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Review Article

Mapping the evolution of the water-energy-food-ecosystem (WEFE) nexus: A comprehensive review of the methods, scales, and sustainability challenges

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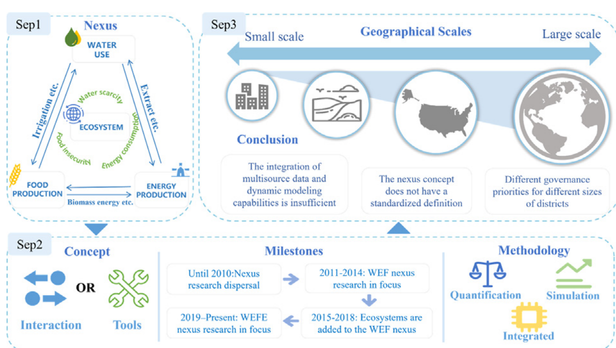
HIGHLIGHTS

- Water-energy-food-ecosystem (WEFE) nexus research from 2010 to 2024 is systematically evaluated.
- Ecosystems are integral components embedded within the water-energy-food nexus.
- WEFE research shifts from static assessments toward dynamic, integrated modelling.
- Unified frameworks, integrated data, and cross-scale governance should be promoted.

GRAPHICAL ABSTRACT



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ABSTRACT

Worldwide crises related to water, energy, food, and ecosystems are expected in the future. Although a number of studies have focused on the water-energy-food-ecosystem (WEFE) nexus, a comprehensive review that integrates bibliometric patterns, methodological approaches, and multi-scale applications within a unified WEFE framework remains lacking. To address this gap, this study applies the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review protocol and conducts bibliometric and content analyses of publications from 2010 to 2024. The results show a steady increase in WEFE-related studies and a paradigm shift from the traditional water-energy-food (WEF) triad toward a four-component framework that explicitly incorporates ecosystems. Moreover, the WEF nexus remains a central research theme. Methodological approaches can be categorized into quantitative assessment, simulation and prediction, and integrated management; however, most rely on static analysis and therefore cannot sufficiently capture dynamic feedbacks. Scale-based analysis indicates that regional and urban studies dominate the field and focus on resource integration and internal resource management optimisation, respectively, whereas transboundary-scale research remains limited. This review is the first

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to systematically synthesize the conceptual evolution, methodological pathways, and scale-specific challenges of the WEFE nexus within a unified paradigm. Moreover, this review identifies key directions for future research, including framework standardization, multi-source data integration, and scale-appropriate governance strategies, thereby providing theoretical insights and empirical support for advancing sustainable WEFE nexus research.

1. Introduction

Water, energy, and food form the bases for human social life and economic development, while ecosystems provide the foundation for all human activities. In the context of global climate change, water scarcity, energy security, and food crises have represented the major challenges threatening sustainable development (Tian et al., 2018; Pritchard, 2019). Previous studies project that the global demand for water, energy, and food will increase by approximately 40 %, 50 %, and 35 % by 2030 and 55 %, 80 %, and 60 % by 2050, respectively (Alexandratos and Bruinsma, 2012; FAO, 2014). These trends place enormous pressure on resources and the environment and thus pose a significant threat to achieving Sustainable Development Goals (SDGs).

The demand for food is expected to double as economies develop and populations grow, with changes in the dietary structure predicted to drive increases in the demand for dairy and meat products, which will lead to a surge in the demand for freshwater for food extraction and processing, thereby placing new pressures on natural resources (Zhang et al., 2018). Moreover, approximately 80 % of global energy consumption still relies on non-renewable fossil resources and shows an annual growth rate of approximately 2 % under population and economic expansion. However, the overreliance on fossil fuels has resulted in the rapid consumption of substantial amounts of existing oil and natural gas reserves within just a few decades; thus, future generations will be deprived of these energy options. Furthermore, the consumption of fossil fuels has led to increased atmospheric carbon dioxide concentrations, thereby exerting significant impacts on the global climate. With the increasing global emphasis on the ecological environment, it is important to comprehensively analyse the relationship between the supply and consumption of resources across systems by considering their impact on the ecological environment.

Against this backdrop, increasing research attention has focused on the water-energy-food-ecosystem (WEFE) nexus has garnered increasing attention because neglecting any component within this system may lead to unforeseen and potentially detrimental consequences. In this study, ecosystems are defined as dynamic composite systems that provide critical services, such as freshwater supply and climate regulation. They not only form the foundation for the water, food, and energy subsystems but also actively couple with these subsystems through a series of complex feedback mechanisms (Hernández-Blanco et al., 2022). Fig. 1 illustrates the intricate bidirectional interactions and feedback mechanisms between these subsystems, emphasising the ecosystem's pivotal role as both a service provider and a recipient of impacts. Consequently, ensuring secure supplies of water, food, and energy while minimising ecosystem damage has become a critical sustainability challenge that requires urgent attention.

The WEFE nexus is a complex cross-sectoral system currently undergoing a paradigm shift from a triad to quad system. Both domestic and international scholars have conducted theoretical discussions (Hightower and Pierce, 2008; Rosa et al., 2020; Lucca et al., 2023) and case studies (Gulati et al., 2013;Hussien et al., 2017; Taniguchi et al., 2017; Ding and Deng, 2022; Teutschbein et al., 2023) on the water-energy-food (WEF) nexus from various perspectives, including quantitative modelling and integrated analysis of resources. However, previous studies have rarely incorporated ecosystems as a subsystem within the WEF nexus framework and thus have failed to examine the interrelationships of this nexus from a holistic perspective (Rasul and Sharma, 2016). The lack of comprehensive ecosystem protection has increased the difficulty of achieving overall water, energy, and food security in many regions (Melo et al., 2021). Therefore, studies focusing on the WEFE nexus will provide theoretical support for systematically improving the efficiency of water, energy, and food use, reducing resource conflicts, creating synergies, and ensuring effective ecosystem protection (Bazilian et al., 2011).

With the increased research focus on the WEFE nexus, the number of studies in related fields has gradually increased. For instance, Karabulut et al. (2018) proposed an integrated matrix system and incorporated it into a life cycle model to assess the impacts of interactions among food, energy, and ecosystems; Wu et al. (2025) constructed a multi-objective optimisation model of water-land-energy-economy-environment-food and analysed the optimal cropping structure and spatial layout of crops under different scenarios; and Dang et al. (2024) used a system dynamics model to track and manage water-food-environment-ecosystem relationships in a groundwater irrigation district in the Hebei Plain. These advancements collectively indicate the close interconnections and mutual constraints among the elements of the WEFE system, highlighting the urgent need to develop an integrated analytical framework to reveal sectoral synergies and assess the cross-system impacts of management strategies. For example, Meehan et al. (2010) showed that although the expansion of biofuels contributes to the low-carbon en-

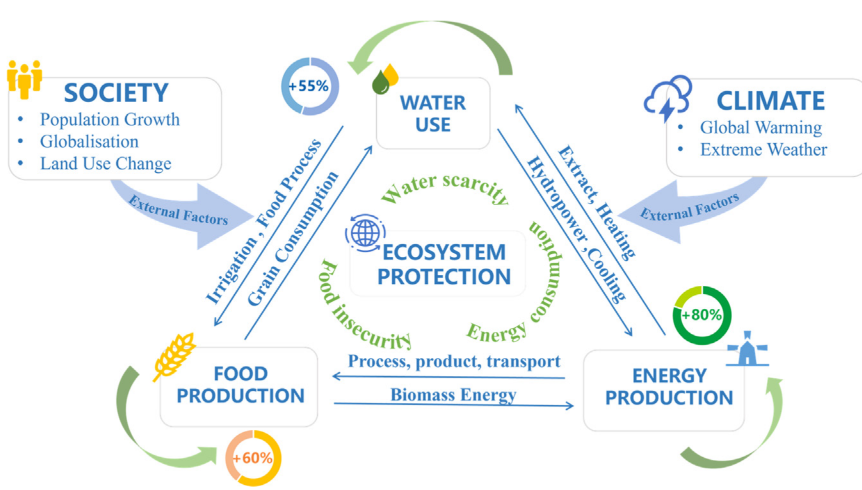

Fig. 1. Conceptual framework illustrating the interlinkages and feedbacks among water, energy, food, and ecosystem. The circular charts indicate projected percentage increases in water, energy, and food demand by 2050.

ergy transition, it also triggers land-use conflicts due to the cultivation of biomass crops, ultimately leading to biodiversity loss and increased food security risks. This contradiction exposes the decision-making limitations of the traditional WEF framework (Guo et al., 2020).

In recent years, extensive research has explored the WEF nexus from various perspectives, including resource flow calculations, technology application assessments, and system performance quantification. Furthermore, multiple literature reviews have elucidated the conceptual framework of this nexus (Endo et al., 2017; Zhang et al., 2018), associated simulation tools (Dai et al., 2018), and nexus application in regional governance (Lucca et al., 2023; Wang et al., 2023; Castelli et al., 2024; Mayar et al., 2024;Chaibi et al., 2024). These efforts have substantially advanced our understanding of the WEF nexus system. Nevertheless, despite a paradigm shift towards incorporating "ecosystems" into core frameworks, previous systematic reviews have not integrated bibliometric analysis, methodological summaries, and multi-scale case comparisons under a unified WEFE quadruple framework. Existing reviews may fail to incorporate ecosystems into analyses of the WEF nexus due to limitations in their frameworks or the lack of a multi-perspective approach. Thus, these reviews have neglected to link macro-level literature trends, meso-level methodological tools, and micro-scale applications for integrated analysis.

Therefore, this study aims to (1) delineate for the first time the macro-development trajectory and research hotspots within the WEFE nexus framework by retrieving and quantitatively analysing the literature from 2010 to 2024 and summarising the evolution of conceptual definitions and theoretical advances in the literature; (2) examine the prevailing WEFE linkage analytical approaches, including quantitative assessment, simulation forecasting, and integrated management, and evaluate their applicability, limitations, and deployment across varying geographical scales; and (3) elucidate the application priorities and differentiated challenges of WEFE linkages at distinct geographical scales through systematic, unified-framework cross-scale comparisons. Through this work, future research directions are identified to advance the sustainable development of the WEFE nexus.

2. Materials and methods

2.1. Literature search strategy

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to comprehensively investigate research on the WEFE nexus. Literature searches were performed in the Web of Science Core Collection and Scopus databases, covering the period from 2010 to 2024. These databases are regarded as the most popular and reputable platforms for conducting systematic reviews and meta-analyses of peer-reviewed scientific works (Singh and Tayal, 2022). This timeframe corresponds to the formal establishment and rapid development of the WEF nexus as an integrated analytical framework. Early foundational studies (e.g., Hightower and Pierce, 2008) are cited to illustrate the conceptual evolution but were excluded from the systematic analysis. Additionally, 82 relevant records were identified through manual screening of reference lists in review articles. The search strategy employed the following comprehensive query terms across the title, abstract, and keyword fields: (water AND energy AND food) AND (ecosystem* OR ecolog* OR environment* OR "ecosystem service*") AND ("water-energy-food" OR "water energy food" OR WEF OR "water-energy-food-ecosystem" OR WEFE OR nexus).

2.2. Literature screening

2.2.1. Inclusion and exclusion criteria

The study selection process employed explicit criteria to ensure methodological rigor. The following inclusion criteria were applied to the articles: (1) peer-reviewed publications from 2010 to 2024; (2) explicitly employing the nexus concept to analyse inter-subsystem interactions or using it as an analytical framework; (3) addressed at least three of the four WEFE subsystems, with ecosystems as an essential component; and (4) provided substantive analysis of inter-sectoral interactions through specific methodologies (e.g., modelling, empirical assessment) or systematic evaluation.

The following exclusion criteria were applied: (1) duplicate publications; (2) non-English literature; (3) exclusive focus on individual systems or pairwise relationships; and (4) unavailable full texts.

2.2.2. Screening process

The PRISMA-2020 guidelines were used to structure the screening process, as illustrated in Fig. 2. The initial identification yielded 3,983 records from databases (Web of Science: 1,753; Scopus: 2,230), which were supplemented by 82 records from manual searches, totalling 4,065 records. After duplicate removal, 2,109 unique records underwent title and abstract screening, which excluded 1,159 records. The remaining 950 publications advanced to full-text assessment, which excluded 661 articles due to an absent nexus framework (n = 267), insufficient WEFE coverage (n = 189), inadequate interaction analysis (n = 199), or inaccessible full texts (n = 6). Finally, 289 studies qualified for inclusion, of which 224 were research articles and 65 were review articles.

2.3. Data analysis and synthesis

The analytical approach integrated bibliometric and qualitative methods to address the research objectives. Bibliometric analysis using VOSviewer examined keyword co-occurrence patterns based on a frequency threshold of five, which was optimized to balance network clarity and informational richness. Qualitative content synthesis systematically categorized the methodologies, spatial scales, key findings, and challenges across studies, enabling cross-scale comparison and identification of emerging research priorities in WEFE nexus studies.

3. Results

3.1. Keyword analysis of WEFE nexus

Quantitative analysis of the literature on WEFE nexus research published from 2010 to 2024 revealed that the number of annual publications (Fig. 3) exhibited year-on-year growth, with a gradual increase in interest in the WEFE nexus over time. The number of publications in the years leading up to 2015 was relatively low (<10 per year), although a phase of rapid growth was subsequently observed. This growth was particularly significant after 2019. By 2024, the number of annual publications reached 59 and the cumulative number of publications reached 329, suggesting that the research community has increasingly focused on sustainable resource management. The cumulative number of publications (Fig. 3) increased annually, indicating the rapidly increasing popularity of the concept.

Concurrently, we observed that WEFE research outputs were predominantly published in a series of leading journals within the fields of environmental, energy, and sustainability sciences. Among the reviewed articles, they were most frequently published in the journals Sustainability, Science of the Total Environment, and Water (Fig. 4a). In addition, most of the research focused on quantitative analyses, which accounted for 81.25 % of the weight of all articles, while research focused on qualitative analysis only accounted for 12.5 % (Fig. 4b).

As shown in Fig. 5, the WEFE nexus keyword network map was divided into five clusters, with different colours representing different clusters. The keywords within each cluster are highly relevant and often co-occur in the literature. For example, the red cluster contain keywords such as "water-energy-food nexus", "climate change", and "nexus", which indicate that these concepts have been widely discussed

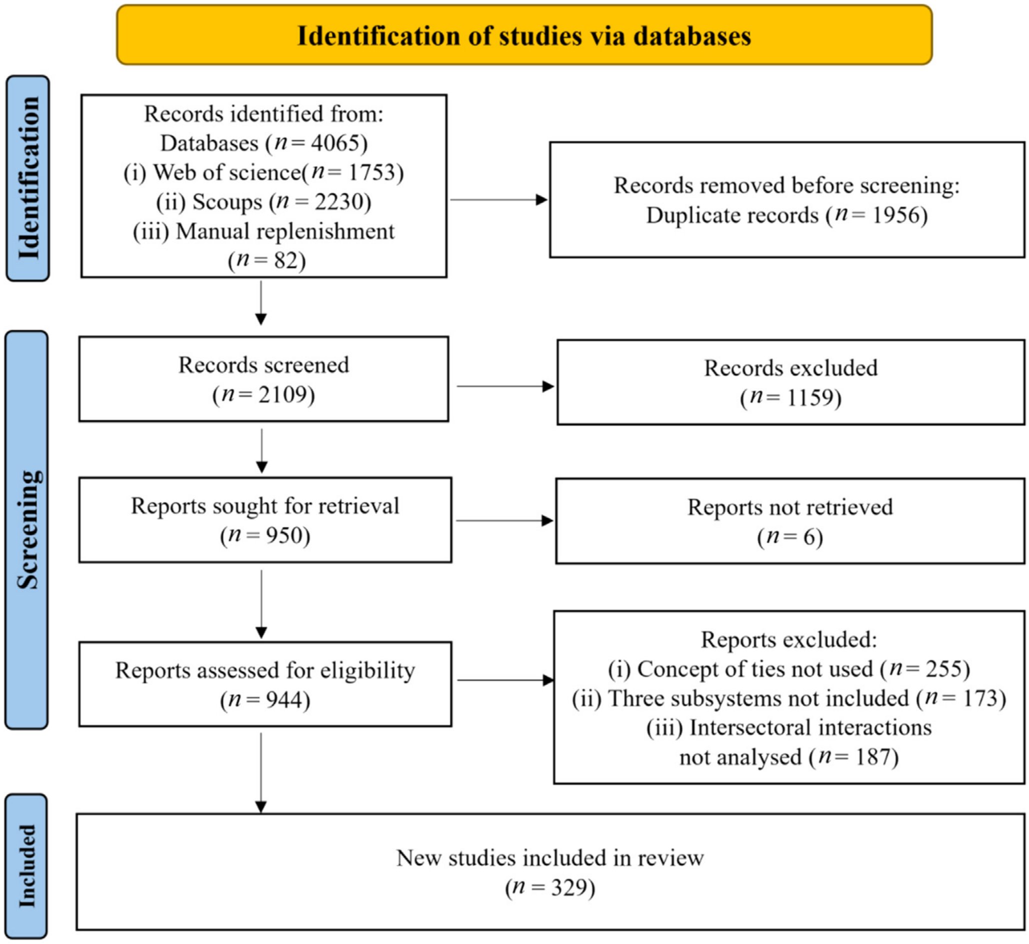

Fig. 2. Flow diagram of study identification, screening, and inclusion in the systematic review.

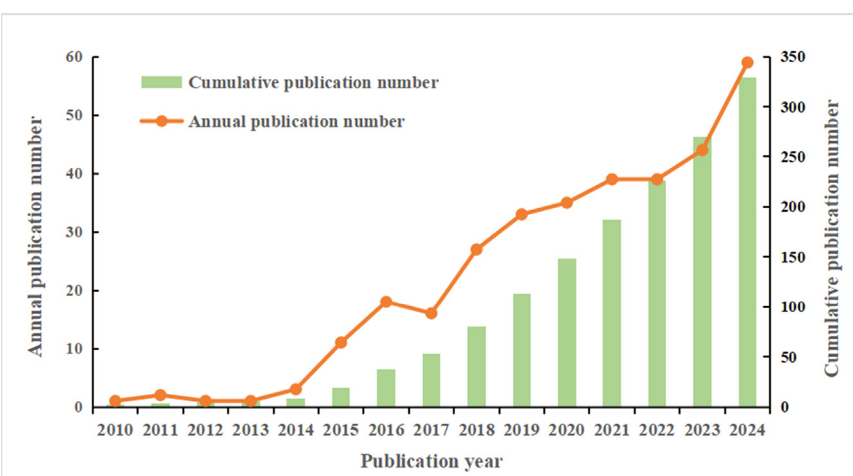

Fig. 3. Annual and cumulative number of publications related to the water–energy–food–ecosystem nexus from 2010 to 2024.

in research in this field. The node size reflects the frequency of occurrence of the keywords in the literature, with larger nodes indicating that the keywords appear more frequently in the literature. Nodes such as "water-energy-food nexus" and "sustainable development" were large, indicating the importance of these keywords in the research area. The keyword "sustainable development" was one of the most prominent in the diagram, while the keywords "water-energy-food nexus", "climate change", and "resource management" were also important themes in the field and closely related to ecosystems. Therefore, it is particularly important to include ecosystems as independent subsystems in the study of the WEF nexus.

3.2. Four stages of WEFE nexus evolution

With the development of socioeconomic conditions, dietary patterns have changed, leading to an increased demand for dairy products and meat. By 2050, the production of dairy and meat products is projected to increase by 65 % and 76 %, respectively (Di Paola et al., 2017). These

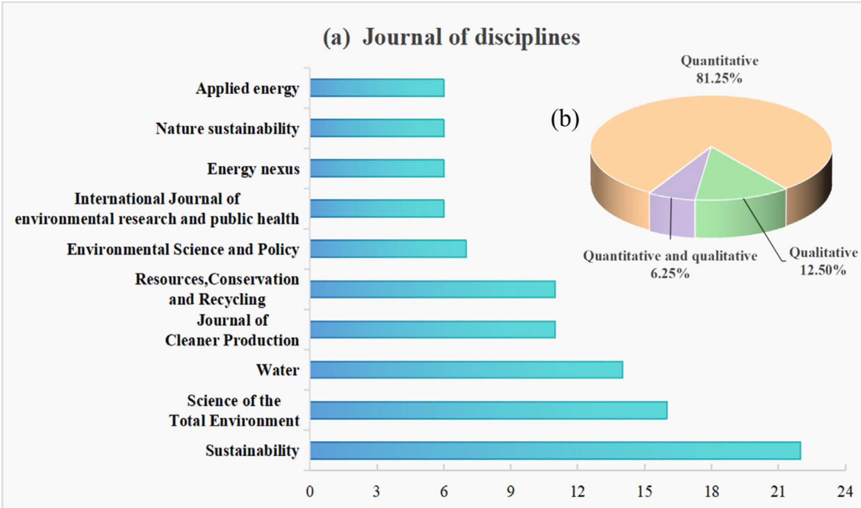

Fig. 4. Publication outlets and analytical approaches for water–energy–food–ecosystem (WEFE) nexus research. (a) Distribution of journals publishing WEFE-related studies. (b) Proportional distribution of quantitative, qualitative, and mixed analytical approaches.

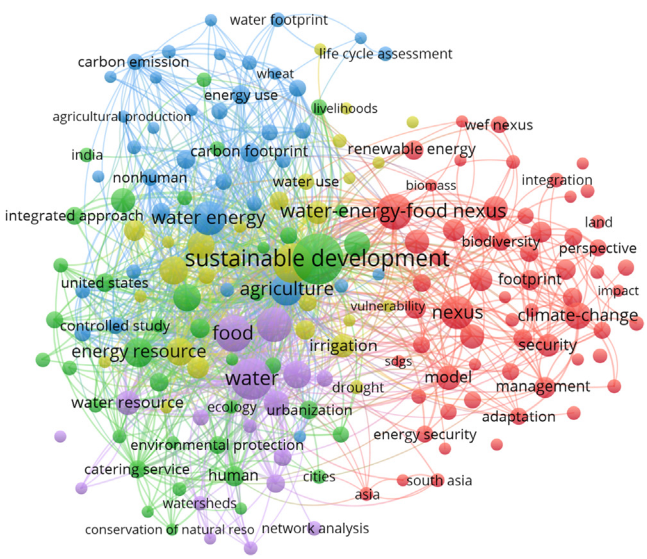

Fig. 5. Bibliometric analysis of keywords in the water–energy–food–ecosystem publications from 2000 to 2024.

changes in dietary patterns have placed greater pressure on water resources, food production, and ecosystems, thereby intensifying resource competition across various sectors. Against this backdrop, the challenge of meeting water, energy, and food demands while minimizing negative environmental impacts has become the focus of recent research. Consequently, the WEFE nexus has emerged as an interdisciplinary research field, evolving through four major developmental stages (Fig. 6).

Phase 1 (until 2010): Research on nexus relationships in this phase was relatively fragmented, with most studies focusing on individual systems (water) or the relationships between pairs of systems (water-energy), lacking a systematic approach. Hanjra and Qureshi (2010) examined the global water supply and demand situation and the link between water supply and food security. They emphasized that ensuring future food security requires actions from multiple dimensions, highlighting the critical role of sustainable water resource management in achieving food security.

Phase 2 (2011–2014): With increasing global resource scarcity and the growing demand for interdisciplinary research, the WEF nexus began to gain broader attention. The 2011 Bonn conference summarized the relationships among water security, energy security, and food security, and introduced for the first time the term “water-energy-food nexus”, thereby recognizing the interdependent connections among these three resources (Hoff, 2011). Subsequently, Bazilian et al. (2011) analysed the interconnections among water, energy, and food from the perspective of developing countries. They proposed integrated resource planning tools and optimization models to understand water, energy, and food relationships. Research during this phase marked a shift in WEF nexus studies from a focus on individual sectors to a multidimensional, interdisciplinary integration, which represented an emerging field of increasing interest among scholars.

Phase 3 (2015–2018): With the launch of the Sustainable Development Goals (SDGs) in 2015, research began to unfold within a broader framework, with the intersection of economic, environmental, and social objectives offering new perspectives on the interrelationships between water, energy, and food. The introduction of SDGs connected WEF nexus research more closely to global sustainability issues, thereby promoting the development of interdisciplinary and integrative studies. During this phase, early studies focused on the impact of individual systems on other elements (e.g., the impact of water on crop yield) (Endo et al., 2017; Zhang et al., 2019) or examined the relationships between just two systems (D’Odorico et al., 2018). Although studies generally concentrated on the relationship among the three systems (WEF), scholars gradually began to incorporate ecosystems as a subsystem within the WEF nexus, recognizing the increasingly important role of ecosystems in supporting water, energy, and food resources (Fasel et al., 2016; Lu et al., 2015; Yang et al., 2019). Bidoglio and Brander (2016) were the first to include ecosystems in the WEF system, thereby forming the four pillars of the WEFE nexus and laying the foundation for further research in this area. Subsequently, Bleischwitz et al. (2018) formally defined the WEFE nexus, marking a shift towards a more systematic and theoretical approach to studying the role of ecosystems in the WEF relationship. During this period, significant advances were also made in modelling techniques, with new methods such as integrated models, dynamic models, and simulation tools for assessing resource interlinkages gradually becoming mainstream, driving the development of both WEFE nexus theory and practice (Garcia et al., 2019). Therefore, during this phase, research into the interconnections between ecosystems and water, energy, and food gradually became a new focal point.

Phase 4 (2019–Present): Since 2019, the interdependencies among water, food, energy, and ecosystems have intensified because of global changes, particularly the impacts of the COVID-19 pandemic and climate change, and the increasingly severe challenges faced by global resource security. Karabulut et al. (2019) highlighted that ecosystem restoration represents a key policy for alleviating resource scarcity and

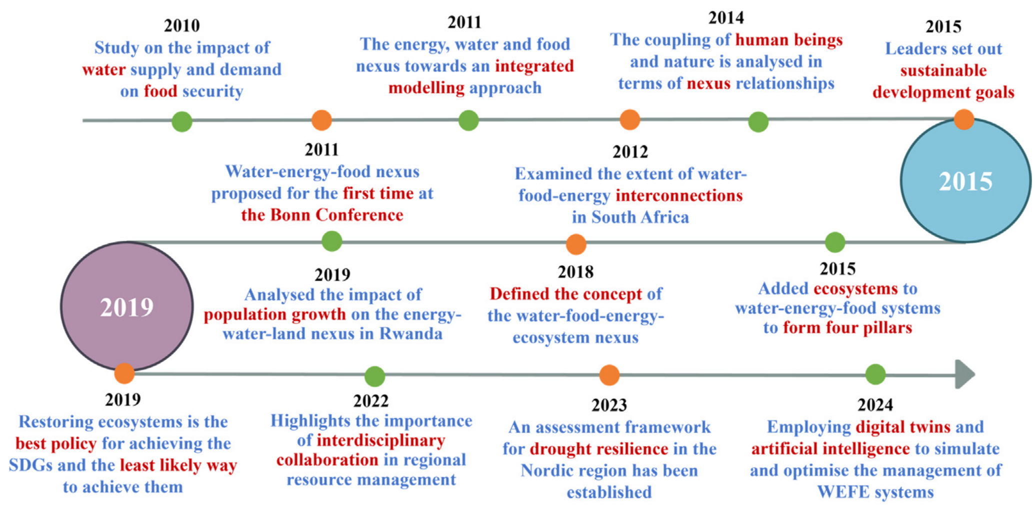

Fig. 6. Timeline of research progress and key milestones in the evolution of the water–energy–food–ecosystem nexus (2010–2024).

ensuring sustainability, although its implementation remains highly challenging. Against this backdrop, new research directions and emerging hotspots have begun to take shape. The integration of digital technologies with WEFE nexus research is at the forefront. For instance, Shehadeh et al. (2024) applied digital twins and artificial intelligence to simulate and optimize WEFE system management. Simultaneously, in response to the increasingly variable climate, the assessment and enhancement of the resilience of WEFE systems have become core research focuses. Qin et al. (2022) emphasized the importance of interdisciplinary collaboration in regional resource management, while Teutschbein et al. (2023) developed a drought resilience assessment framework for Northern Europe. Research attention has also expanded to social dimensions and systematically considered equity and governance in resource management. For example, Favi et al. (2024) highlighted challenges related to just transitions in the adoption of agro-photovoltaic technologies in West Africa, and Apeh and Nwulu (2024) developed frameworks to evaluate the impacts of policy interventions on different social groups. Overall, current WEFE nexus research has moved beyond the early stage of conceptual clarification and entered a new period focused on addressing real-world challenges through technological innovation, resilience building, and equitable governance, thereby pursuing systematic solutions.

3.3. Application and development of WEFE nexus analytical methods

The methods used in WEFE nexus research vary depending on the specific focus of the nexus system and can generally be divided into three types: quantitative assessment, simulation forecasting, and model integration (Fig. 7). Owing to the interdisciplinary and cross-sectoral nature of nexus research, no single method is applicable in all situations.

3.3.1. Quantitative assessment methods

Studies on quantitative assessments fall into two main categories: state assessments and physical association. State assessments, which assess the state of security and the spatial variability, efficiency, resilience, vulnerability, and sustainability of the WEFE nexus, are generally performed via approaches such as the Investigations And Mathematical Statistics (IAMS) method and Integrated Index Method (IIM).

IAMS illustrates linkages through field surveys, expert panels, public data collections released by local agencies and governments, and relevant literature and thus is the most widely used method for exploring the interactions between linked sectors. Combining multiple multicriteria analyses, researchers quantitatively assess the interactions within

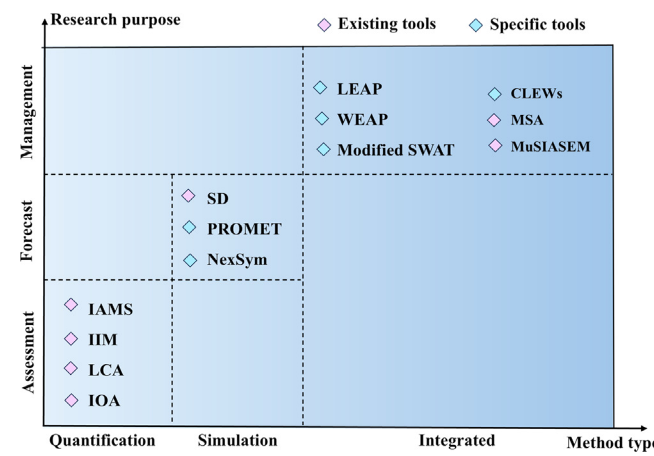

Fig. 7. Classification of tools in water–energy–food–ecosystem nexus research. Existing Tools: models not exclusively designed for the nexus; Specific Tools: tools custom-developed for nexus studies.

the WEFE nexus by tracking and analysing the consumption of relevant resources associated with the production process of a given resource. Van den Heuvel et al. (2020) analysed the water-energy-food-land-climate nexus in Sweden from the perspective of ecosystem services and performed literature and expert assessments to examine the impact of human pressures from related sectors on ecosystem functions and services. At the same time, this method helps to capture the key factors that dominate the evolutionary processes of water, energy, food, and ecosystems (Van den Heuvel et al., 2020). Using this approach, Wolde et al. (2021) systematically explored the drivers that lead to the degradation of linkage resources and revealed that social (48 %), economic (19 %), and policy and institutional changes (14 %) are the main linkage resource driver indicators.

The IIM usually presents the various social and environmental characteristics of a system through multiple indicators and captures the overall characteristics of the nexus system by constructing indicators for a comprehensive assessment. For example, Li et al. (2022) used the IIM approach to quantify the coupled coordination degree of WEFE nexus in 30 Chinese provinces from 2006 to 2009, and their results showed that most provinces were at the barely coordinated stage. Halytsia et al. (2024) developed a composite indicator at the policymaker-farm level to capture the interlinkages between agricultural production and the water, energy, and environment nexus pillars. However, the application of these indicators to the WEFE nexus remains challenging because it is highly dependent on the system database, and the uncertainty of the study boundary leads to difficulties in constructing a rational indicator system and eliminating the bias that arises from the use of weights among the indicators (Yigitcanlar et al., 2015).

Physical linkages refer to the inter-consumption relationships among water, energy, food, and ecosystem resources. Generally, two complementary approaches are available: bottom-up Life Cycle Assessment (LCA) and top-down Input-Output Analysis (IOA). LCA is a typical method of quantifying the environmental impacts of a given product or process throughout its life cycle. Naranjo et al. (2023) used the LCA methodology to assess the environmental and socio-economic impacts of irrigated agricultural production in Ecuador and revealed that banana production has the highest environmental impacts. IOA links WEFE to economic activities to describe the input and output processes of WEFE resources in different economic systems and has been extensively applied at various scales to examine the relationships between WEFE flows and economic activities across regions and sectors, including metabolic flows in urban metabolism (Chen and Chen, 2016) and global energy trade (Duan and Chen, 2017).

3.3.2. Modelling prediction methods

In addition to quantitative assessments, extensive work has been conducted on modelling predictions for the WEFE nexus. Such research covers a wide range of social and natural sciences fields, and forecasting modelling methods assess the impacts of multiple economic, social, and climatic factors on the resource system by constructing multi-scenario frameworks. The field is dominated by system dynamics (SD) methods, the Process-based Hydroagroecological Model (PROMET), and a unique instrumental Nexus Simulation System (NexSym).

SD is based on causal mechanisms and assumes that the behaviour of a system is determined by its structure. By establishing causal feedback loops within a system, SD facilitates systematic analysis of multi-sector systems at both macro and micro levels, making it particularly suited for examining the multidisciplinary interactions and multi-stakeholder issues within the WEFE nexus. For example, Feng et al. (2016) used this approach to model the dynamics of the water supply, power generation, and environment in the Yellow River region to illustrate the impact of different driving variables on changes in the state of the system. This approach has been widely used for policy assessment. In addition, Susnik et al. (2021) collected relevant policy information as input for an SD model to assess the impact of future policies and found that by 2050, consumption will level off while food and energy production will increase.

PROMET is a process-based framework that simulates land surface energy and material fluxes (water, carbon, nitrogen) following physical principles while strictly conserving energy and mass. It enables detailed modelling of the interactions and feedbacks between dynamic plant growth and terrestrial water balance (Mauser et al., 2015). Probst et al. (2024) used this framework to quantify the trade-offs between agriculture, hydropower, and (aquatic) ecosystems by simulating three maize irrigation practices. Their results showed that maintaining water-efficient irrigation is economically advantageous and improving irrigation water use efficiency is the key to mitigating competition for water in agriculture.

The NexSym tool was designed for local-scale applications, and it models co-located technological and ecological processes within a geographically defined area where decision-making and implementation can be coordinated. It is intended to simulate the processes and their interactions within local production systems. Martinez-Hernandez et al. (2017) used the NexSym simulation tool to assess the co-design of local linkage systems in UK eco-towns. The limitations of this model are that it is only applicable to local towns in the UK and thus is not applicable at a larger scale (national or global), has high data requirements, only focuses on the impacts of resource depletion and the environment, and does not integrate economic and social aspects.

3.3.3. Modelling integration methods

Optimal decision-making that considers multiple systems, stakeholders, and their interactions is a complex process involving various modelling and computational complexities (Zhang et al., 2019). Integration tools use a systems thinking paradigm to consider the resource requirements of different future scenarios and integrate simulation forecasting models to help decision-makers develop appropriate resource management strategies. Compared with quantitative assessment and simulation prediction, model integration is still less researched; however, it represents a hot future direction.

Integrated models typically use a series of existing methods and tools to support decision-making for WEFE nexus management. The models that guide strategic policymaking are generally divided into two main categories. The first includes models dedicated to natural systems modelling, including energy modelling (Long Range Energy Alternatives Planning, LEAP), water modelling (Water Evaluation and Planning Model, WEAP) (Nasrollahi et al., 2021), and integrated modelling (modified Soil and Water Assessment Tool (SWAT) (Karabulut et al., 2016) and integrated Climate Change-Land-Energy-Water models (CLEWs) (Hermann et al., 2012)).

The second includes models dedicated to modelling human activities, such as the Multi-sectoral Systems Analysis (MSA) model (Villarroel Walker et al., 2012), which provides a systematic understanding of material (water, food, nutrients, etc.) and energy flows and the impact of human activities on urban metabolism; and the Multiscale Integrated Assessment of Social and Ecosystem Metabolism (MuSIASEM) model (Apeh and Nwulu, 2024), which is used to study the relationships between structural and functional components of social-ecological systems, among others. These models provide a deeper representation of the complexity of the WEFE nexus through a multisystem modelling approach and support the management of WEFE for policymakers and stakeholders. Integrating these tools requires using the output of one model as an input for another; however, the models do not share uniform accuracy standards for the data.

To facilitate a clearer comparison across these three methodological categories, Table 1 summarizes their key characteristics in terms of analytical focus, representative approaches and tools, strengths, limitations, and typical application scales in WEFE nexus research.

3.4. Case studies of WEFE nexus applications at different spatial scales

The interdependencies betwee WEFE components form core issues within contemporary sustainable development. With population growth, skyrocketing resource demands, and ongoing climate change impacts, effectively coordinating and managing these resources has become a global priority. These challenges are not confined to a single country or region but rather span various scales from urban to global. Fig. 8(a) illustrates the distribution of the WEFE nexus types across different regions and highlights the regional variations in the focus on various nexus types. In North America, the water ecology nexus accounts for the largest proportion, indicating a strong emphasis on the relationship between water resources and ecosystems. Although the climate-related and food-energy nexus are also present, their proportions are relatively smaller. In contrast, Europe demonstrates a more balanced focus and exhibits relatively similar proportions among the water-energy, climate-related, and water-food nexus. The water-food nexus is the dominant focus in Asia, Africa, and South America, with Asia leading in the number of related publications. This suggests that more attention should be paid to water resource management and agricultural sustainability in this region. In addition, Oceania places greater emphasis on the food ecology nexus.

Fig. 8(b) and 8(c) further demonstrate significant regional variations in the distribution of WEFE nexus research across different scales. At the urban scale, research in Asia represents the highest proportion, whereas that in South America is significantly limited. At the regional scale, both Asia and Africa stand out based on their substantial contributions.

Table 1
Comparison of major analytical methods for the water-energy-food-ecosystem nexus.

Method	Main purpose	Approaches and tools	Strengths	Limitations	Scale	Citation
Quantitative assessment	Assess system status, efficiency, coordination, and sustainability or quantify resource consumption between systems	IAMS, IIM, LCA, IOA	• Simple structure • Suitable for cross-regional comparison • Effective for identifying dominant drivers	• Strong dependence on indicator selection and system boundaries • Weighting subjectivity • Limited representation of dynamic feedbacks	Urban, Regional, National	Van den Heuvel et al. (2020); Li et al. (2022)
Simulation forecasting	Explore system dynamics and future scenarios under socio-economic and climatic drivers	SD, PROMET, NexSym	• Captures feedback mechanisms and temporal evolution • Suitable for policy scenario analysis	• High data requirements • Strong dependence on model assumptions • Limited scalability in some tools	Urban, Regional	Feng et al. (2016); Probst et al. (2024)
Model integration	Support policy-oriented decision-making through multi-system coupling	WEAP–LEAP, SWAT, CLEWs, MuSIASEM, MSA	• Integrates natural and socio-economic subsystems • Supports multi-sector and multi-stakeholder analysis	• Model coupling complexity • Data consistency and accuracy constraints • High computational demand	Regional, National, Transboundary	Villarroel Walker et al. (2012); Nasrollahi et al. (2021); Apeh and Nwulu, (2024)

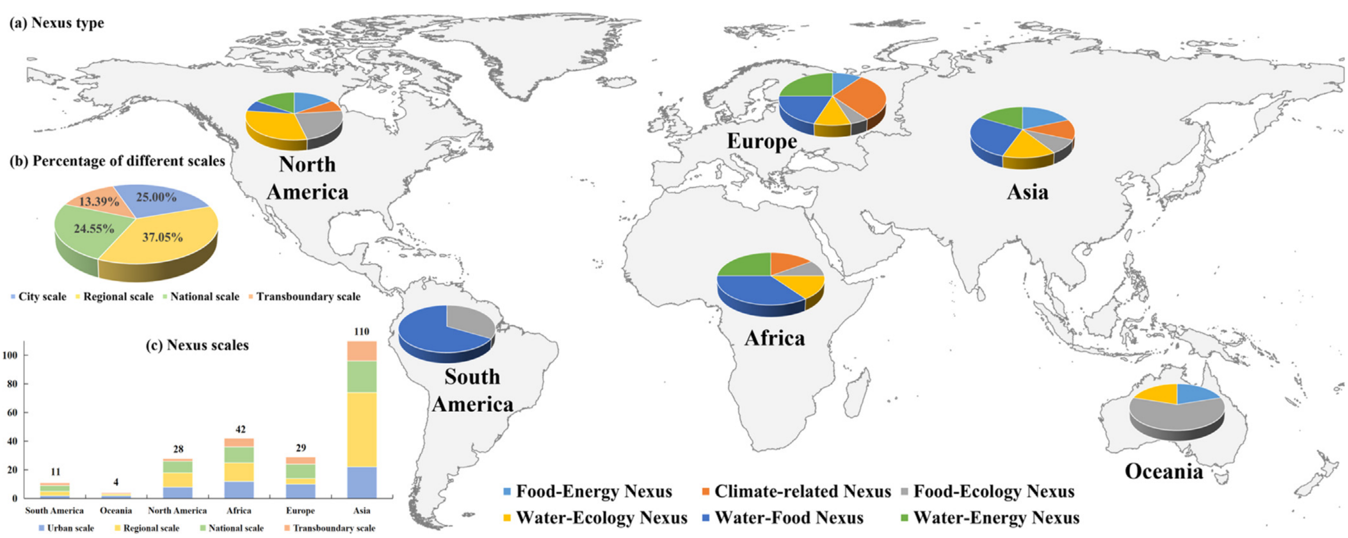

Fig. 8. Distribution of bond types and scales in different regions. (a) Nexus types in different regions; (b) representation of the percentage of different scales globally; (c) distribution areas of nexus at different geographic scales.

National-scale research is concentrated in Africa and Europe, whereas transboundary research is predominantly conducted in Asia and Africa. Overall, most research on the WEFE nexus has focused on regional and urban scales, with relatively little attention given to the transboundary scale.

To fully understand the challenges of the WEFE nexus across different geographical scales, this study analysed and summarized existing research at four scales: urban, regional, national, and transboundary. The aim was to explore the key focus areas and differences in the WEFE system at each level and provide theoretical and practical insights for future cross-scale resource management.

3.4.1. Urban scale

Population growth and urbanization represent defining societal features in recent decades. Approximately 50 % of the global population resides in urban areas, which is expected to reach 70 % by 2050 (Zhang, 2016). As urban populations continue to grow, the resources within cities will become insufficient to meet the associated demands, thus requiring large external inputs of resources. In this process, the interactions among water, energy, food, and ecosystems have become increasingly complex. Against the backdrop of urbanization, cities have become the focal point for global research on water, energy, food, and ecosystems. Urban-scale studies are primarily concentrated in Asia, a trend closely linked to the region's rapid urbanization process and the resulting pressure on resources (Zhuang et al., 2021).

Urban-scale research focuses on the management of intra-city resources and system optimization. By constructing a WEFE nexus evaluation indicator system or methodological framework, the complex relationships between subsystems can be evaluated to optimize resource allocation and enhance urban resilience (Fig. 9). For example, Yang et al. (2024) assessed ecosystem services in the Beijing-Tianjin-Hebei region using the InVEST model, analysed the impact of urbanization on ecological resources, and provided important insights and recommendations for sustainable resource management. Ling et al. (2024) investigated the evolutionary trends of water, energy, food, and ecosystems in Henan Province using a SD model and proposed optimization strategies for future resource management. These studies reflect the significant contributions of Asian cities to improving resource efficiency, reducing waste emissions, and promoting resource recycling.

By comparison, urban research on African cities comes second. For example, in the Irbid refugee camp in Africa, monitoring and regulating the supply and demand of resources through digital methods has helped alleviate the resource pressures of rapid population growth (Yigitcanlar et al., 2015). However, such studies are clearly underrep-

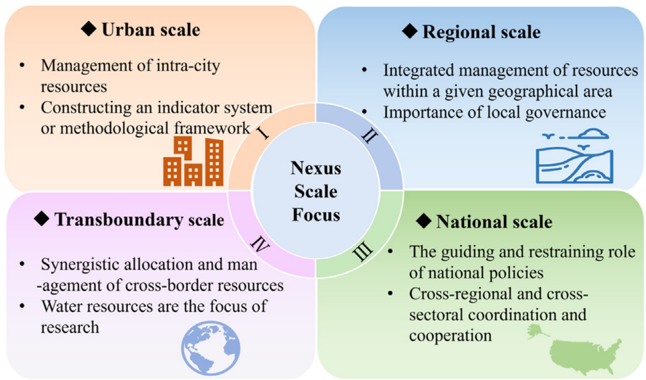

Fig. 9. Research focus of the water–energy–food–ecosystem nexus across urban, regional, national, and transboundary levels.

resented, and more resource management studies for African cities are needed in the future, primarily to address the challenges of rapid urbanization and poor infrastructure.

3.4.2. Regional scale

Integrated studies at the regional level usually cover large geographical areas and are based mainly on river basins; thus, they include cities and wider watersheds. A number of important conclusions can be drawn from regional-scale studies, which emphasize the integrated management of resources within a given geographical area and address the sharing and coordination of resources between different regions (Fig. 9). Asia and Africa dominate regional-scale studies, thus reflecting the complex resource management needs of these two regions, such as regional resource sharing and policy systems across different regions.

In Africa, Gebre et al. (2023) used an optimization model to analyse the allocation of land and water resources in the Omo-Gibe River Basin in Ethiopia and proposed strategies to maximize benefits and minimize conflict trade-offs. This study demonstrated the outstanding contribution of regional-scale research in Africa to the efficient use of water resources and reduction of conflicts. Similarly, a study of smallholder economies in the North African region highlighted the threat of climate change to food security and proposed regional policy response strategies (Kertolli et al., 2024). Studies in Asia at the regional scale include typical cases such as the Yellow River Basin and revealed that extensive irrigated agriculture in the Yellow River Basin not only consumes large amounts of water and energy but also poses challenges to food supply and ecosystem sustainability (Zhang et al., 2024).

Studies at the regional scale also emphasize the importance of local governance, which can be better adapted to specific social and environmental conditions by encouraging the participation of local communities in resource management. Studies have shown that the application of digital technologies in urban environments can effectively manage the WEFE nexus in cities and improve regional sustainability and resilience (Shehadeh et al., 2024). This local governance model contributes to policy effectiveness and enhances ecosystem services. The application of models such as WEAP, LEAP, and InVEST in regional studies not only reveals synergies in resource management but also highlights the threats of climate change to regional ecology (Nasrollahi et al., 2021). In the future, regional-scale studies should focus on integrating ecosystem restoration and local community participation to achieve sustainable resource use (Hanes et al., 2018).

3.4.3. National scale

Compared with urban- and regional-scale studies that focus on internal resource management and coordination and emphasize specific technical solutions and local management approaches, national-scale research places greater emphasis on macro-level policy formulation, strategic resource allocation, and cross-regional and cross-sectoral coordination and cooperation (Barati et al., 2023; Blicharska et al., 2024). National policies guide and constrain water, energy, food, and ecosystem security and typically support technological innovation (Papadopoulou et al., 2022) to improve people's livelihoods (Fig. 9). Asia and Africa play significant roles in national-scale research.

In sub-Saharan African countries, solar photovoltaic systems are being promoted to improve rural resource supply conditions (Favi et al., 2024). In contrast, the policy goals of Nordic countries exhibit synergies and conflicts. Climate policy objectives align with energy and groundwater quality goals, whereas agricultural and forestry production targets conflict with environmental quality goals, with the key issue lying in the context or interpretation of these goals (Blicharska et al., 2024). At the national scale, we found that water scarcity, climate change, and population growth continue to be challenges many countries face. Strategic resource allocation plays a crucial role in addressing these challenges and ensuring the balance between water, energy, and food supply and demand. For example, in response to the Aral Sea disaster, Uzbekistan used a tailored framework to assess the relationships between the WEFE nexus and provide strong policy support for arid regions (Song et al., 2023). Additionally, when developing policies for resource allocation, nations must consider the timeliness of legislation and improvements in institutional structures to minimize environmental damage (Wolde et al., 2021).

Resource management in national-level WEFE nexus studies represents an issue for individual sectors or regions that often involve cross-regional and cross-sectoral coordination. Research by Blicharska et al. (2024) indicated that the coordination between water, energy, and climate policies could effectively promote sustainable resource management. In the context of global climate change, countries must not only strengthen the integration of domestic policies but also engage in international cooperation to address global challenges such as droughts. Research in Sweden has also emphasized the importance of international cooperation frameworks, highlighting the key role of transnational collaboration in solving global resource issues (Teutschbein et al., 2023) (Fig. 9).

3.4.4. Transboundary scale

Transboundary resource management and planning across multiple countries is more complex than that for a single city, country, or large regions of multiple countries (Dai et al., 2018). As shown in Fig. 8, at the transboundary scale, research on the WEFE nexus is concentrated in Asia and Africa, focusing on the collaborative allocation and management of cross-border resources. Resource flows transcend political boundaries, and cooperation among countries ensures the sustainable use of resources. Wang et al. (2024) noted that the management of transboundary water resources requires a comprehensive consideration of the needs and policies of different countries to ensure the continuity and stability of ecosystem services. By establishing cross-border cooperation mechanisms, stakeholders can more effectively address issues of resource scarcity and environmental degradation. Ma et al. (2024) applied multilevel opportunity-constrained fuzzy programming to optimize the allocation of water and energy resources for sustainable resource use in a study of Central Asian countries. Moreover, transboundary research has revealed the profound impact of climate change on regional ecosystems, particularly in vulnerable ecological areas (Qi et al., 2017). Studies have shown that trans-boundary governance can promote stakeholder participation, thereby better addressing the challenges posed by climate change. Through collaborative management and information sharing, regions can develop greater resilience and reduce the negative impacts of climate change on resources and ecosystem services (Hurtado et al., 2024). Such cooperation not only improves resource use efficiency but also promotes sustainable development across regions (Fig. 9).

In the transboundary context, water has been investigated as a shared resource because the security of the supply and demand of water resources determines whether a region is stable and sustainable. For example, in the Amu Darya River Basin in Central Asia, water-related disputes have occurred between upstream countries seeking to construct reservoirs for power generation and downstream countries seeking to irrigate agricultural fields. The uncoordinated water management in this basin has created tensions and undermined the trust between the countries, thus reducing the opportunities for regional cooperation. The focus on water resource management in other transboundary regions varies according to the geography, resource needs, and policy contexts. For example, the Zambezi and Niger river basins in Africa are mainly concerned with trade-offs between water resources and ecosystems due to population growth (Apeh and Nwulu, 2024). De Strasser et al. (2016) proposed the Transboundary River Basin Nexus Approach (TRBNA) to assess the WEFE nexus in transboundary river basins and help identify and resolve conflicts and synergies between resources and sectors such as water and food. Similar studies in the Danube River Basin and Mediterranean region (Raviv et al., 2024) have proposed corresponding framework models to explore how benefits can be shared between these countries.

This review shows that different interpretations and methodologies have been applied to the WEFE nexus when addressing various scales. Although the associated concepts and theoretical frameworks for practical WEFE nexus management are lacking, empirical nexus research is thriving and increasing in popularity. Ecosystem components are being progressively incorporated into nexus research. Overall, WEFE nexus research is primarily conducted at transboundary and regional scales, while research at the urban scale (i.e., the relationship between WEFE resources and population, society, and economy) is relatively rare. Many nexus studies are case studies specific to certain fields.

4. Discussion

4.1. Evolution of the WEFE nexus conceptual framework

Although the WEFE nexus has emerged as a prominent analytical paradigm in global resource studies, its interdisciplinary nature and multi-scalar dynamics have precluded the establishment of a universally accepted definition and system boundary. Such ambiguity undermines the comparability of research findings and constrains the framework's applicability in policy practice. In general, previous studies reflect two main orientations, with one emphasizing the internal flows and interactions among resources (e.g., water–energy coupling) (Liu et al., 2016) and the other viewing the nexus as an integrative analytical approach for identifying synergies and trade-offs across systems (Keskinen et al., 2015). These orientations differ substantially in terms of research scale, boundary delineation, and goal setting. Researchers often define system boundaries based on geographical context, resource flow pathways, or policy needs, which limits the generalizability of these findings in cross-regional or cross-sectoral comparisons (Hoff, 2011). When examining systemic relationships solely within a single department or spatial scale, extrapolating conclusions to broader contexts is often difficult. For instance, in their study of embedded energy within US agricultural, municipal, and industrial water use, Liu et al. (2016) found that embedded energy accounted for only 1.0 %–1.9 % of the total energy consumption when considering only narrow boundaries. However, when the scope was expanded to include broader applications such as steam-driven power generation, this proportion increased to 47 %. Future research should work toward clarifying system boundaries, specifying interaction mechanisms, and developing standardized indicator systems to advance the conceptual coherence and methodological robustness of the WEFE framework.

Moreover, the debate over the practical value of the nexus framework is intensifying. Some scholars argue that although the nexus has gained substantial policy traction, it is sometimes invoked without providing clear mechanisms for implementation. Mehta et al. (2014) contended that overly technocratic nexus framings may obscure underlying political-economic inequities and environmental justice issues. Meanwhile, in an examination of the water-employment-migration nexus, Hussein and Ezbakhe (2023) demonstrated that many emerging nexus approaches remain conceptually appealing but lack concrete pathways for operationalization. In contrast, other researchers underscore the analytical and governance benefits of the nexus perspective. Albrecht et al. (2018) showed that quantitative WEF nexus tools can systematically capture cross-sector linkages and support integrated resource allocation decisions. Similarly, Al-Saidi and Hussein, (2021) argued that system-wide shocks such as COVID-19 revealed the depth of interdependencies among water, energy and food systems, underscoring the need for risk-sensitive, integrated planning rather than silo-based management. Taken together, these debates illustrate that the nexus is not a static concept but rather an evolving analytical framework (Vanham et al., 2016). Despite its limitations, extensive empirical evidence confirms the intricate interconnections between water, food, energy and ecosystems. Neglecting these interactions risks fragmented policy-making and unintended systemic consequences, thereby further underscoring the necessity for sustained WEFE linkage research.

4.2. Critical role of ecosystems within the WEFE nexus

The literature indicates that ecosystems are not merely peripheral contexts within the WEF nexus, but rather active components that shape system interactions and determine the direction of synergies or trade-offs. Ecosystems provide diverse regulatory, provisioning, support, and cultural services and thus modulate hydrological processes, promote agricultural productivity, and mitigate environmental impacts arising from energy production. Neglecting these ecological feedbacks frequently leads to fragmented cross-sectoral governance and unintended consequences.

In the water–ecosystem nexus, ecosystems such as forests and wetlands play a central role in water supply security by sustaining water sources, regulating runoff, and improving water quality (Melo et al., 2021). However, excessive human exploitation of water resources, such as large-scale reservoir operations and groundwater over-extraction, can disturb hydrological processes and lead to the degradation of ecosystem structure and function (Mirzaei et al., 2019). In the energy–ecosystem nexus, ecosystems serve as both spatial carriers for energy development and recipients of its environmental impacts. When land-use competition is not properly considered, the expansion of bioenergy may trigger deforestation, increaseed in food prices, and higher carbon emissions (Tilman et al., 2011). In the food–ecosystem nexus, services such as pollination, nutrient cycling, and soil retention constitute the ecological foundation of agricultural production (Lu et al., 2015). However, agricultural intensification, excessive fertilizer use, and land-use change frequently lead to eutrophication, soil degradation, and biodiversity loss (Hanjra and Qureshi, 2010). These bidirectional interactions indicate that ecosystems function as the "critical hub" of the WEFE framework, with their feedback mechanisms shaping the direction of system synergies or conflicts. Neglecting ecosystem processes frequently leads to policy failure, as observed with the rise in food prices and forest loss associated with biofuel policies (Tilman et al., 2011).

Therefore, future governance should systematically integrate ecosystems into the internal structure of water-energy-food interactions, thereby driving a shift from "optimising resource efficiency" towards "enhancing system resilience". Integrating natural capital accounting and quantified ecosystem services into WEFE models can help balance ecological, economic, and social objectives in decision-making. Such an ecosystem-oriented governance paradigm not only addresses the limitations of traditional nexus frameworks but also provides new pathways for achieving SDGs.

4.3. Challenges in data integration and dynamic modelling

Although significant progress has been made in the methods and modelling applications for WEFE research, key challenges remain, including dispersed data, limited model feedback, and insufficient multi-source information integration. First, differences in research objectives and scales lead to substantial variations in data sources, quality, and structure (Zhang et al., 2018). This issue is particularly pronounced in developing countries, where data are often obtained from multiple governmental departments and lack unified standards and sharing mechanisms, thereby reducing model reliability and comparability. Second, multi-model coupling analyses commonly face "input–output mismatches". For instance, input–output models rely on annual statistical data, whereas SD models require continuous time-series data, thereby limiting the precision of model integration (Hermann et al., 2012). In addition, most existing assessment tools remain static (e.g., life-cycle assessment and linear programming), thereby increasing the difficulty of capturing feedback associated with climate change and socio-economic dynamics (McAvoy et al., 2021).

These limitations weaken the predictive capacity of WEFE research and constrain its policy relevance. To address these challenges, future studies should focus on the integration of multi-source data and development of dynamic simulation methods. On one hand, combining remote sensing, Internet of Things-based monitoring, and statistical data can create cross-scale and cross-sectoral integrated databases, which will reduce biases caused by fragmented data (Vanham et al., 2013). On the other hand, models should evolve from static assessments toward dynamic feedback simulations by integrating LCA and SD approaches, which will enhance the models' responsiveness to complex system changes (Sušnik, 2018). Furthermore, exploring real-time decision-support platforms based on artificial intelligence and digital twin technologies can improve scenario adaptability and policy applicability.

4.4. Complexity and variation of governance across different geographical scales

Sustainable governance of the WEFE nexus is essential for achieving coordinated resource management. However, governance objectives, constraints, and priorities vary significantly across geographic scales (Dai et al., 2018). At the urban level, the focus is on technological innovation and resource recycling, such as smart water management and energy recovery. At the regional level, emphasis is placed on ecosystem restoration and climate adaptation. At the national level, the priority is resource self-sufficiency and macro-level regulation, while at the transboundary government level, the focus is on complex international cooperation mechanisms. Interactions across these scales shape how resource conflicts and synergies are manifested. In this study, the classification of scales follows functional resource-management units, particularly river basins at the regional scale, rather than administrative hierarchies because resource management units more accurately capture hydrological and ecological interactions across boundaries. Nevertheless, future research could benefit from incorporating nested multi-level analyses, including provincial-scale comparisons, to better reconcile administrative governance structures with the cross-boundary dynamics of the WEFE nexus. From a global perspective, governance challenges differ across regions. For example, in Europe, policy trade-offs between agricultural subsidies and hydropower allocation are observed (Kurian, 2017); in South Asia, transboundary rivers such as the Brahmaputra highlight the dual challenges of climate change and geopolitical tensions (Yang et al., 2016); in Africa, weak infrastructure and data scarcity impede effective resource monitoring (Chirisa and Bandauko, 2015); and in the Americas and Oceania, the main challenges lie in balancing energy development with ecological conservation.

To address these variations, future research should advance the following actionable policy and practice pathways. At the operational level, real-time resource monitoring systems should be established to leverage digital technologies to enhance the dynamic assessment capabilities of integrated models such as SWAT and LEAP. At the institutional level, market-based policy instruments, including ecological compensation schemes and resilient water quotas, can be designed to reconcile resource competition with ecological conservation objectives (Cai, 2020). Furthermore, efforts should be made to formally incorporate WEFE nexus system assessments into national voluntary review reporting frameworks for SDGs. At the organisational level, multi-stakeholder collaboration platforms such as "Transboundary WEFE Coordination Committees" should be actively established. Through knowledge sharing, technology transfer, and conflict arbitration mechanisms, cross-border resource governance cooperation can be strengthened, thereby systematically enhancing governance effectiveness and resilience at both global and regional scales (Wang et al., 2024).

Of note, certain methodological limitations of the present review should be mentioned. Although explicit inclusion and exclusion criteria were applied to reduce potential bias and enhance transparency, a degree of subjectivity is inevitably involved in decisions regarding the inclusion or exclusion of publications. Consequently, this review may not capture all potentially relevant studies. Nevertheless, the analysed body of literature provides a robust and representative synthesis of the current state, dominant trends, and key challenges in WEFE nexus research.

5. Conclusions

This review systematically examined the evolution of WEFE nexus research from 2010 to 2024 using the PRISMA methodology combined with bibliometric analysis. The study shows that the field has rapidly evolved from early conceptual analyses and the WEF triad framework to a comprehensive quaternary paradigm that incorporates ecosystem dimensions. Publication trends and keyword dynamics reveal a growing emphasis on ecosystem integration, system resilience, and sustainability under global change, suggesting a clear maturation of the field from conceptual exploration toward more applied and system-oriented research. The review further shows that WEFE research is characterized by a diverse but uneven methodological landscape. Quantitative indicator-based assessments remain the most widely adopted approaches due to their operational simplicity and comparability, whereas simulation-based methods, particularly SD and process-based models, provide stronger capabilities for scenario analysis and policy evaluation but are constrained by data availability and model complexity. Integrated modelling frameworks, although less frequently applied, demonstrate substantial potential for supporting cross-sectoral decision-making. Importantly, the application priorities and analytical challenges of WEFE linkages vary markedly across urban, regional, national, and transboundary scales, underscoring the need for scale-sensitive methods and governance strategies rather than one-size-fits-all solutions.

Despite notable progress, persistent challenges remain, including inconsistent conceptual definitions and system boundaries, fragmented and heterogeneous data sources, limited incorporation of dynamic feedback mechanisms, and insufficient cross-sectoral and cross-scale governance coordination. Addressing these issues will require greater conceptual standardization, enhanced integration of multisource data, and the development of dynamic, feedback-enabled modelling tools that better capture socio-ecological interactions. By advancing these directions, future WEFE research can more effectively support sustainable resource management and evidence-based policy-making at regional, national, and global scales.

Declaration of competing interests

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

CRediT authorship contribution statement

Xiyan Wang: Writing – original draft, Visualization, Methodology, Formal analysis. **Weili Duan:** Writing – review & editing, Supervision,

Funding acquisition, Conceptualization. **Shan Zou:** Writing – review & editing, Supervision. **Zhonghao Zhang:** Writing – review & editing, Data curation. **Wei Wei:** Writing – review & editing, Data curation. **Meiqing Feng:** Data curation. **Yanfeng Di:** Data curation. **Chengkun Li:** Data curation.

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