fifths of the corpus (41%), and clean air in only 15%. The frequent invocation of ecosystem services to justify productivity gains, set against the neglect of biodiversity, protected areas, and air quality, risks eliding the biophysical limits on which long-term resilience depends. Because these ecological attributes underpin the water, energy, and food systems, the ecosystem pillar is better understood as the foundation of the core Nexus than as an optional addition, and its selective coverage is one of the clearest imbalances that the review identifies.

The peripheral dimensions of economy, society, and governance are gaining ground but remain unevenly operationalized. Economic growth (50%) and income distribution (34%) are the most frequently coded socioeconomic indicators, whereas employment (18%) and access to resources for vulnerable groups (21%) are among the least addressed across the entire corpus. Governance is often discussed, with integrated decision-making (60%) and policy tools (58%) moderately represented, yet it is seldom coupled to the biophysical indicators as a measurable component of Nexus performance. A contrast between the thirty-five theoretical and eighty-five empirical studies further revealed a coverage gap, in which conceptual work articulates the governance, equity, and ecosystem dimensions more fully than empirical work is able to measure them. These observations support the study's conceptual proposal of a tightly coupled core Nexus of water, energy, food, and ecosystem, surrounded by a peripheral WEFE Nexus of socioeconomic conditions, governance and institutions, climate change, and technological drivers, formalized as an emerging WEFE + Nexus.

Taken together, these results carry direct implications for agricultural water management. The most consequential trade-offs in irrigated systems arise between water and energy, between individual and shared resources, between irrigation expansion and ecological-flow maintenance, and between short-run productivity and equitable access, and the evidence indicates that they are best managed through integrated water-energy-agriculture decision-making bodies, licensing regimes that embed enforceable ecological-flow thresholds and abstraction caps, and incentives tied to water- and energy-use efficiency rather than to volumetric consumption. These challenges are especially acute in Mediterranean and other semi-arid settings, where climatic volatility, energy-intensive water infrastructure, and institutional fragmentation converge. The WEFE framework is therefore evolving toward deeper ecosystem integration and fuller recognition of socioeconomic and governance interdependencies, but its comprehensive operationalization will be achieved only by embedding economic analysis, social equity, and adaptive, cross-scale governance within a common analytical structure that transcends siloed resource management.

Several limitations qualify these findings. First, this study is deliberately restricted to the agricultural sector and to peer-reviewed journal articles indexed in Scopus and Web of Science; excluding the industrial, urban, and domestic Nexus, grey literature, and the reports of international organizations may under-represent applied and policy-oriented knowledge and bias the evidence toward academic framings. Second, retrieval was limited to the title, abstract, and keyword fields and to the terms and synonyms listed in Appendix A, so studies that address WEFE interactions without using this vocabulary, or that treat a pillar implicitly, may have been missed. Third, the synthesis distinguishes empirical from theoretical studies but now incorporates a formal, design-specific methodological quality appraisal of each included study, reported in the Results Section as a quality distribution and a quality-stratified synthesis; the appraisal was nonetheless conducted without formal inter-coder reliability testing, and because no single instrument fits every design in the corpus, the resulting quality tiers should be read as indicative rather than definitive. Fourth, the coding scheme captures twenty-six criteria, of which twenty-three are substantive resource indicators, across seven categories but necessarily compresses complex constructs, particularly within the governance and social pillars, into a limited number of binary indicators, which understates finer distinctions such as policy enforcement, gender, and education. Fifth, the binary coding of indicator presence records whether a topic is addressed but not how substantively or with what effect size, and the coding, although guided by an explicit framework, carries an irreducible element of interpretive judgement; formal inter-coder reliability testing was not performed, which introduces a degree of uncertainty into the reported frequencies and associations. These sources of uncertainty warrant caution in reading small differences between indicators as substantive. These constraints bound the generalizability of the conclusions to peer-reviewed, agriculture-focused WEFE research and should be read alongside the interpretive, rather than confirmatory, nature of a systematic review.

The analysis points to specific, actionable research priorities. On evidence quality, this review now applies a design-specific appraisal and reports quality-stratified findings that show a predominantly moderate evidence base whose core coverage patterns hold across all quality tiers, so the main conclusions of the review are robust to study quality; the outstanding priority is to extend bibliometric mapping with temporal (time-sliced) co-occurrence and author- and institution-level collaboration networks to trace how the field is evolving and where it is siloed. On the ecosystem pillar, priority questions include how the biodiversity, protected-area, and air-quality indicators can be measured and coupled to water, energy, and food outcomes, and how ecological-flow requirements can be endogenized as objectives rather than treated as constraints in allocation models. On methods, the field needs dynamic, uncertainty-aware, and cross-scale models that link the farm, basin, and national scales and report transferable parameters, moving beyond static single-basin optimization. On the peripheral dimensions, future coding frameworks should disaggregate governance into design, implementation, and enforcement, and social equity into gender, education, and income, and should test empirically the causal and feedback linkages summarized in Fig. 15, for example between renewable-energy adoption and agricultural water-use efficiency, or between income distribution and vulnerable-group access to Nexus resources. Advancing these questions in the Mediterranean and other semi-arid regions, where climatic volatility and institutional fragmentation are most acute, would do most to convert the WEFE + Nexus from a conceptual advance into an operational tool for agricultural water management.

Overall, this review shows that the integrative ambition of the WEFE Nexus is, in the agricultural literature, only partially realized; attention concentrates on the water, energy, and food pillars, indicator associations cluster within rather than across pillars, and several cross-pillar links, including the water-energy interface, are weak or statistically absent. The ecosystem pillar, although foundational to the framework, is represented almost entirely through ecosystem services, while biodiversity, protected areas, and air quality remain marginal. The economic, social, and governance dimensions, in turn, are more fully conceptualized than they are yet measured. The principal contribution of this study is to quantify these imbalances within a single coded corpus and to formalize a core-and-periphery reading, the WEFE + Nexus, that treats ecological integrity and equity as constitutive of the framework rather than peripheral to it. Converting this conceptual advance into an operational tool for agricultural water management will require coupling the currently neglected ecosystem and equity indicators to biophysical outcomes within dynamic, cross-scale models, and situating water, energy, food, and governance decisions in a common analytical structure. Progress on these fronts, most urgently in the Mediterranean and other semi-arid regions where climatic and institutional pressures converge, will determine whether the WEFE Nexus matures from an organizing concept into a rigorous basis for sustainable resource management.

CRediT authorship contribution statement

Dimitra Despoina Tosiliani: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marios Vasileiou:** Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. **Leonidas Sotirios Kyrgiakos:** Formal analysis, Methodology, Writing – review & editing. **Fadi Abdelradi:** Formal analysis, Visualization, Writing – review & editing. **Christina Kleisiari:** Formal analysis, Methodology, Writing – review & editing. **Kyriaki Kechri:** Visualization. **Georgios Kleftodimos:** Project administration, Validation, Visualization, Writing – review & editing. **George Vlontzos:** Funding acquisition, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Funding

This work has received funding from the PRIMA program and European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 2341. Acronym: DIONYSUS.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received funding from the PRIMA program and European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 2341. Acronym: DIONYSUS.

Appendix A

Scopus database:

TITLE-ABS-KEY (WEFE NEXUS) OR TITLE-ABS-KEY (WATER ENERGY FOOD ECOSYSTEM NEXUS) AND TITLE-ABS-KEY (AGRICULTURE) AND PUBYEAR > 2014 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")).

WoS database:

(TS=(WEFE NEXUS) OR TS= (WATER ENERGY FOOD ECOSYSTEM NEXUS) AND TS= (AGRICULTURE)) and 2015–2025 (Publication Years) and Article (Document Types).

Data availability

The data that support the findings of this study are available within the article.

References

Abdelhamid, M.A., Abdelkader, T.Kh, Sayed, H.A.A., Zhang, Z., Zhao, X., Atia, M.F., 2025. Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture. Sci. Rep. 15 (1), 11761. https://doi.org/10.1038/s41598-025-94251-3.

Abera, W., Getaneh, Y., Balcha, Y., Assefa, T., Mulatu, C.A., Ebrahim, G.Y., Tesfaye, M., Dawit, M., Abebe, W.B., Taye, M.T., 2024. Framing water–energy–food–ecosystem (WEFE) nexus interactions in the Tana-Beles Sub-basin of Ethiopia. Sustain. Nexus Forum 32 (1), 2. https://doi.org/10.1007/s00550-024-00540-2.

Adorno, T.W., Tiedemann, Rolf, Nicholsen, S.Weber, & Kottman, P.A.. (2019). *Notes to literature*. https://books.google.com/books/about/Notes_to_Literature.html?hl=el&id=HIp-DwAAQBAJ.

Al-Saidi, M., Elagib, N.A., 2017. Towards understanding the integrative approach of the water, energy and food nexus. Sci. Total. Environ. 574, 1131–1139. https://doi.org/10.1016/j.scitotenv.2016.09.046.

Amorim-Maia, A.T., Olazabal, M., 2025. Beyond adjustment: a new paradigm for climate change adaptation in a complex world. Glob. Environ. Change 93, 103027. https://doi.org/10.1016/j.gloenvcha.2025.103027.

Araujo, H.F.P. de, Machado, C.C.C., Pareyn, F.G.C., Nascimento, N.F.F., do, Araújo, L.D. A., Borges, L.A. de A.P., Santos, B.A., Beirigo, R.M., Vasconcellos, A., Dias, B., de, O., Alvarado, F., Silva, J.M.C. da, 2021. A sustainable agricultural landscape model for tropical drylands. Land. Use Policy 100, 104913. https://doi.org/10.1016/j.landusepol.2020.104913.

Avgoustaki, D.D., Xydis, G., 2020. Indoor vertical farming in the urban nexus context: business growth and resource savings. Sustainability 12 (5), 1965. https://doi.org/10.3390/su12051965.

Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P., Sušnik, J., 2020. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. Sci. Total. Environ. 708, 134874. https://doi.org/10.1016/j.scitotenv.2019.134874.

Barker, T.H., Stone, J.C., Sears, K., Klugar, M., Leonardi-Bee, J., Tufanaru, C., Aromataris, E., Munn, Z., 2023. Revising the JBI quantitative critical appraisal tools to improve their applicability: an overview of methods and the development process. JBI Evidence Synthesis, 21 (3), 478–493. https://doi.org/10.11124/JBIES-22-00125.

Basumatary, B., Yuvaraj, M., Verma, N.K., Verma, M.K., 2025. Mapping of the selected literature on robotic technology applications in libraries based on Scopus database: a subjective computational review. Libr. Hi Tech. 43 (1), 224–248. https://doi.org/10.1108/LHT-02-2023-0031.

Bateni, S.M., Rezaie, F., Tran, T.T.K., Jun, C., Heggy, E., Knievel, J.C., Menzel, A., Matin, M.A., Zarei, A., Lakshmi, V., Madani, K., 2025. Sustainability Nexus AID: wildfire. Sustain. Nexus Forum 33 (1), 11. https://doi.org/10.1007/s00550-025-00569-x.

Bell, A., Matthews, N., Zhang, W., 2016. Opportunities for improved promotion of ecosystem services in agriculture under the Water-Energy-Food Nexus. J. Environ. Stud. Sci. 6 (1), 183–191. https://doi.org/10.1007/s13412-016-0366-9.

Besser, H., Mahjoubi, A., Theodotou Schneider, X., Abdelli, F., Caporali, E., Rizzo, B.M., Nardi, F., Ouessar, M., 2025. WEFE nexus management plan for sustainable development and gender equity in the Matmata region, SE Tunisia. Front. Water 7. https://doi.org/10.3389/frwa.2025.1563873.

Bidoglio, G., Brander, L., 2016. Enabling management of the Water-Food-Energy-Ecosystem Services Nexus. Ecosyst. Serv. 17, 265–267. https://doi.org/10.1016/j.ecoser.2016.02.001.

Brooks, C., Parr, L., Smith, J.M., Buchanan, D., Snioch, D., Hebishy, E., 2021. A review of food fraud and food authenticity across the food supply chain, with an examination of the impact of the COVID-19 pandemic and Brexit on food industry. Food Control. 130, 108171. https://doi.org/10.1016/j.foodcont.2021.108171.

Caputo, S., Schoen, V., Specht, K., Grard, B., Blythe, C., Cohen, N., Fox-Kämper, R., Hawes, J., Newell, J., Poniży, L., 2021. Applying the food-energy-water nexus approach to urban agriculture: From FEW to FEWP (Food-Energy-Water-People). Urban. For. & Urban. Green. 58, 126934. https://doi.org/10.1016/j.ufug.2020.126934.

Carriço, N., Felícissimo, D., Antunes, A., Luz, P.B. da, 2025. Simulating Water Application Efficiency in Pressurized Irrigation Systems: A Computational Approach. Water 17 (8), 1217. https://doi.org/10.3390/w17081217.

Chadegani, A.A., Salehi, H., Yunus, M.M., Farhadi, H., Fooladi, M., Farhadi, M., Ebrahim, N.A., 2013. A Comparison between Two Main Academic Literature Collections: Web of Science and Scopus Databases. Asian Social. Sci. 9 (5). https://doi.org/10.5539/ass.v9n5p18.

Chapagain, S.K., Pandey, V.P., Dangol, S., Guenther, E., 2024. Operationalizing Resource Nexus: a systematic review from water perspective. Sustain. Nexus Forum 32 (1), 15. https://doi.org/10.1007/s00550-024-00553-x.

Chen, B., Zhang, X., Gu, B., 2025. Managing nitrogen to achieve sustainable food-energy-water nexus in China. Nat. Commun. 16 (1), 4804. https://doi.org/10.1038/s41467-025-60098-5.

Chen, T., Zhang, Y., Jiang, C., Li, H., 2023. How does energy efficiency affect employment? Evidence from Chinese cities. Energy 280, 128071. https://doi.org/10.1016/j.energy.2023.128071.

Cheng, B., Duan, Q., Li, H., Cheng, W., Li, Q., Shi, Y., 2026. Hybrid Agricultural Compensation Mechanism for Protection of Ecological Flow in Rivers in Water-Scarce Areas of Northwest China. Water 18 (3), 336. https://doi.org/10.3390/w1803033.

Cook, M., Webber, M., 2016. Food, fracking, and freshwater: the potential for markets and cross-sectoral investments to enable water conservation. Water 8 (2), 45. https://doi.org/10.3390/w8020045.

Correa-Cano, M.E., Salmoral, G., Rey, D., Knox, J.W., Graves, A., Melo, O., Foster, W., Naranjo, L., Zegarra, E., Johnson, C., Viteri-Salazar, O., Yan, X., 2022. A novel modelling toolkit for unpacking the Water-Energy-Food-Environment (WEFE) nexus of agricultural development. Renew. Sustain. Energy Rev. 159, 112182. https://doi.org/10.1016/j.rser.2022.112182.

Cotella, V.A., Aburamadan, R., Erekat, A., Neagu, C.D., Shehadeh, A., Moghayedi, A., Mujtaba, I.M., 2025. A critical success factor (CSF) framework for implementing net-positive housing in the water, energy, food, environment (WEFE) Nexus: insights from Jordan and South Africa. J. Build. Eng. 106, 112659. https://doi.org/10.1016/j.jobe.2025.112659.

Covarrubias, M., 2019. The nexus between water, energy and food in cities: towards conceptualizing socio-material interconnections. Sustain. Sci. 14 (2), 277–287. https://doi.org/10.1007/s11625-018-0591-0.

Cui, S., Adamowski, J.F., Wu, M., Zhang, P., Yue, Q., Cao, X., 2024. An integrated framework for improving green agricultural production sustainability in human-natural systems. Sci. Total. Environ. 945, 174153. https://doi.org/10.1016/j.scitotenv.2024.174153.

De Strasser, L., Lipponen, A., Howells, M., Stec, S., Bréthaut, C., 2016. A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. Water 8 (2), 59. https://doi.org/10.3390/w8020059.

Del Borghi, A., Tacchino, V., Moreschi, L., Matarazzo, A., Gallo, M., Arellano Vazquez, D., 2022. Environmental assessment of vegetable crops towards the water-energy-food nexus: a combination of precision agriculture and life cycle assessment. Ecol. Indic. 140, 109015. https://doi.org/10.1016/j.ecolind.2022.109015.

Demir, E., Alp, E., 2025. A framework for assessing the circular economy potential in the water and agriculture sectors in Türkiye through the water-energy-food-ecosystem nexus. Sustain. Prod. Consum. 54, 335–347. https://doi.org/10.1016/j.spc.2025.01.009.

Dhar, A.R., 2025. Building Climate-Resilient Food Systems Through the Water–Energy–Food–Environment Nexus. Environments 12 (5), 167. https://doi.org/10.3390/environments12050167.

Ding, T., Chen, J., Fang, L., Ji, J., 2024. Identifying and optimizing ecological security patterns from the perspective of the water-energy-food nexus. J. Hydrol. 632, 130912. https://doi.org/10.1016/j.jhydrol.2024.130912.

Do, P., Tian, F., Zhu, T., Zohidov, B., Ni, G., Lu, H., Liu, H., 2020. Exploring synergies in the water-food-energy nexus by using an integrated hydro-economic optimization model for the Lancang-Mekong River basin. Sci. Total. Environ. 728, 137996. https://doi.org/10.1016/j.scitotenv.2020.137996.

van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84 (2), 523–538. https://doi.org/10.1007/s11192-009-0146-3.

Erfanmanesh, M., Morovati, M., 2019. Published errors and errata in library and information science journals. Collect. Curation 38 (3), 61–67. https://doi.org/10.1108/CC-12-2018-0024.

Falchetta, G., Semeria, F., Tuninetti, M., Giordano, V., Pachauri, S., Byers, E., 2023. Solar irrigation in sub-Saharan Africa: economic feasibility and development potential. Environ. Res. Lett. 18 (9), 094044. https://doi.org/10.1088/1748-9326/acefe5.

Fleischmann, J., Birkel, C., Blechinger, P., Ribbe, L., Nauditt, A., Corigliano, S., Platzer, W., 2024. Guiding the data collection for integrated Water-Energy-Food-Environment systems using a pilot smallholder farm in Costa Rica. Energy Nexus 13, 100259. https://doi.org/10.1016/j.nexus.2023.100259.

Forsetlund, L., O'Brien, M.A., Forsén, L., Mwai, L., Reinar, L.M., Okwen, M.P., Horsley, T., Rose, C.J., 2021. Continuing education meetings and workshops: effects on professional practice and healthcare outcomes. Cochrane Database Syst. Rev. 2021 (9). https://doi.org/10.1002/14651858.CD003030.pub3.

Fürst, C., Luque, S., Geneletti, D., 2017. Nexus thinking – how ecosystem services can contribute to enhancing the cross-scale and cross-sectoral coherence between land use, spatial planning and policy-making. Int. J. Biodivers. Sci. Ecosyst. Serv. & Manag. 13 (1), 412–421. https://doi.org/10.1080/21513732.2017.1396257.

Galani, A., Tsatsou, A., González-Camejo, J., Georgiou, I., Barros, V.G., Eusebi, A.L., Stepišnik Perdih, T., Malamis, S., Fatone, F., Noutsopoulos, C., 2025. Participatory Selection of Nature-Based Solutions and Bioeconomy Solutions for WEFE Nexus Implementation: Applications on Tinos Island, Greece. Circ. Econ. Sustain. 5 (3), 2549–2575. https://doi.org/10.1007/s43615-025-00535-1.

Garau, E., de Abreu, G., Perez-Ramirez, I., Schütze, N., Farhat, Y.A., Loureiro, J., El Moussaoui, H., Mahjoub, O., Amami, H., Sandri, S., Alshyab, N., Drei, P., Maistrello, G., Asmaa, A., Khouya, K., López, A.M.L., Restoy, R.C., Thiel, A., Castro, A.J., 2025b. Diverse values of nature can drive transformative change in the WEFE nexus governance in Mediterranean countries. Sustain. Sci. https://doi.org/10.1007/s11625-025-01757-w.

Garau, E., de Abreu, G., Pérez-Ramírez, I., Schütze, N., Farhat, Y., El Moussaoui, H., Loureiro, J., Mahjoub, O., Ben Slimane, A., Amami, H., Zairi, A., Thiel, A., Castro, A. J., 2025a. Exploring agricultural stakeholders' mental models of the water-energy-food-ecosystems (WEFE) Nexus: Insights from Mediterranean case studies. Environ. Sci. Policy 171, 104196. https://doi.org/10.1016/j.envsci.2025.104196.

Gkatsikos, A., Mattas, K., Loizou, E., Psaltopoulos, D., 2022. The neglected water rebound effect of income and employment growth. Water Resour. Manag. 36 (1), 379–398. https://doi.org/10.1007/s11269-021-03032-w.

Guo, L., Wu, Y., Huang, F., Jing, P., Huang, Y., 2024. An approach to complex transboundary water management in Central Asia: evolutionary cooperation in transboundary basins under the water-energy-food-ecosystem nexus. J. Environ. Manag. 351, 119940. https://doi.org/10.1016/j.jenvman.2023.119940.

Haldar, S., Behura, D., Nuppenau, E.-A., Rahaman, S.M., Susovita, S., Sathyan, A.R., Funk, C., 2026. Exploring institutional innovation in groundwater sharing: driving market-led farming systems in Coastal Odisha, India. Agric. Water Manag. 331, 110417. https://doi.org/10.1016/j.agwat.2026.110417.

Halytsia, O., Vrachioli, M., Sauer, J., 2024. Assessing performance of crop producers from Water-Energy-Food-Environment Nexus perspective: a composite indicator approach. Sci. Total. Environ. 935, 173436. https://doi.org/10.1016/j.scitotenv.2024.173436.

Hanes, R.J., Gopalakrishnan, V., Bakshi, B.R., 2018. Including nature in the food-energy-water nexus can improve sustainability across multiple ecosystem services. Resour. Conserv. Recycl. 137, 214–228. https://doi.org/10.1016/j.resconrec.2018.06.003.

Hashemi, S., 2025. Advancing healthy and sustainable environmental stewardship: reimagining strategies for air, water, food, and waste management. Sustainability 17 (4), 1345. https://doi.org/10.3390/su17041345.

He, X., Feng, K., Li, X., Craft, A.B., Wada, Y., Burek, P., Wood, E.F., Sheffield, J., 2019. Solar and wind energy enhances drought resilience and groundwater sustainability. Nat. Commun. 10 (1), 4893. https://doi.org/10.1038/s41467-019-12810-5.

Henseler, M., 2025. A WEFE Nexus CGE Model. R. éUnion. Isl. REWEFE Model.

Hiebl, M.R.W., 2023. Sample selection in systematic literature reviews of management research. Organ. Res. Methods 26 (2), 229–261. https://doi.org/10.1177/1094428120986851.

Hoff, H., 2011. Underst. Nexus.

Hong, Q.N., Gonzalez-Reyes, A., Pluye, P., 2018. Improving the usefulness of a tool for appraising the quality of qualitative, quantitative and mixed methods studies, the <scp>Mixed Methods Appraisal Tool</scp> (<scp>MMAT</scp>). J. Eval. Clin. Pract. 24 (3), 459–467. https://doi.org/10.1111/jep.12884.

Hong, J., Zhang, T., Shen, X., Zhai, Y., Bai, Y., Hong, J., 2022. Water, energy, and carbon integrated footprint analysis from the environmental-economic perspective for apple production in China. J. Clean. Prod. 368, 133184. https://doi.org/10.1016/j.jclepro.2022.133184.

Huang, D., Li, G., Chang, Y., Sun, C., 2023. Water, energy, and food nexus efficiency in China: A provincial assessment using a three-stage data envelopment analysis model. Energy 263, 126007. https://doi.org/10.1016/j.energy.2022.126007.

Huang, D., Shen, Z., Sun, C., Li, G., 2021. Shifting from production-based to consumption-based nexus governance: evidence from an input–output analysis of the local water-energy-food nexus. Water Resour. Manag. 35 (6), 1673–1688. https://doi.org/10.1007/s11269-021-02797-4.

Hurtado, A.R., Mesa-Pérez, E., Berbel, J., 2024. Systems modeling of the water-energy-food-ecosystems nexus: insights from a region facing structural water scarcity in southern Spain. Environ. Manag. 74 (6), 1045–1062. https://doi.org/10.1007/s00267-024-02037-6.

Hussein, H., Ezbakhe, F., 2023. The water–employment–migration nexus: buzzword or useful framework? Dev. Policy Rev. 41 (3). https://doi.org/10.1111/dpr.12676.

Ioannidou, S., Litskas, V., Stavrinides, M., Vogiatzakis, I. N, 2022. Placing ecosystem services within the water–food–energy–climate nexus: a case study in mediterranean mixed orchards. Agronomy 12 (9), 2224. https://doi.org/10.3390/agronomy12092224.

Jain, S.K., Sikka, A.K., Alam, M.F., 2023. Water-energy-food-ecosystem nexus in India—A review of relevant studies, policies, and programmes. Front. Water 5. https://doi.org/10.3389/frwa.2023.1128198.

Kaddoura, S., El Khatib, S., 2017. Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. Environ. Sci. & Policy 77, 114–121. https://doi.org/10.1016/j.envsci.2017.07.007.

Karnib, A., Elbendary, N., Abouelhassan, M., Dawoud, M., 2025. Sustainability assessment of solar-powered drip irrigation for sugarcane in Egypt: A water–energy–food–ecosystem nexus perspective. World Water Policy 11 (2), 393–409. https://doi.org/10.1002/wwp2.12247.

Karri, R.R., Ravindran, G., Pingili, V., Mubarak, N.M., Ruslan, K.N., Tan, Y.H., 2026. Integrating the Food-Energy-Water Nexus: Strategies for climate change mitigation with SDG alignment. Environ. Impact Assess. Rev. 116, 108070. https://doi.org/10.1016/j.eiar.2025.108070.

KC, S., KC, S., Pokhrel, A., Paudel, S., Mishra, A., Buchy, M., Khadka, M., Aryal, A., 2025. Nexus governance in practice: a stakeholder-driven framework for groundwater sustainability in Barahathawa Municipality, Madhesh Province. Sustain. Nexus Forum 33 (1), 20. https://doi.org/10.1007/s00550-025-00579-9.

Kertolli, E., Prosperi, P., Harbouze, R., Moussadek, R., Echchgadda, G., Belhouchette, H., 2024. The water–energy–food–ecosystem nexus in North Africa dryland farming: a multi-criteria analysis of climate-resilient innovations in Morocco. Agric. Food Econ. 12 (1), 34. https://doi.org/10.1186/s40100-024-00327-5.

Khan, I., Xue, J., Zaman, S., Mehmood, Z., 2023. Nexus Between FDI, Economic Growth, Industrialization, and Employment Opportunities: Empirical Evidence from Pakistan. J. Knowl. Econ. 14 (3), 3153–3175. https://doi.org/10.1007/s13132-022-01006-w.

Kleftodimos, G., Kyrgiakos, L.S., Kartakis, S., Kleisiari, C., Vasileiou, M., Kremantzis, M. D., Vlontzos, G., 2024. Promoting excellence or discouraging mediocrity – a policy framework assessment for precision agriculture technologies adoption. Precis. Agric. 25 (6), 2903–2920. https://doi.org/10.1007/s11119-024-10160-x.

Kumar, A., 2018. 4. Global Environment Facility (GEF). Yearb. Int. Environ. Law 29, 416–422. https://doi.org/10.1093/yiel/yvz035.

Kyrgiakos, L.S., Hazimeh, M., Vasileiou, M., Kleisiari, C., Kleftodimos, G., Vlontzos, G., 2024. The Food Fraud Landscape: A Brief Review of Food Safety and Authenticity. 17th Int. Conf. Hell. Assoc. Agric. Econ. 6. https://doi.org/10.3390/proceedings2024094006.

Lamalice, A., Haillot, D., Lamontagne, M.-A., Herrmann, T.M., Gibout, S., Blangy, S., Martin, J.-L., Coxam, V., Arsenault, J., Munro, L., Courchesne, F., 2018. Building food security in the Canadian Arctic through the development of sustainable community greenhouses and gardening. Écoscience 25 (4), 325–341. https://doi.org/10.1080/11956860.2018.1493260.

Lame, G., 2019. Systematic Literature Reviews: An Introduction. Proc. Des. Soc. Int. Conf. Eng. Des. 1 (1), 1633–1642. https://doi.org/10.1017/dsi.2019.169.

Laspidou, C.S., Mellios, N.K., Spyropoulou, A.E., Kofinas, D., Th, Papadopoulou, M.P., 2020. Systems thinking on the resource nexus: modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. Sci. Total. Environ. 717, 137264. https://doi.org/10.1016/j.scitotenv.2020.137264.

Li, M., Cao, X., Liu, D., Fu, Q., Li, T., Shang, R., 2022. Sustainable management of agricultural water and land resources under changing climate and socio-economic conditions: a multi-dimensional optimization approach. Agric. Water Manag. 259, 107235. https://doi.org/10.1016/j.agwat.2021.107235.

Li, M., Chen, Y., Liu, D., Xue, M., Wang, Y., Fu, Q., 2024. Synergetic management of the water-energy-food nexus for cropland ecosystems under climate change: toward a multistakeholder-based systematic optimization approach. Renew. Energy 220, 119597. https://doi.org/10.1016/j.renene.2023.119597.

Li, G., Huang, D., Sun, C., Li, Y., 2019. Developing interpretive structural modeling based on factor analysis for the water-energy-food nexus conundrum. Sci. Total. Environ. 651, 309–322. https://doi.org/10.1016/j.scitotenv.2018.09.188.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P.A., Clarke, M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. PLoS. Med. 6 (7), e1000100. https://doi.org/10.1371/journal.pmed.1000100.

Lin, C., He, L., 2020. Targeted monetary policy and agriculture business loans. North. Am. J. Econ. Financ. 54, 101290. https://doi.org/10.1016/j.najef.2020.101290.

Liu, Z., Huang, Q., He, C., Wang, C., Wang, Y., Li, K., 2021. Water-energy nexus within urban agglomeration: An assessment framework combining the multiregional input-output model, virtual water, and embodied energy. Resour. Conserv. Recycl. 164, 105113. https://doi.org/10.1016/j.resconrec.2020.105113.

Lu, Z., Yang, S., Chen, W., Lu, L., Fan, Y., Yue, C., Shi, Y., 2025. Coupling coordination and driving factors of the water-energy-food nexus in China: A sustainable development perspective. Energy Nexus 20, 100545. https://doi.org/10.1016/j.nexus.2025.100545.

Lucca, E., El Jeitany, J., Castelli, G., Pacetti, T., Bresci, E., Nardi, F., Caporali, E., 2023. A review of water-energy-food-ecosystems Nexus research in the Mediterranean: evolution, gaps and applications. Environ. Res. Lett. 18 (8), 083001. https://doi.org/10.1088/1748-9326/ace375.

Ma, Y., Li, Y., Huang, G., Liu, Y., Zhang, Y., 2024. Collaborative Management of Water-Energy-Food-Ecosystems Nexus in Central Asia Under Uncertainty. Water Resour. Res. 60 (3). https://doi.org/10.1029/2023WR035166.

Malagó, A., Comero, S., Bouraoui, F., Kazezyılmaz-Alhan, C.M., Gawlik, B.M., Easton, P., Laspidou, C., 2021. An analytical framework to assess SDG targets within the context of WEFE nexus in the Mediterranean region. Resour. Conserv. Recycl. 164, 105205. https://doi.org/10.1016/j.resconrec.2020.105205.

Malamataris, D., Chatzi, A., Babakos, K., Pisinaras, V., Hatzigiannakis, E., Willaarts, B.A., Bea, M., Pagano, A., Panagopoulos, A., 2023. A participatory approach to exploring nexus challenges: a case study on the pinios river basin, Greece. Water 15 (22), 3949. https://doi.org/10.3390/w15223949.

McCoshan, K. (2020). Climate Change Adaptation in East Africa: Mainstreaming gender-responsive and participatory approaches.

MedECC. (2024). Session title: Interlinking climate change with the Water-Energy-Food-Ecosystems (WEFE) nexus in the Mediterranean Basin, new MedECC Special Report Lead organisations: Mediterranean Experts on Climate and environmental Change (MedECC) and Union for the Mediterranean (UfM) Short description: Background.

Mellios, N., Vrachioli, M., Tseva, G., Renner, B., Papadopoulou, C.-A., Adamos, G., Laspidou, C., 2026. Advancing the WEFE nexus: expert insights on implementation and challenges. PLOS One 21 (7), e0350133. https://doi.org/10.1371/journal.pone.0350133.

Meng, F., Yuan, Q., Bellezoni, R.A., de Oliveira, J.A.P., Cristiano, S., Shah, A.M., Liu, G., Yang, Z., Seto, K.C., 2023. Quantification of the food-water-energy nexus in urban green and blue infrastructure: a synthesis of the literature. Resour. Conserv. Recycl. 188, 106658. https://doi.org/10.1016/j.resconrec.2022.106658.

Mitić, P., Fedajev, A., Radulescu, M., Rehman, A., 2022. The relationship between CO2 emissions, economic growth, available energy, and employment in SEE countries. Environ. Sci. Pollut. Res. 30 (6), 16140–16155. https://doi.org/10.1007/s11356-022-23356-3.

Mooren, C.E., Munaretto, S., La Jeunesse, I., Sievers, E., Hegger, D.L.T., Driessen, P.P.J., Hüesker, F., Cirelli, C., Canovas, I., Mounir, K., Madrigal, J.G., 2025. Water–energy–food–ecosystem nexus: how to frame and how to govern. Sustain. Sci. https://doi.org/10.1007/s11625-025-01691-x.

Morales-García, M., Rubio, M.Á.G., 2023. Sustainability of an economy from the water-energy-food nexus perspective. Environ. Dev. Sustain. 26 (2), 2811–2835. https://doi.org/10.1007/s10668-022-02877-4.

Mortensen, J.G., González-Pinzón, R., Dahm, C.N., Wang, J., Zeglin, L.H., Van Horn, D.J., 2016. Advancing the Food-Energy–Water Nexus: Closing Nutrient Loops in Arid River Corridors. Environ. Sci. & Technol. 50 (16), 8485–8496. https://doi.org/10.1021/acs.est.6b01351.

Moss, T., Hüesker, F., 2019. Politicised nexus thinking in practice: integrating urban wastewater utilities into regional energy markets. Urban. Stud. 56 (11), 2225–2241. https://doi.org/10.1177/0042098017735229.

Muhirwa, F., Li, L., Laspidou, C., 2025. Global ecosystem sustainability indexing and patterns in the success of SDGs of water, energy and food security. J. Clean. Prod. 516, 145830. https://doi.org/10.1016/j.jclepro.2025.145830.

Nikolaidis, N.P., Troullaki, K., Lilli, M.A., Halasah, S., Lehrer, D., Rozakis, S., Wald, S., Al Ajrami, A., Al-Attili, S., Zemah-Shamir, S., Jayyousi, A., Kan, I., Reznik, A., 2025. An integrated participatory framework for WEFE nexus strategic planning: the Jordan Valley case study. J. Environ. Manag. 375, 124246. https://doi.org/10.1016/j.jenvman.2025.124246.

Niu, G., Zheng, Y., Han, F., Qin, H., 2019. The nexus of water, ecosystems and agriculture in arid areas: a multiobjective optimization study on system efficiencies. Agric. Water Manag. 223, 105697. https://doi.org/10.1016/j.agwat.2019.105697.

Onah, O.G., Enete, A.A., Okoye, C.U., Ume, C.O., Onyia, C.C., 2024. Impact of credit access of farmers in cooperative societies on financial performance: the predictive effect of financial literacy. Int. J. Social. Econ. 51 (11), 1420–1433. https://doi.org/10.1108/IJSE-10-2023-0837.

Paez, A., 2017. Gray literature: an important resource in systematic reviews. J. Evid. -Based Med. 10 (3), 233–240. https://doi.org/10.1111/jebm.12266.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Moher, D., 2021. Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. J. Clin. Epidemiol. 134, 103–112. https://doi.org/10.1016/j.jclinepi.2021.02.003.

Page, M.J., Moher, D., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McKenzie, J.E., 2021. PRISMA 2020 explanation and elaboration:

updated guidance and exemplars for reporting systematic reviews. BMJ n160. https://doi.org/10.1136/bmj.n160.

Palmatier, R.W., Houston, M.B., Hulland, J., 2018. Review articles: purpose, process, and structure. J. Acad. Mark. Sci. 46 (1), 1–5. https://doi.org/10.1007/s11747-017-0563-4.

Panjehpour, A., Zarrinpoor, N., 2025. A network design of a canola-to-biodiesel supply chain by considering the water-energy-food-land-ecosystem-undesirable climate change nexus. Comput. & Ind. Eng. 199, 110610. https://doi.org/10.1016/j.cie.2024.110610.

Papadopoulou, C.-A., Papadopoulou, M.P., Laspidou, C., 2022. Implementing water-energy-land-food-climate nexus approach to achieve the sustainable development goals in Greece: indicators and policy recommendations. Sustainability 14 (7), 4100. https://doi.org/10.3390/su14074100.

Pastori, M., Udias, A., Cattaneo, L., Moner-Girona, M., Niang, A., Carmona-Moreno, C., 2021. Bioenergy Potential of Crop Residues in the Senegal River Basin: A Cropland–Energy–Water-Environment Nexus Approach. Sustainability 13 (19), 11065. https://doi.org/10.3390/su131911065.

Paul, J., Barari, M., 2022. Meta-analysis and traditional systematic literature reviews—What, why, when, where, and how? Psychol. & Mark. 39 (6), 1099–1115. https://doi.org/10.1002/mar.21657.

Petsch, D.K., Cionek, V. de M., Thomaz, S.M., dos Santos, N.C.L., 2023. Ecosystem services provided by river-floodplain ecosystems. Hydrobiologia 850 (12–13), 2563–2584. https://doi.org/10.1007/s10750-022-04916-7.

Petticrew, M., 2001. Systematic reviews from astronomy to zoology: myths and misconceptions. BMJ 322 (7278), 98–101. https://doi.org/10.1136/bmj.322.7278.98.

Policy Brief Changing Policy Concepts of Food Security. (2006). http://www.foodsecinfoaction.org/.

Pourfallah Asadabadi, S., Sadeghi, S.H., Vafakhah, M., Delavar, M., 2025. Significance of the Water-Energy-Food Nexus on the Watershed Health Status. Water Resour. Manag. 39 (5), 2217–2250. https://doi.org/10.1007/s11269-024-04064-8.

Probst, E., Fader, M., Mauser, W., 2024. The water-energy-food-ecosystem nexus in the Danube River Basin: Exploring scenarios and implications of maize irrigation. Sci. Total. Environ. 914, 169405. https://doi.org/10.1016/j.scitotenv.2023.169405.

Pulido-Chadid, K., Virtanen, E., Geldmann, J., 2023. How effective are protected areas for reducing threats to biodiversity? A systematic review protocol. Environ. Evid. 12 (1), 18. https://doi.org/10.1186/s13750-023-00311-4.

Qian, R., Hao, S., Zou, X., Zhao, R., Li, R., Daniel Tang, K.H., 2026. Technological developments and feasibility of hydrogen energy systems: production, storage, and distribution. Fuel 409, 137917. https://doi.org/10.1016/j.fuel.2025.137917.

Raffo-Babici, V., Calderon-Cisneros, J., Peralta-Gamboa, D., Coloma-Casanova, A., 2025. Multidimensional analysis of access to resources and its relationship with food security in vulnerable populations. Clinical Nutrition Open Science 61, 317–328. https://doi.org/10.1016/j.nutos.2025.05.001.

Raihan, A., Tanchangya, T., Rahman, J., Ridwan, M., 2024. The Influence of Agriculture, Renewable Energy, International Trade, and Economic Growth on India's Environmental Sustainability. J. Environ. Energy Econ. 3 (1), 37–53. https://doi.org/10.56946/jeee.v3i1.324.

Ravar, Z., Zahraie, B., Sharifinejad, A., Gozini, H., Jafari, S., 2020. System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran. Ecol. Indic. 108, 105682. https://doi.org/10.1016/j.ecolind.2019.105682.

Recanati, F., Castelletti, A., Dotelli, G., Melià, P., 2017. Trading off natural resources and rural livelihoods. A framework for sustainability assessment of small-scale food production in water-limited regions. Adv. Water Resour. 110, 484–493. https://doi.org/10.1016/j.advwatres.2017.04.024.

Rhouma, A., Mellios, N., Brouwer, F., José Maria, G., Laspidou, C., 2025. Assessing vineyard sustainability through a Water-Energy-Food-Ecosystems Nexus indicator using System Dynamics Modelling. Clean. Environ. Syst. 19, 100346. https://doi.org/10.1016/j.cesys.2025.100346.

Rosenheim, N.P., Watson, M., Casellas Connors, J., Safayet, M., Peacock, W.G., 2024. Food Access After Disasters. J. Am. Plan. Assoc. 90 (3), 452–470. https://doi.org/10.1080/01944363.2023.2284160.

Sadeghi, S.H.R., Sharifi Moghadam, E., 2021. Integrated Watershed Management Vis-a-Vis Water-Energy-Food Nexus. Chapter 3. In: Muthu, S.S. (Ed.), The Water-Energy-Food Nexus. Springer, Singapore, pp. 69–96. Chapter 3.

Sadeghi, S.H.R., Sharifi Moghadam, E., Delavar, M., Zarghami, M., 2020. Application of water-energy-food nexus approach for designating optimal agricultural management pattern at a watershed scale. Agric. Water Manag. 233, 106071.

Sanchez, L., Warziniack, T., Knowles, M., 2023. The inequitable exposure of socially vulnerable groups to water shortages across the United States. Environ. Res. Lett. 18 (4), 044022. https://doi.org/10.1088/1748-9326/acb06d.

Sánchez-Zarco, X.G., Ponce-Ortega, J.M., 2023. Water-energy-food-ecosystem nexus: an optimization approach incorporating life cycle, security and sustainability assessment. J. Clean. Prod. 414, 137534. https://doi.org/10.1016/j.jclepro.2023.137534.

Sarbijan, S.R., Mehrjerdi, M.R.Z., Mirzaei, A., Boshrabadi, H.M., Khalilabad, H.R.M., 2025. Evaluation of water resource management policies for achieving sustainable agricultural development using the distance-to-optimal solution index: application of the WEFE Nexus and NSGA-II method. Curr. Res. Environ. Sustain. 10, 100310. https://doi.org/10.1016/j.crsust.2025.100310.

Schwanitz, V., Wierling, A., Shah, P., 2017. Assessing the Impact of Renewable Energy on Regional Sustainability—A Comparative Study of Sogn og Fjordane (Norway) and Okinawa (Japan). Sustainability 9 (11), 1969. https://doi.org/10.3390/su9111969.

Serrano-Tovar, T., Peñate Suárez, B., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V., Giampietro, M., 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. Sci. Total. Environ. 689, 945–957. https://doi.org/10.1016/j.scitotenv.2019.06.422.

Sethi, L., Behera, P., Behera, B., Sethi, N., 2024. Unravelling the role of renewable energy, information and communication technology and agricultural credit for sustainable agricultural productivity in developing countries. Int. J. Sustain. Dev. & World Ecol. 31 (7), 989–1003. https://doi.org/10.1080/13504509.2024.2366474.

Sharifi Moghadam, E., Sadeghi, S.H.R., Zarghami, M., Delavar, M., 2019. Water-energy-food nexus as a new approach for watershed resources management: a review. Environ. Resour. Res. 7 (2), 129–135.

Sharifi Moghadam, E., Sadeghi, S.H.R., Zarghami, M., Delavar, M., 2023. Developing sustainable land-use patterns at watershed scale using nexus of soil, water, energy, and food. Sci. Total. Environ., 158935

Shehadeh, A., Alshboul, O., Arar, M., 2024. Enhancing Urban Sustainability and Resilience: Employing Digital Twin Technologies for Integrated WEFE Nexus Management to Achieve SDGs. Sustainability 16 (17), 7398. https://doi.org/10.3390/su16177398.

Shifflett, S.D., Culbreth, A., Hazel, D., Daniels, H., Nichols, E.G., 2016. Coupling aquaculture with forest plantations for food, energy, and water resiliency. Sci. Total. Environ. 571, 1262–1270. https://doi.org/10.1016/j.scitotenv.2016.07.161.

Shokri, N., Aminzadeh, M., Flury, M., Jin, Y., Matin, M.A., Panagos, P., Razavi, B.S., Robinson, D.A., Smith, P., Todd-Brown, K., Toth, G., Zarei, A., Madani, K., 2025. Sustainability Nexus AID: soil health. Sustain. Nexus Forum 33 (1), 3. https://doi.org/10.1007/s00550-025-00560-6.

Shrimpton, E.A., Balta-Ozkan, N., 2024. A Systematic Review of Socio-Technical Systems in the Water–Energy–Food Nexus: Building a Framework for Infrastructure Justice. Sustainability 16 (14), 5962. https://doi.org/10.3390/su16145962.

Sievers, E., Canovas, I., Kristensen, D., Hüesker, F., 2025. Assessing to act: A water-energy-food-ecosystem (WEFE) nexus governance assessment for the Inkomati-Usuthu river basin in South Africa. Environ. Sci. & Policy 164, 103986. https://doi.org/10.1016/j.envsci.2025.103986.

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. J. Bus. Res. 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Soares, P.M.M., Lima, D.C.A., 2022. Water scarcity down to earth surface in a Mediterranean climate: The extreme future of soil moisture in Portugal. J. Hydrol. 615, 128731. https://doi.org/10.1016/j.jhydrol.2022.128731.

Sofiyah, E.S., Sianipar, I.M.J., Rahman, A., Caesarina, N.P., Suhardono, S., Suryawan, I. W.K., Lee, C.-H., 2025. Adaptive governance in the water-energy-food-ecosystem nexus for sustainable community sanitation. World Dev. Sustain. 6, 100220. https://doi.org/10.1016/j.wds.2025.100220.

Solano-Pereira, P., García-González, A., Miguel González, L.J., 2025. Economic Representation in Water–Energy–Food Nexus Models: A Systematic Review of System Dynamics Approaches. Energies 18 (4), 966. https://doi.org/10.3390/en18040966.

Soltani, S., Mosavi, S.H., Saghaian, S.H., Azhdari, S., Alamdarlo, H.N., Khalilian, S., 2023. Climate change and energy use efficiency in arid and semiarid agricultural areas: A case study of Hamadan-Bahar plain in Iran. Energy 268, 126553. https://doi.org/10.1016/j.energy.2022.126553.

Sood, A., Nicol, A., Arulingam, I., 2019. Unpacking Water-Energy-Environ. -Food Nexus. Work. Across Syst. https://doi.org/10.5337/2019.210.

Staupe-Delgado, R., Coombes, P.R., 2020. Life in Anticipation of Wind Power Development: Three Cases from Coastal Norway. Sustainability 12 (24), 10666. https://doi.org/10.3390/su122410666.

Sun, J., Zhang, J., Wang, X., Liu, Y., Zhang, J., Zhang, X., Li, D., 2025. Evaluation of cooperative security and coupling coordination of water-energy-food-ecosystems nexus: a case study of Yulin City. Water-Energy Nexus 8, 101–114. https://doi.org/10.1016/j.wen.2025.04.001.

Taghdisian, A., Bukkens, S.G.F., Giampietro, M., 2022. A Societal Metabolism Approach to Effectively Analyze the Water–Energy–Food Nexus in an Agricultural Transboundary River Basin. Sustainability 14 (15), 9110. https://doi.org/10.3390/su14159110.

Tamura, J., Itaya, Y., Hayashi, K., Yamamoto, K., 2026. Statistical inference of the Matthews correlation coefficient for multiclass classification. J. Appl. Stat. 1–26. https://doi.org/10.1080/02664763.2026.2666305.

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., Gröne, M.-C., 2018. Energising the WEF nexus to enhance sustainable development at local level. J. Environ. Manag. 223, 409–416. https://doi.org/10.1016/j.jenvman.2018.06.037.

The WEF Nexus Index. (n.d.). Retrieved October 20, 2025, from https://wefnexusindex.org/.

Tidwell, T.L., 2016. Nexus between food, energy, water, and forest ecosystems in the USA. J. Environ. Stud. Sci. 6 (1), 214–224. https://doi.org/10.1007/s13412-016-0367-8.

Vanham, D., 2016. Does the water footprint concept provide relevant information to address the water–food–energy–ecosystem nexus? Ecosyst. Serv. 17, 298–307. https://doi.org/10.1016/j.ecoser.2015.08.003.

Varsha P S, Chakraborty, A., Kar, A.K., 2024. How to Undertake an Impactful Literature Review: Understanding Review Approaches and Guidelines for High-impact Systematic Literature Reviews. South. Asian J. Bus. Manag. Cases 13 (1), 18–35. https://doi.org/10.1177/22779779241227654.

Vasović, D., Vranjanac, Ž., Radjenović, T., Živković, S., Janaćković, G., 2025. Advancing the WEFE Nexus Approach with Multi-Criteria Decision Analysis and Standardization Refinements. Sustainability 17 (5), 2220. https://doi.org/10.3390/su17052220.

de Vito, R., Portoghese, I., Pagano, A., Fratino, U., Vurro, M., 2017. An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food nexus framework. Adv. Water Resour. 110, 423–436. https://doi.org/10.1016/j.advwatres.2017.10.027.

Voelker, T., Blackstock, K., Kovacic, Z., Sindt, J., Strand, R., Waylen, K., 2022. The role of metrics in the governance of the water-energy-food nexus within the European Commission. J. Rural. Stud. 92, 473–481. https://doi.org/10.1016/j.jrurstud.2019.08.001.

Vrachioli, M., Mellios, N., Alp, E., Borchard, N., Calheiros, C.S.C., Castelli, G., Coletta, V. R., Carvalho, P.N., Domínguez-Soberanes, J., Fader, M., Giordano, R., Madrid-López, C., Oral, H.V., Papadopoulou, C.-A., Papadopoulou, M., Pereira, S.I.A., Pineda-Martos, R., StepisnikPerdih, T., Vamvakeridou-Lyroudia, L., Laspidou, C., 2025. WEFE nexus unveiled: a comprehensive review of monitoring and modelling methods in the water-energy-food-ecosystems nexus. Environ. Res. Lett. 20 (11), 113005. https://doi.org/10.1088/1748-9326/ae0da3.

Wang, X., Duan, W., Zou, S., Zhang, Z., Wei, W., Feng, M., Di, Y., Li, C., 2026. Mapping the evolution of the water-energy-food-ecosystem (WEFE) nexus: A comprehensive review of the methods, scales, and sustainability challenges. Geogr. Sustain. 7 (3), 100447. https://doi.org/10.1016/j.geosus.2026.100447.

WEF NEXUS Indicator Framework Content. (2020).

Weitz, N., Strambo, C., Kemp-Benedict, E., Nilsson, M., 2017. Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. Glob. Environ. Change 45, 165–173. https://doi.org/10.1016/j.gloenvcha.2017.06.006.

Xiao, Y., Watson, M., 2019. Guidance on Conducting a Systematic Literature Review. J. Plan. Educ. Res. 39 (1), 93–112. https://doi.org/10.1177/0739456X17723971.

Xu, W., Gao, M., Fan, S., Zhu, C., 2026. Impacts of high-standard farmland construction on farmers' income in China: A comparative analysis of moderate-scale farmers and smallholders. Food Policy 138, 102994. https://doi.org/10.1016/j.foodpol.2025.102994.

Yudha, P., Putri, A., Adi, K., & Saputra, K. (n.d.). WRITING OF SCIENTIFIC WORKS IN A DISERTATION CONTEXT AND THE DIFFERENCE WITH THESIS. *International Journal of Business, Economics and Law*, *24*.

Yue, Q., Wu, H., Wang, Y., Guo, P., 2021. Achieving sustainable development goals in agricultural energy-water-food nexus system: An integrated inexact multi-objective optimization approach. Resour. Conserv. Recycl. 174, 105833. https://doi.org/10.1016/j.resconrec.2021.105833.

Zhang, C., Chen, X., Li, Y., Ding, W., Fu, G., 2018. Water-energy-food nexus: Concepts, questions and methodologies. J. Clean. Prod. 195, 625–639. https://doi.org/10.1016/j.jclepro.2018.05.194.

Zhang, Y., Jiang, Y., Wei, T., Wang, Y., Liu, Y., Xu, L., He, J., Wang, X., 2024. A quantitative analysis framework for analyzing impacts of climate change on water-food-energy-ecosystem nexus in irrigation areas based on WEAP-MODFLOW. J. Clean. Prod. 470, 143315. https://doi.org/10.1016/j.jclepro.2024.143315.

Zhang, C., Wei, Y., Zhao, X., Hu, J., 2025. Assessment and enhancement pathways of the water-energy-food-economy-ecosystem nexus in China's yellow river basin. Energy 316, 134492. https://doi.org/10.1016/j.energy.2025.134492.

Zhu, Y., 2025. A study of the index time of early access articles. Scientometrics 130 (1), 159–186. https://doi.org/10.1007/s11192-024-05188-9.

Zhu, J., Liu, W., 2020. A tale of two databases: the use of Web of Science and Scopus in academic papers. Scientometrics 123 (1), 321–335. https://doi.org/10.1007/s11192-020-03387-8.