

The Water-Energy-Food nexus as a tool for advancing sustainable and resilient agrifood systems: A systematic review

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1. Introduction

Sustainability and resilience have become central guiding principles for development in a world shaped by a finite resource base, climate uncertainty, and growing socioeconomic inequalities. Sustainability focuses on the responsible use and management of natural resources to ensure environmental integrity, economic viability, and social well-being for present and future generations (Roy and Moradkhani, 2025). Resilience complements this perspective by emphasizing the capacity of systems to absorb shocks, adapt to changing conditions, and continue functioning under stress (Kc et al., 2024). Rather than separate ideas, sustainability and resilience are closely linked, providing a practical framework for understanding complex socio-ecological systems characterized by uncertainty, feedback loops, and interactions across scales (Hassan et al., 2025). Their integration is increasingly recognized as necessary for achieving the ambitions of the United Nations 2030 Agenda for Sustainable Development, which underscores that long-term human well-being depends on protecting ecosystems while strengthening society's capacity to cope with environmental, economic, and social disruptions (Muhirwa et al., 2025).

Global disruptions have underscored the urgency of embedding sustainability and resilience within development planning. Climate change is intensifying droughts, floods, and extreme weather events. At the same time, biodiversity loss and land degradation are reducing ecosystem productivity. Volatile energy markets and geopolitical tensions are also reshaping resource access and affordability, while pandemics such as COVID-19 have exposed vulnerabilities in global supply chains and institutional response systems (Hassan et al., 2025). These pressures threaten progress toward multiple SDGs, particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Muhirwa et al., 2025). Sustainability stresses the responsible management of natural capital to ensure that development gains today do not undermine resource availability for future generations, while resilience emphasizes diversity, adaptive capacity, and flexibility as essential features that enable systems to withstand shocks and maintain functionality (Hassan et al., 2025). Translating these theoretical frameworks into practice requires a comprehensive analysis of agrifood systems.

Agrifood systems are fundamental to human well-being, ensuring food security, supporting livelihoods, and driving economic activity. These systems encompass the full spectrum of activities from agricultural input provision and production to processing, distribution, consumption, and waste management. Beyond food provision, agrifood systems shape rural employment, ecosystem services, nutrition outcomes, and social stability (Crumpler et al., 2025). Their performance is therefore directly linked to achieving SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-

Being), SDG 8 (Decent Work and Economic Growth), and SDG 15 (Life on Land) (Mai et al., 2025).

Driven by population growth, meeting future food demand will require substantial increases in agricultural production (Hanumante et al., 2022). Overcoming food insecurity is central to achieving SDG 2 and is closely linked to SDG 1 and SDG 3, which depend on reliable access to sufficient and nutritious food. However, expanding output through conventional intensification alone risks accelerating environmental degradation and further straining already limited water, energy, and land resources, thereby undermining progress toward SDG 6, SDG 7, and SDG 13 (Molefe and Inglesi-Lotz, 2023). Therefore, there is a need to transition to a sustainable and resilient agrifood system.

A sustainable agrifood system, as defined by the FAO (2018), delivers food security and nutrition for all and future generations without compromising the economic, social, and environmental bases. It emphasizes that sustainability requires balancing immediate food and livelihood needs with the protection of natural resources and system integrity necessary for long-term food security. Resilience, on the other hand, describes an agrifood system's capacity to anticipate, absorb, recover from, and adapt to disruptions and shocks, ensuring the provision of sufficient, appropriate, and accessible food even in the face of various and unforeseen disturbances (Ulimwengu, 2024). Both sustainability and resilience consider social, environmental, and economic dimensions, sharing a mutual focus on maintaining the system's long-term functionality (Hassan et al., 2025). Critically, the literature suggests that if systems are not sufficiently resilient, they cannot be truly sustainable, highlighting resilience as a prerequisite for achieving sustainability (Roosevelt et al., 2023, Kc et al., 2024, Rojas-Flores et al., 2026).

The sustainability and resilience of agrifood systems are constrained by interconnected factors (Mkumbukiy et al., 2025). Environmental pressures, including climate variability, recurrent droughts and floods, soil degradation, and increasing water scarcity, undermine the stability of agricultural production and threaten long-term resource integrity (Crumpler et al., 2025). These pressures are compounded by economic barriers such as high input costs, limited access to finance, and weak market integration (El Bilali et al., 2021). Social factors further influence system performance, such as poverty, unemployment, and persistent inequality, access to land, inputs, and services shape vulnerability and constrain adaptive capacity (El Bilali et al., 2021). At the institutional level, fragmented policy frameworks, insecure land tenure, and limited extension and support services weaken coordinated resource management and discourage long-term investment (El Bilali et al., 2021). Collectively, these interconnected constraints reinforce systemic inefficiencies and vulnerabilities, thereby restraining efforts to increase agricultural productivity.

Agricultural productivity depends heavily on interconnected resources, and unsustainable expansion can weaken the very systems that support long-term productivity (El Bilali et al., 2021). Therefore, increasing food production must be pursued through resource-efficient, environmentally sustainable, and climate-resilient pathways that enhance productivity while

safeguarding natural systems (Hassan et al., 2025). This challenge highlights the need for integrated approaches that balance production goals with resource conservation, ensuring that efforts to achieve food security do not compromise ecosystem integrity or the capacity of future generations to meet their needs. The Water–Energy–Food (WEF) nexus has emerged as a valuable framework for understanding and managing the interdependencies among critical resources, enabling more coordinated, efficient, and resilient agrifood system planning and management (Lv et al., 2023)

WEF nexus rose to prominence in global policy dialogue during the World Economic Forum Annual Meeting 2011, and the framework recognizes the interdependence of water, energy, and food sectors, where actions in one sector influence the others (Hoff, 2011). Rather than treating sectors in isolation, the WEF nexus framework seeks to identify synergies, minimize trade-offs, and optimize resource use across interconnected systems (Taguta et al., 2022). As a decision-support and analytical tool, the WEF nexus enables integrated planning by helping with evaluating resource flows, system efficiencies, and cross-sector impacts under alternative policy or management scenarios (Molefe and Inglesi-Lotz, 2023, Mai et al., 2025). This integrative perspective directly supports SDG implementation by promoting policy coherence and cross-sector coordination necessary for achieving interconnected goals.

Since its inception, the WEF nexus has gained prominence across academic, policy, and societal spheres as an integrative framework for managing interdependent resources, enhancing security, improving efficiency, and strengthening policy coherence across sectors (Purwanto et al., 2021). Within agrifood systems, a growing body of research applies the nexus as a decision-support tool to guide planning and resource allocation across scales, recognizing the interdependencies among water, energy, and food systems while accounting for external pressures such as climate variability and socio-economic change (Akinsete et al., 2022). Beyond its analytical function, the nexus supports the identification of knowledge gaps, promotes integrated data and assessment platforms for evidence-based policymaking, and is increasingly operationalized through participatory, multi-stakeholder processes that translate nexus thinking into practical action aligned with sustainability targets and the SDGs (Molefe and Inglesi-Lotz, 2023). Nevertheless, comprehensive evidence demonstrating how the WEF nexus has been effectively implemented to enhance sustainability and resilience outcomes in agrifood systems remains limited.

This systematic review examines how the Water–Energy–Food (WEF) nexus has been employed as a tool for advancing sustainable and resilient agrifood systems. The review synthesizes existing research to assess trends and patterns in WEF nexus studies, examine how sustainability and resilience are conceptually framed and measured, investigate how water, energy, and food components are represented and integrated, evaluate the extent to which the environmental, social, economic, and governance pillars are addressed, and identify the methods, analytical tools, and indicators used to evaluate system performance.

2. Methodology

2.1. Search strategy

This study conducted a systematic review of WEF nexus research within agrifood systems to determine how the WEF nexus is being used as a tool for transitioning towards resilience and sustainability. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was used (Moher et al., 2009, Page et al., 2021). Reflecting a global shift toward standardized reporting, the PRISMA statement has become one of the preferred frameworks for rigorous evidence synthesis, as demonstrated by its consistent utilization in many studies (Mabhaudhi et al., 2024, Bamgboye et al., 2025, Mai et al., 2025). By adhering to the PRISMA guidelines, this review ensures that every phase, from the initial search for relevant studies to the final analysis, is conducted in a standardized and methodologically consistent manner (Parums, 2021).

The Population, Intervention, Comparison, and Outcomes (PICO) framework (Page et al., 2021) guided the development of the search strategy, helping to structure the literature retrieval process systematically and minimize selection bias while ensuring comprehensive coverage (Table 1).

Table 1. PICO framework guiding the development of the search strategy

Component	Description
Population	Agrifood systems
Indicator	WEF nexus framework applied as a tool
Comparison	Not applicable
Outcome	Sustainability and resilience of agrifood systems

A literature search was performed using two electronic databases, Scopus and the Web of Science Core Collection (WoS). The search terms were applied to the Title, Abstract, and Keywords fields within both databases to ensure a comprehensive retrieval of relevant studies. The final search was conducted on 13 July 2025. The specific search criteria and exact boolean strings applied in each database are detailed in Table 2.

Table 2. Search criteria

Search Topic	Keywords / Search String
Topic 1	water AND energy AND food AND nexus
Topic 2	evaluat* OR apprais* OR examin* OR analys* OR investigat* OR assess* OR review* OR develop*
Topic 3	agr*

Scopus and Web of Science databases were chosen for their extensive multidisciplinary coverage, high-quality peer-reviewed content, and broad indexing of journals across agriculture, environmental science, and sustainability research. Their use ensured a thorough and reliable retrieval of studies examining the sustainability and resilience of agrifood systems using the WEF nexus as a tool. The search was limited to English-language peer-reviewed journal articles, book chapters, and conference proceedings published up to 13 July 2025. The initial search yielded 1,843 records, comprising 777 from Scopus and 1,066 from the Web of Science Core Collection. After removing 844 duplicates, 999 unique records remained for screening (Fig 1). These records were exported to Microsoft Excel for organization and review.

In accordance with the objectives of this systematic review, titles, abstracts, and keywords were screened against predefined inclusion criteria. Studies were retained if they:

- I. addressed all three WEF nexus components (water, energy, and food) and their interconnections,
- II. were situated within an agrifood system context,
- III. examined sustainability and/or resilience outcomes,
- IV. were peer-reviewed scholarly outputs to ensure analytical rigor and reliability.

Following title, abstract, and keyword screening, 117 articles met the eligibility criteria and progressed to full-text assessment. After full-text evaluation, 55 articles were excluded for not meeting the inclusion criteria, and a total of 62 studies met the inclusion criteria and were retained for the final analysis. Fig 1 illustrates the systematic workflow adopted for this review, detailing the search syntax and the iterative stages of study screening and selection based on PRISMA guidelines.

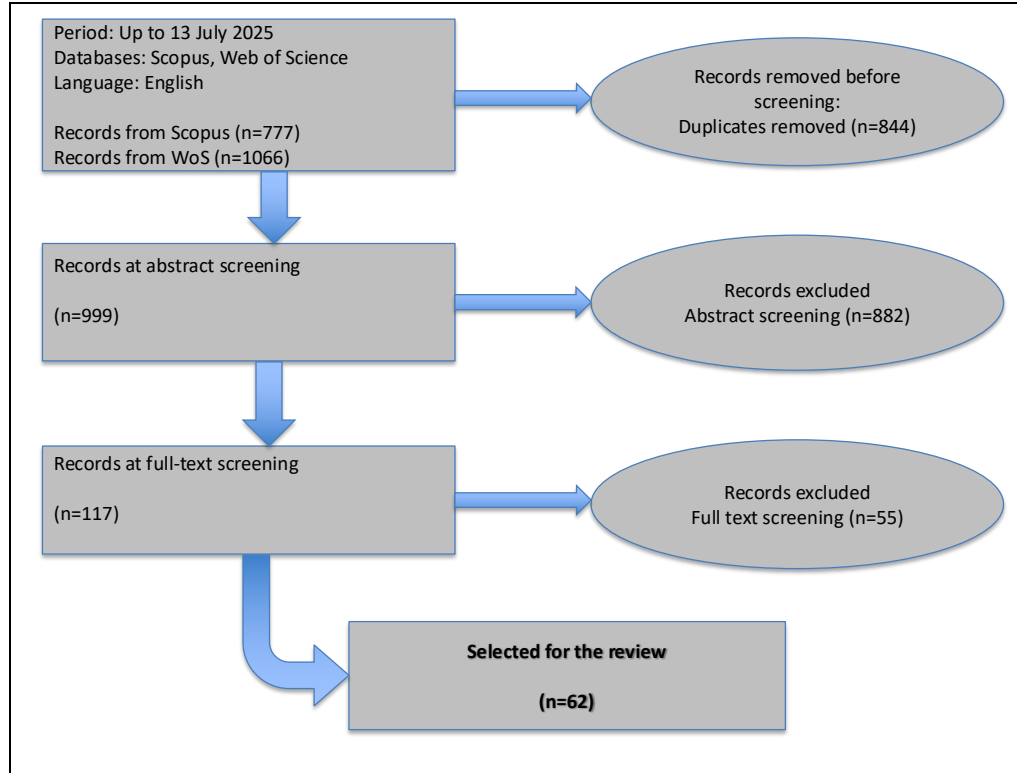


Fig 1 Literature search syntax and study selection workflow based on the PRISMA approach

2.2. Data collection

A data extraction sheet was designed in simple, flexible, and functional MS Excel based on the study objectives. Key data on the selected papers were extracted from the eligible studies and organized in the data extraction sheet.

For each study, the following information was recorded:

- Bibliographic and contextual details
- Authors and publication year
- Study objectives
- Geographic location and scale of analysis
- Methodological characteristics
- Analytical tools and modelling approaches
- Assessment of Sustainability and Resilience
- Parameters used for water, energy, and food components
- Sustainability and resilience pillars (environmental, social, governance, and economic)

2.3. Assessment of Sustainability and Resilience

To evaluate sustainability and resilience comprehensively, each study was assessed against the four foundational pillars. This multidimensional approach emphasises the integration of environmental, economic, social, and governance dimensions (Khourchid et al., 2024, Hunecke et al., 2025). A

dimension was considered addressed when at least one parameter representing that pillar was explicitly included in the study methodology as shown in Table 3.

Table 3. Dimensions and their parameters

Dimension	Key Focus Areas	Core Parameters
Social	Equity, well-being, and access	• Accessibility and affordability of water, energy and food • Livelihood • Gender • Population dynamics • Stakeholder participation • Employment (Akinsete et al., 2022)
Economic	Productivity and financial sustainability	• Productivity • Costs of production and profitability • Market access • Affordability • GDP (Akinsete et al., 2022, Solano-Pereira et al., 2025)
Governance	Governance and policy coordination	• Policy • Regulatory frameworks and tenure security • Cross-sector coordination mechanisms • Decision-making processes (Kapucu et al., 2021, Akinsete et al., 2022)
Environmental	Ecosystem integrity and resource sustainability	• Soil health and land degradation • Climate impacts and greenhouse gas emissions • Biodiversity and ecosystem services • Renewable energy integration and resource-use intensity (El Bilali et al., 2021, Eslami et al., 2024)

2.4. WEF Domain Indicators

To ensure comprehensive sectoral representation, data were extracted for each nexus component (Table 4), namely water, energy and food, in accordance with established WEF nexus analytical frameworks (Shannak et al., 2018, Naraghi et al., 2024, Tian et al., 2025)

Table 4. Water, energy and food parameters

Sector	Key Focus	Core Parameter
Water	Availability, efficiency and access	• Water productivity • Water demand • Water availability • Water access • Water trade (virtual/transboundary flows) (Zhang et al., 2024, Zhang et al., 2025)
Energy	Supply, efficiency and security	• Energy productivity • Energy demand • Energy availability • Energy access • Energy trade • Energy

		sources (renewable vs non-renewable) (Yuan et al., 2021, Yang et al., 2023, World Economic Forum, 2025)
Food	Production and system sustainability	• Cereals, vegetables and livestock production • Other crops (legumes, fruits, cash crops) • Food demand and post-harvest losses • Food security • Food accessibility • Land-use dynamics (Zhu et al., 2020, Zhang et al., 2024)

2.5. Data Synthesis and Analytical Approach

The review employed a mixed analytical strategy combining quantitative descriptive synthesis and qualitative thematic analysis. Descriptive synthesis was used to identify patterns in geographic distribution, study scale, methodological tools, and parameter emphasis across WEF components. Thematic synthesis enabled the identification of recurring drivers, trade-offs, synergies, and methodological gaps influencing sustainability and resilience outcomes (Rhouma et al., 2024).

3. Results and discussion

3.1. WEF nexus as a tool in sustainability and resilience within agrifood systems studies.

Of the thousands of studies on the WEF nexus, only 62 specifically investigated its application in agrifood systems. While the WEF nexus research has expanded into thousands of publications across diverse sectors, the systematic integration of sustainability and resilience within agrifood applications remains remarkably uneven. Evidence from this review shows that out of this vast body of literature, only 62 studies specifically engaged with these dimensions in an agrifood context. Within this sample, sustainability was consistently assessed across all 62 cases, whereas only 4 (6.5%) also incorporated resilience (Fig 2). Significantly, no study evaluated resilience in isolation without simultaneously assessing sustainability, indicating that the two concepts are closely interconnected, with resilience commonly framed as a mechanism for sustaining system functionality, stability, and adaptive capacity within agrifood systems. Oftentimes, resilience is conceptually acknowledged but weakly translated into measurable and systematically applied frameworks (Roosevelt et al., 2023). Early critiques by Tendall et al. (2015) highlighted the absence of consistent definitions and indicators, a concern reinforced by (Béné et al., 2023), who noted the predominantly rhetorical use of the term (Ulimwengu, 2024) and (Ujjwal et al., 2025) further demonstrate that existing metrics remain oversimplified and insufficiently standardized for application within agrifood systems.

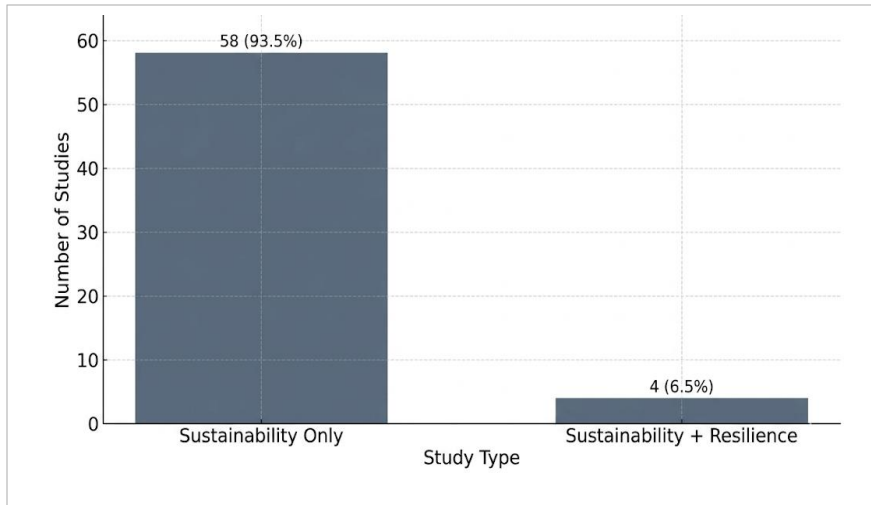


Fig 2 WEF studies that incorporate Sustainability and Resilience

3.2. Trends and patterns of WEF nexus studies assessing agrifood systems sustainability and resilience

3.2.1. Temporal evolution

The temporal evolution of the field reflects a growing momentum toward empirical operationalization, particularly following the adoption of the UN Sustainable Development Goals (SDGs) in 2015. Analysis of publication trends within this review indicates that the first study specifically assessing sustainability in agrifood systems appeared in 2016 (Psomas et al., 2016), with resilience first being incorporated in 2021 (Namany et al., 2021). In the decade following the SDGs, research volume transitioned from a single foundational study in 2016 to seven in 2021; following a minor decrease to five in 2022, the count rose significantly to 11 in 2023 and reached a peak of 18 in 2024 (Fig 3).

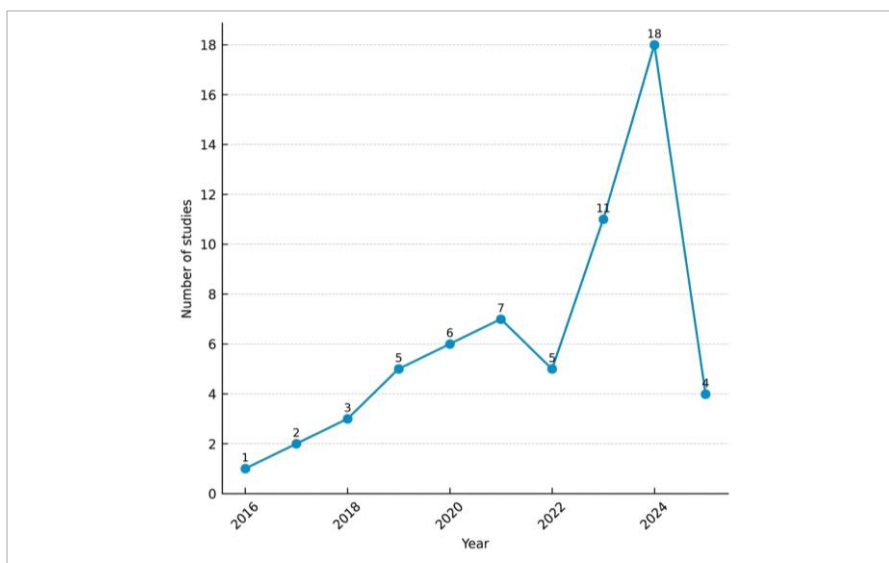


Fig 3 Trend of studies over the years

3.2.2. Global distribution of the studies.

The geographic distribution of the reviewed studies reveals a significant bias. Research is primarily concentrated in China (16 studies) and Iran (8 studies), followed by moderate representation in the United States, Brazil, Mexico, and South Africa (3 studies each). In contrast, contributions from European nations and Australia are limited, and substantial gaps persist across Latin America and Asia. This disparity is most pronounced in Africa (Fig 4), which remains underrepresented in research concerning sustainable and resilient agrifood systems compared to the rest of the globe.

Aside from the cases recorded in South Africa and Nigeria, the continent shows minimal engagement, a trend corroborated by multiple systematic reviews (Sarkodie and Owusu, 2020, Zhu et al., 2020, Lv et al., 2023). The lack of integrated research suggests that nexus resource management in Africa is still an emerging field. This research gap helps explain the persistent paradox where the continent's vast natural resource wealth has not yet translated into systemic solutions for food insecurity and poverty (Botai et al., 2021, Mabhaudhi et al., 2024).



Fig 4 Global distribution of WEF nexus research on sustainability and resilience within agrifood systems

3.2.3. Spatial scale of research

The spatial scale of the 62 reviewed cases reveals a distinct preference for larger geographic units, which directly influences how the nexus is operationalized (Fig 5). The provincial scale was the most frequent level of analysis, accounting for 35.48% (22 studies). This was followed by basin or watershed-level assessments at 27.42% (17 studies), underscoring the dominance of administrative and hydrological boundaries in nexus planning. Local-scale studies, encompassing city, district, or municipal levels, comprised only 14.52% (9 studies), while national-level assessments represented 12.9% (8 studies). Global-scale analyses accounted for 6.45% (4 studies), with sub-national, regional, and continental scales each representing a marginal 1.61% (1 study) of the total.

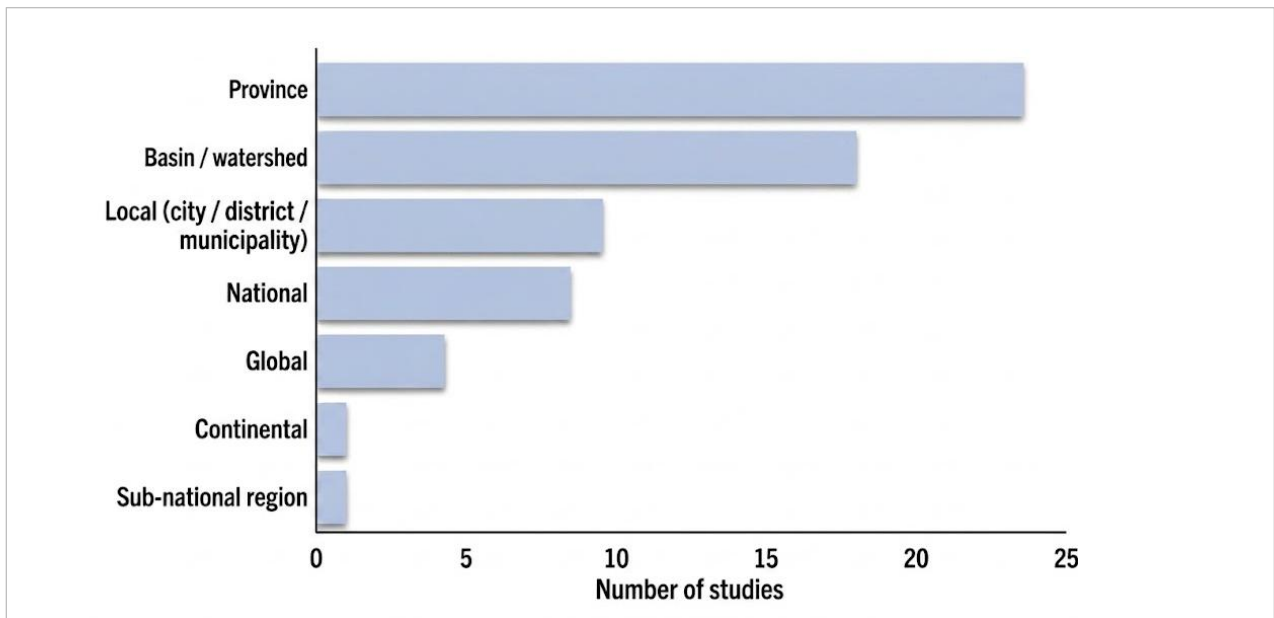


Fig 5 Spatial scale of the studies

Crucially, the analysis reveals no significant relationship between the year of publication and the spatial scale of study. Rather than a progressive transition toward more granular or place-specific analyses over time, the literature shows a persistent alternation between scales. This lack of temporal evolution suggests that the field has not yet shifted its focus to address the local complexities of agrifood systems.

This scale bias indicates that nexus analyses tend to prioritize aggregated system interactions over the place-specific dynamics through which water, energy, and food systems are implemented. Consequently, the WEF nexus often remains positioned as a conceptual or analytical framework rather than an operational decision-support tool. This pattern is consistent with broader critiques in the literature, which argue that the dominance of large-scale assessments creates scale mismatches that limit policy relevance and practical uptake (Nhamo et al., 2020, Correa-Porcel et al., 2021, Purwanto et al., 2021). Scholars further note that the absence of a transition toward local-scale empirical work obscures contextual variability and distributional effects, reinforcing the theoretical character of WEF nexus research (Mabhaudhi et al., 2024, Bamgboye et al., 2025, Mai et al., 2025).

3.3. Parameter Representation within Food, Water and Energy Sectors

The effectiveness of WEF nexus research in agrifood systems is heavily contingent upon balanced sectoral representation and the selection of parameters that truly depict system dynamics. However, the results from the total pool of 62 cases indicate a persistent bias towards biophysical parameters.

3.3.1. Food-related parameters

While 38.7% of studies focused on a single food parameter, most commonly productivity, only 27.4% and 16.1% extended their analysis to two or three parameters, respectively. More

comprehensive integration was uncommon, with 9.7% incorporating four parameters, and 8.1% not explicitly operationalizing any food-related parameter in their methodological frameworks. This limited multidimensional treatment suggests that, even where food is included, it is rarely examined across availability, access, demand, and loss dimensions simultaneously. Such narrow operationalization constrains the ability of nexus models to reflect the complexity of food security, which extends beyond supply to include distribution, affordability, and stability.

Across the included studies, food productivity clearly dominated the food sector, appearing in 82.3% of studies. In contrast, food demand was considered in 38.7% and food security in 29%, while trade-related parameters were included in only 12.9% (Fig 6a). Even fewer studies incorporated food losses (4.8%) or food accessibility (4.8%). This uneven distribution indicates that nexus literature remains strongly oriented toward production-side metrics (He et al., 2024). The prominence of productivity reflects the historical development of WEF frameworks as tools for analyzing resource interdependencies and optimizing water and energy inputs to agricultural output. As noted in previous reviews, nexus research tends to prioritize quantifiable synergies and trade-offs (Mabhaudhi et al., 2024, Mai et al., 2025). The current findings therefore, reinforce the argument that food, within much of the nexus literature, is treated primarily as a biophysical output rather than as a multidimensional system outcome.

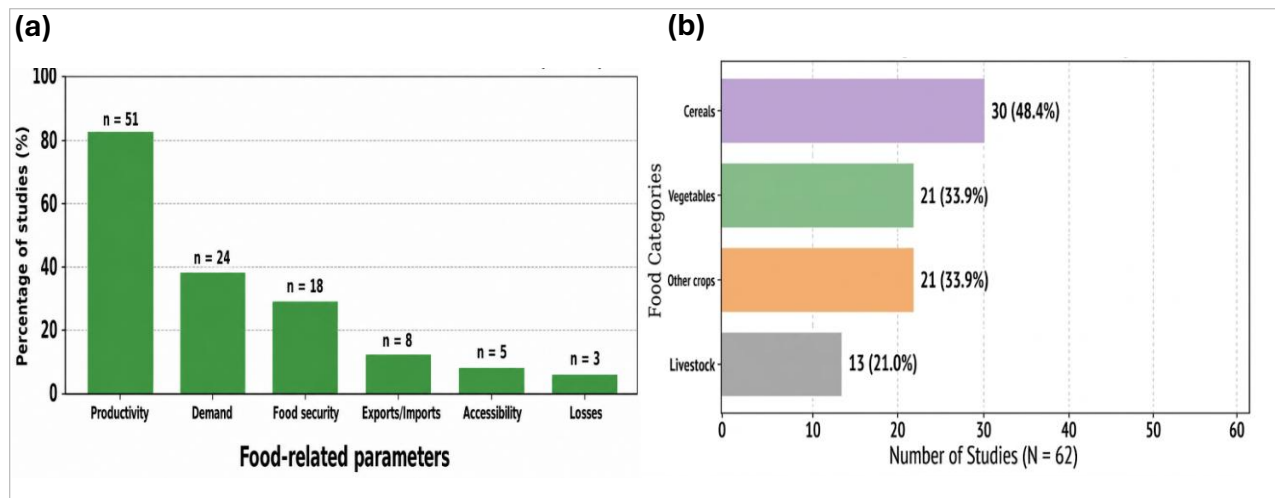


Fig 6 (a) Food-related parameters (b) Food categories within the WEF nexus studies on sustainability and resilience within agrifood systems.

The distribution of food categories mirrors this production-centered emphasis. Cereals were most frequently analyzed (48.4%), followed by vegetables (33.9%) and other crops (33.9%), while livestock systems appeared in 21.0% (Fig 6b). The predominance of cereals indicates that food availability is frequently interpreted through the lens of staple crop production, particularly cereals, which contrasts with the multidimensional definition of food security that emphasizes access to diverse and nutritious foods such as meat, legumes, fruits, and edible oils (He et al., 2024, Ulimwengu, 2024).

Livestock systems were less frequently represented in reviewed studies. This is notable given the sector's strong interconnections with the water, energy, and food components of agrifood systems. Livestock production competes with human food consumption for crops used as feed, while simultaneously serving as an important source of dietary protein and other essential nutrients. The sector is also resource-intensive, requiring significant water for animal hydration and feed production, as well as energy for feed processing, transportation, housing, and cold chains within livestock value chains. In many regions, livestock holds important socio-economic and cultural value, often functioning as a marker of social status and a form of household wealth. At the same time, the sector is a major contributor to greenhouse gas emissions within food systems. Despite these important linkages and impacts, several critiques of agrifood systems research highlight that livestock remains comparatively underrepresented in integrated resource assessments (Viana et al., 2023, Viana et al., 2025).

Taken together, these findings reveal that the WEF nexus literature in agrifood systems remains heavily skewed toward production optimization rather than holistic food systems analysis. While this orientation is consistent with the nexus's origins in resource efficiency and intersectoral trade-off modelling (Mabhaudhi et al., 2024, Mai et al., 2025), it stands in partial contrast to evolving global policy discourse. The 2024 High-Level Political Forum on Sustainable Development emphasizes integrated, multi-sectoral approaches linking water, food, health, gender, and climate (United Nations Economic and Social Council, 2024), signaling that contemporary food systems governance extends well beyond production metrics. Against this backdrop, the limited incorporation of food access, trade dynamics, and post-harvest losses within the reviewed studies suggests that nexus applications have not yet fully aligned with broader sustainability and equity priorities. Expanding food-related metrics to include demand, access, trade, and loss dimensions would enhance the capacity of the WEF nexus to engage with the full spectrum of contemporary food system challenges.

3.3.2. Water-related parameters

Across the included studies, water availability was the most frequently assessed parameter, reported in 71% of studies, followed by water demand (64.5%) and water productivity (58.1%). In contrast, water quality and water access were less commonly considered, appearing in 21% and 17.7% of studies, respectively, while water imports/exports were addressed in only a small proportion of the literature (8.1%) (Fig 7). In terms of analytical scope, most studies incorporated multiple water-related parameters. Specifically, 37.1% of studies assessed two parameters, followed by studies examining a single parameter (24.2%), three parameters (17.7%), and four parameters (17.7%), while only a small subset of studies incorporated five parameters. Among studies assessing two parameters, the combination of water availability and water demand was most common, occurring in ten studies out of the 62. Studies focusing on a single parameter most frequently examined water productivity and water availability.

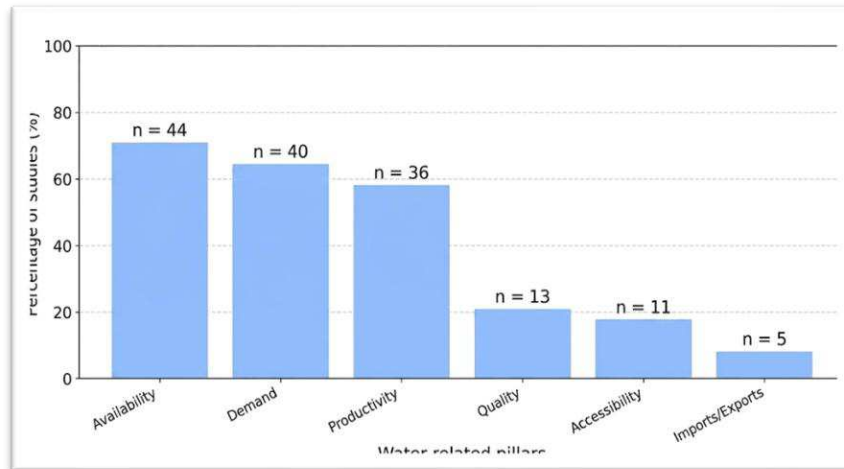


Fig 7 Water-related parameters used within WEF nexus studies on sustainability and resilience within agrifood systems

The pattern of water parameters shows that quantitative and biophysical aspects of water tend to dominate WEF nexus studies. Water availability, followed by demand and productivity, are the parameters most assessed, reflecting a strong focus on physical resource supply and efficiency trade-offs. This suggests that many studies in this review emphasize resource flows. By contrast, water quality, accessibility, and imports/exports are far less assessed. The low representation of water quality indicates that chemical, ecological, and health-related water conditions receive limited attention relative in WEF nexus research, as supported by other studies (Heal et al., 2021, Gartsyanova et al., 2024). Accessibility, which encompasses social, infrastructural, and equity dimensions, is also underrepresented, highlighting a continued gap in integrating socio-institutional factors into nexus analyses (Afkhami et al., 2024). Similarly, considerations of virtual water trade and embedded water flows across borders are comparatively rare, despite their relevance for water stress and food security in globalized systems.

3.3.3. *Energy-related parameters*

Energy-related parameters revealed substantial variation in both analytical emphasis and scope across the reviewed studies. Energy demand emerged as the most frequently examined variable, appearing in 56.5% of studies, followed by energy productivity (50.0%) and energy availability (37.1%). In contrast, energy access received comparatively limited attention (14.5%), while energy exports and imports were rarely considered, appearing in only 3.2% of studies (Fig 8). Some studies incorporated multiple energy indicators within a single analytical framework. However, the overall breadth of analysis remained limited. Most studies focused on a single energy-related parameter (54.8%), followed by two parameters (25.8%) and three parameters (11.3%). Only a small number incorporated four (3.2%) or five parameters (1.6%). This distribution suggests that most WEF nexus assessments adopt a relatively narrow treatment of energy dimensions.

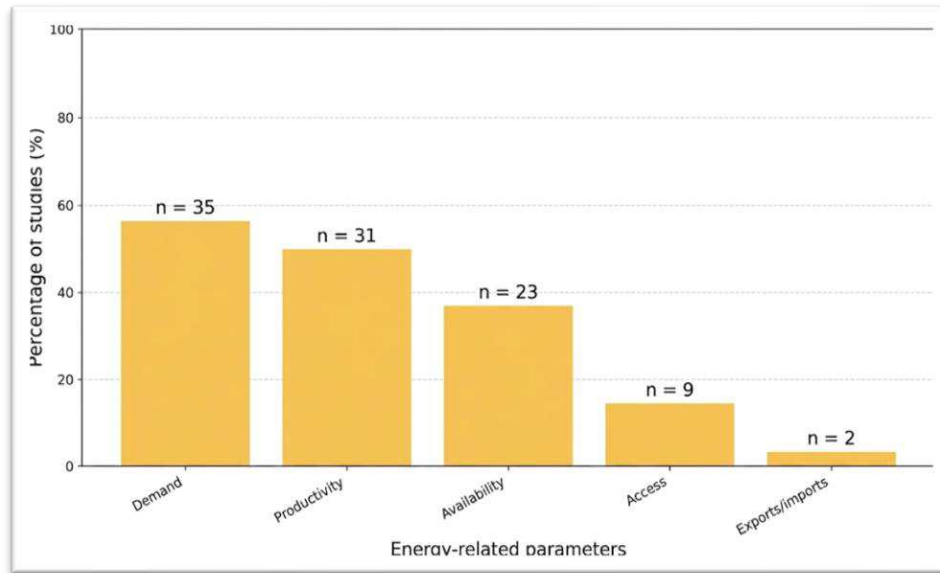


Fig 8 Energy-related parameters within WEF nexus studies on sustainability and resilience within agrifood systems

The emphasis on demand, productivity, and availability reflects how energy is commonly framed within WEF nexus studies. Similar patterns have been reported in broader nexus literature, where energy is primarily treated as a quantifiable biophysical flow rather than as a socially embedded system (Mabhaudhi et al., 2024, Shrimpton and Balta-Ozkan, 2024, Li et al., 2025). Consequently, social and distributional aspects of energy systems receive considerably less analytical attention. This aligns with critiques that nexus research often privileges measurable resource flows over institutional and social dimensions of sustainability (Rezaei Kalvani and Celico, 2024, Li et al., 2025).

The weak representation of energy access and energy trade within the reviewed studies further highlights this limitation. Energy availability does not necessarily translate into accessibility, as access is strongly shaped by affordability, infrastructure, governance, and income levels. This distinction is central to global policy frameworks such as Sustainable Development Goal 7 under the United Nations, which emphasizes universal and affordable access to energy rather than supply alone (UN, 2015). Reports by the International Energy Agency (IEA, 2023) and the World Bank (2022) similarly highlight that energy shortages can persist even where aggregate supply appears sufficient, underscoring the importance of distributional and structural factors. The limited consideration of energy imports and exports also restricts the capacity of nexus studies to capture energy security dynamics, as trade flows significantly influence domestic supply stability, price volatility, and exposure to geopolitical risks (IEA, 2023). By focusing primarily on internal demand and productivity metrics, many nexus assessments risk equating efficiency with sustainability while overlooking broader structural drivers of resilience.

Non-renewable energy systems were the most frequently represented, appearing in 58% of the studies and typically including coal, diesel, oil, and natural gas (Fig 9). Renewable energy sources were identified in 23% of the studies, including solar photovoltaic systems, wind energy, hydropower, and bioenergy such as biogas and biomass. A further 15% of the studies incorporated both renewable and non-renewable sources, representing hybrid energy configurations. Overall, these findings reflect the current dominance of fossil fuel-based energy systems, with comparatively limited attention given to renewable energy transitions. From a sustainability perspective, this reliance on non-renewable sources suggests that many nexus assessments remain tied to existing fossil-based energy structures despite global climate commitments under the Paris Agreement of the United Nations Framework Convention on Climate Change. Both the International Energy Agency (IEA, 2023) and the Intergovernmental Panel on Climate Change (2022) emphasize that expanding renewable energy systems is critical for reducing emissions and achieving long-term sustainability.

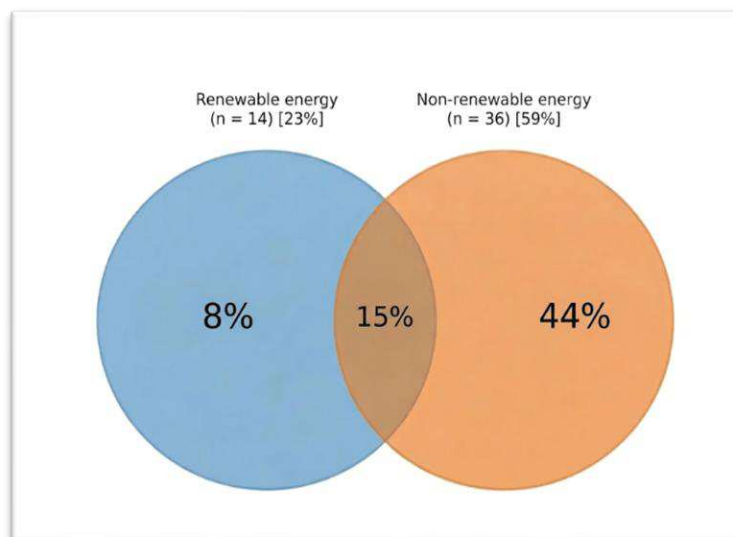


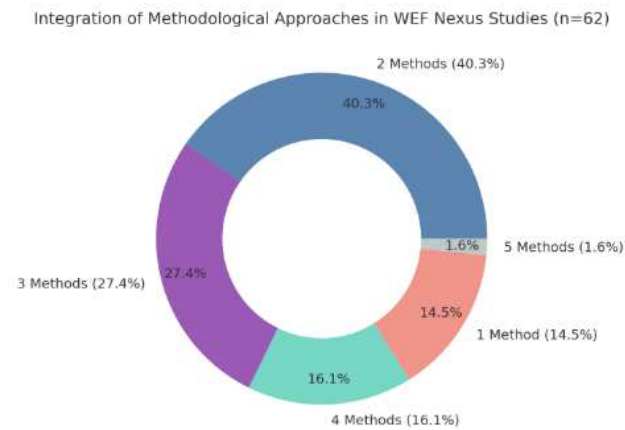
Fig 9 Energy sources recorded within WEF nexus studies on sustainability and resilience within agrifood systems

An additional gap relates to the representation of traditional biomass energy. Across the 62 reviewed studies, only one study by Schwanitz et al. (2017) explicitly accounted for firewood as an energy source. This omission is notable given the widespread reliance on biomass energy across many developing regions, particularly in rural areas. Excluding firewood and other traditional biomass sources can significantly underrepresent the true structure of energy systems, as these energy forms carry important environmental, economic, and social implications, including deforestation pressures, household energy access, and gendered labour burdens associated with fuel collection. Overall, the limited representation of renewable and traditional biomass energy suggests that energy transitions and energy access challenges are not yet fully integrated into many WEF nexus assessments of agrifood systems.

3.4. Methods and Analytical Tools Used in WEF Nexus Assessments of Agrifood Systems' Sustainability and Resilience

The reviewed studies employed a diverse range of methodological approaches to assess sustainability and resilience within WEF nexus systems (Fig 10b), frequently combining multiple tools to capture the environmental, governance, and socioeconomic dimensions of nexus interactions. Most studies applied more than one method, commonly integrating two or three approaches, while only a small proportion relied on a single technique (Fig 10a). This trend toward methodological integration reflects the inherent complexity of agrifood systems, where combining tools enables a more comprehensive understanding of cross-sector linkages, trade-offs and system vulnerabilities. It also underscores the evolving nature of the WEF nexus as an analytical and decision-support framework, with researchers increasingly adopting hybrid approaches.

(a)



(b)

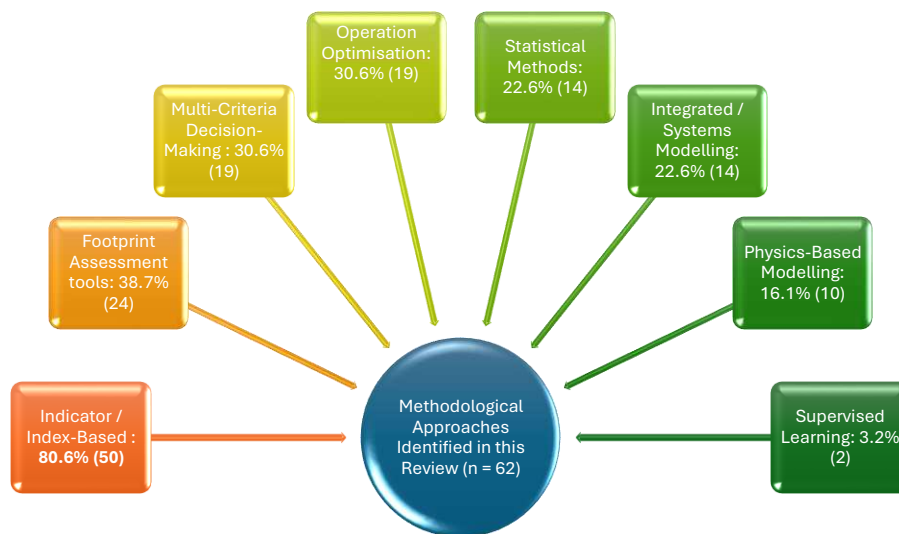


Fig 10 (a) WEF nexus integrated method approach (b) Methodologies used in the WEF nexus sustainability research within agrifood systems.

3.4.1. Footprint Assessment tools

Footprint assessment tools were used in 38.7% (24 of the 62) studies reviewed, making them the most frequently applied approach to evaluating agrifood systems. Often combined with other methods, these methods quantify carbon emissions, water consumption, and energy intensity, using tools like Life Cycle Assessment (LCA) and water/carbon footprint accounting (Ershadfath et al., 2024, van Huyssteen et al., 2025). It was noted that these methods are almost exclusively used to

measure the sustainability of agrifood systems rather than their resilience (Abad-González et al., 2024). This is a major gap because footprint studies mainly measure the normal impacts on food production and do not consider how these systems respond to sudden shocks such as climate disasters or supply chain disruptions.

3.4.2. Optimization Methods

Optimization approaches were implemented in 30.6% of the reviewed studies, reflecting a recognition that water, energy, and land must be allocated efficiently to meet the competing demands of agrifood systems. These studies applied a variety of sophisticated tools, including Multi-Objective Linear Programming (MOLP), Compromise Programming, and Non-dominated Sorting Genetic Algorithm II (NSGA-II). Researchers implemented these through platforms such as the General Algebraic Modeling System (GAMS) and Linear Interactive and General Optimizer (LINGO). By using these tools to minimize water losses and transport distances, these approaches identify the best strategies to lower production costs and reduce environmental burdens. In doing so, they directly support the sustainability of agrifood systems while strengthening resilience by allowing for adaptive resource allocation during droughts, infrastructure failures, or market variability (Rathore et al., 2025).

Notably, optimization featured prominently in the few studies that explicitly quantified resilience. Out of the four studies that measured resilience outcomes, three used optimization-based strategies (Niu et al., 2019, Botai et al., 2021, Cui et al., 2024). In these cases, optimization was used to maintain food production and service delivery even under extreme stress. This pattern suggests that resilience in the agrifood nexus is not just about using less, but about the ability to quickly shift resources to where they are needed most when a disturbance occurs.

Despite their value, these tools remain underutilized, especially in the Global South, where national resource abundance often exists alongside local poverty and food insecurity. This suggests that the problem is not always a lack of resources, but rather inefficiencies in how they are allocated and accessed at the community level. (Dlamini et al., 2023) used the method to support climate adaptation in South Africa's Buffalo River catchment, and (Kahil et al., 2018) developed a continental-scale hydro-economic model using optimization. Decision-Support and

3.4.3. Multi-Criteria Decision-Making

Decision-support and Multi-Criteria Decision-Making (MCDM) methods were applied in 30% of the reviewed studies. These tools are primarily used to structure complex problems in agrifood systems and rank different policy or management options where criteria often conflict, such as choosing between increasing food exports or protecting local water quality. The main function of these tools is to organize diverse indicators and assign weights to competing priorities to support transparent decision-making (Babaei et al., 2023). Common techniques included the Analytic Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and the combined CRITIC–VIKOR (Criteria Importance Through Intercriteria Correlation and VlseKriterijumska Optimizacija I Kompromisno Resenje) methods. Among these,

AHP emerged as the most frequently used approach to navigate these trade-offs (Nhamo et al., 2020, Yuan et al., 2021, Karamian et al., 2023).

These methods contribute to the resilience of agrifood systems by incorporating stakeholder perspectives and improving transparency in how trade-offs are evaluated (Ershadfath et al., 2024). They support sustainability by ensuring a balanced decision-making process across environmental, economic, and social pillars. Notably, out of the studies that included stakeholder participation, more than half (54%) used MCDM, highlighting its value for inclusive resource governance. Furthermore, some studies used these frameworks specifically to evaluate system robustness and adaptive capacity, which are core elements of resilience (Namany et al., 2021, Khourchid et al., 2024).

To add analytical depth, MCDM is often combined with other modeling tools. For instance, researchers have integrated it with Network Systems Modeling (NSM) to assess how infrastructure failures might cascade through a food system, or with System Dynamics Modeling (SDM) to capture long-term feedback behaviors (Javan et al., 2023, Khourchid et al., 2024). By linking participatory decision processes with dynamic system analysis, these hybrid methods provide a more realistic assessment of how agrifood systems can stay sustainable while remaining flexible enough to withstand external shocks.

3.4.4. Physics-Based Modelling

Physics-based modelling approaches were applied in about 22% of the reviewed studies. These studies used specialized simulation tools to model the strict physical and biophysical interactions among these three critical resources (Vrachioli et al., 2025). They quantify exact resource transfers, such as the energy required to pump water or the water needed to cool power plants, within agrifood systems (Vrachioli et al., 2025). The tools applied include the Water Evaluation and Planning (WEAP) system, Modular Groundwater Flow Model (MODFLOW), the Soil and Water Assessment Tool (SWAT), the Agricultural Production Systems Simulator (APSIM), and CropWat (a tool for crop water requirement and irrigation scheduling). These models provide detailed representations of how biophysical systems behave, allowing researchers to assess water availability, groundwater dynamics, and crop yields under changing climatic conditions (Liu et al., 2022).

The strength of these tools lies in their ability to simulate how resources flow and respond to different management scenarios (Liu et al., 2022, Chang et al., 2025). This makes them highly valuable for identifying physical vulnerabilities, such as drought risk or groundwater depletion, and supporting long-term sustainability planning. However, because these models are technical and process-oriented, they are often limited in scope (Akinsete et al., 2022, Gohil and Jain, 2023). Most studies using these tools captured only one or two sustainability pillars, primarily focusing on environmental and economic dimensions while rarely incorporating social or governance factors (Ahani et al., 2024, Vrachioli et al., 2025).

Notably, none of the studies using physics-based modelling explicitly quantified resilience. This reveals a significant research gap: while these models are excellent at diagnosing "biophysical" problems and resource efficiency, they cannot easily capture the adaptive capacity or institutional responses that are essential for resilience. To improve the resilience of agrifood systems, these physics-based tools must be better integrated with socio-economic data to move beyond purely technical assessments.

3.4.5. Systems Modelling and Feedback Analysis

Systems modelling approaches were applied in 23% of the reviewed studies, reflecting a move toward capturing the dynamic feedback mechanisms that define agrifood systems. These included System Dynamics (SD) models developed in platforms like Vensim or Stella, and the Climate, Land-Energy, and Water systems (CLEWS) framework, which links the Water Evaluation and Planning (WEAP) system with the Long-range Energy Alternatives Planning (LEAP) tool. Other techniques included Agent-Based Modelling (ABM) and Network Systems Modelling (NSM), used to analyze how infrastructure failures cascade through a food system, as well as the Generalized Global Sustainability Model (GGSM) for evaluating global interactions.

These tools are uniquely valuable for resilience analysis because they simulate feedback loops and thresholds, allowing researchers to examine how shocks propagate through the system and how the system reorganizes afterward (Francisco et al., 2024). Among the studies using systems modelling, 72% captured all four sustainability pillars: environmental, economic, social, and governance (Francisco et al., 2023, Abad-González et al., 2024). This breadth demonstrates that systems approaches can move beyond "single-sector" counting to capture the complex links between resource availability and social well-being. While only one study explicitly quantified resilience outcomes (Khourchid et al., 2024), system dynamics is inherently capable of evaluating recovery trajectories and adaptive capacity (Solano-Pereira et al., 2025).

The limited use of these tools represents a missed opportunity to capture the dynamic behavior of food systems under the stress of climate change, pandemics, or energy disruptions. Systems modelling is uniquely suited to these challenges because it can integrate both quantitative data (like crop yields) and qualitative inputs (like stakeholder behavior and policy changes) (Francisco et al., 2023). By simulating recovery pathways over time, these models provide a more comprehensive view of how agrifood systems can stay sustainable while remaining flexible enough to handle future uncertainty. Systems modelling is highly applicable to agrifood systems, but it is currently underutilized because it requires a significant amount of high-quality, long-term data which is often missing in many regions (Sušnik and Staddon, 2022).

3.4.6. Indicator and Index-Based tools

Indicator and index-based methods remain the dominant approach, employed in 80% of the reviewed studies. This high frequency is due to the harmonizing function of indices, which allows researchers to standardize variables that are usually expressed in completely different units, such as liters of water, kilowatts of energy, and tons of grain (de Vito et al., 2017, Muhirwa et al., 2025).

By translating these into a single scale, researchers can calculate composite scores such as the Water-Energy-Food Nexus Index (WEFNI), the Sustainability Index (SI), and the Relative Sustainability Index (RSI). Other applied tools include Integrated Risk Indices, coupling coordination indices, and specific resilience evaluation frameworks.

Indicators and indices are widely used because they make complex, multidimensional phenomena measurable, comparable, and easier for policymakers to interpret (Moreira et al., 2022). In the context of agrifood systems, they support benchmarking across different regions and time periods, helping to identify where trade-offs are occurring and where synergies can be found. This makes them essential for translating raw data into decision-relevant insights regarding sustainability performance and resilience capacity. However, as noted throughout this review, the effectiveness of an index is limited by the parameters it includes; if an index relies only on "easy" production data and ignores social "access" or "affordability," it may provide a misleading picture of how resilient an agrifood system actually is (Sušnik et al., 2022).

3.5. Incorporation of Sustainability and Resilience Pillars into Nexus Frameworks

The extent to which WEF studies incorporate sustainability and resilience pillars into their analytical frameworks provides critical insight into their capacity to inform long-term agrifood system transformation. Sustainability within nexus research is generally conceptualized through four interconnected pillars: environmental integrity, economic viability, social equity, and governance (El Bilali et al., 2021, Hunecke et al., 2025). Resilience complements this framework by emphasizing the ability of systems to absorb shocks and maintain functionality under changing conditions (Hunecke et al., 2025). Together, these dimensions determine whether nexus interventions merely improve resource efficiency or contribute to sustainable, equitable, and adaptive food systems.

As shown in Fig 11, studies incorporating all four sustainability dimensions accounted for only 38.7% of the reviewed literature. Relative to the SARAS framework, which advocates for the integrated inclusion of environmental, economic, social, and governance dimensions, this level of adoption remains relatively low. Only three dimensions (27.4%) or two dimensions (22.6%), while a smaller proportion focused on a single dimension (8.1%). These findings indicate that comprehensive integration of sustainability pillars within WEF nexus research remains limited, suggesting that many studies still adopt partial rather than fully holistic sustainability and resilience assessments. Integrating all dimensions of agrifood systems helps reduce trade-offs, strengthen synergies, align with international agreements, and minimize unintended impacts on vulnerable populations (Hunecke et al., 2025).

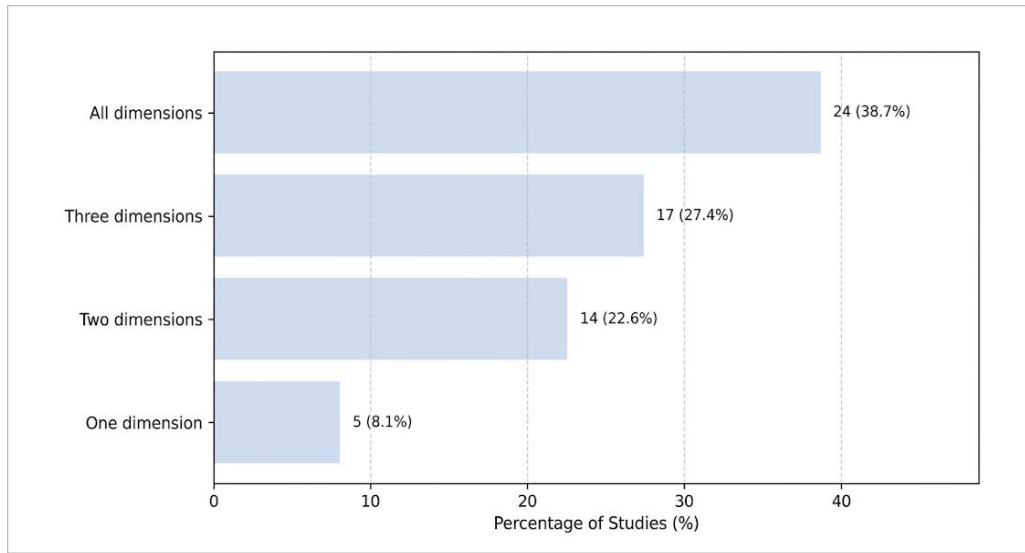


Fig 11 The extent to which these dimensions are incorporated within WEF nexus studies on sustainability and resilience in agrifood systems

The environmental pillar emerged as the most consistently represented, appearing in 93.5% of the reviewed studies (Fig 12). This reflects a strong awareness of the need for responsible environmental stewardship within agrifood systems. Economic viability follows closely (87%), with studies commonly incorporating productivity, cost efficiency, and market indicators. This emphasis underscores the central role of economic returns in shaping agrifood system decisions, as livelihood strategies are strongly influenced by financial incentives and market conditions (El Bilali et al., 2021).

In contrast, social (66.1%) and governance (45.2%) dimensions are less systematically incorporated into research (Fig 12). Although social considerations, such as access to food and water, appear in a moderate proportion of studies, they remain secondary to biophysical and economic metrics. This imbalance suggests that WEF nexus research continues to favor measurable environmental and economic indicators over the social and institutional conditions that underpin adaptive and resilient agrifood systems. Such findings reflect a common critique of nexus studies, namely their emphasis on quantifiable metrics at the expense of less easily measurable governance and social dimensions (Mabhaudhi et al., 2026). Governance and institutional aspects show the weakest representation despite their critical role in strengthening resilience through policy coordination, institutional capacity, and adaptive decision-making (Mwendera et al., 2023, Hunecke et al., 2025). Limited attention to governance also constrains the ability of nexus frameworks to address equity, participation, and long-term system transformation.

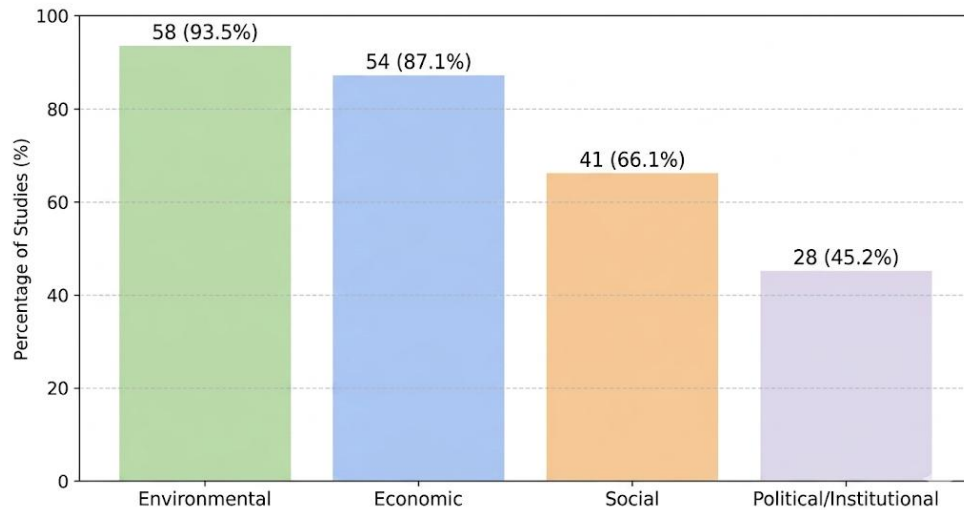


Fig 12 Sustainability and Resilience pillars within WEF nexus studies in agrifood systems

4. Conclusion

This systematic review demonstrates that the WEF nexus has been applied primarily as a framework for improving resource efficiency and productivity within agrifood systems, with less consistent attention given to broader sustainability and resilience outcomes. Across the 62 studies reviewed, water, energy, and food components were largely represented through production, demand, and availability metrics, while dimensions such as accessibility, equity, governance, trade, food losses, and health-related outcomes remained comparatively underexplored. Sustainability was widely addressed, yet resilience was rarely operationalized, indicating that adaptive capacity, recovery, and system flexibility remain weakly integrated within current nexus assessments.

The review further identified strong geographic, scale, and methodological biases. Research was concentrated mainly in China and Iran, while Africa and other parts of the Global South remain underrepresented. Most studies were conducted at provincial or basin scales, with limited attention to local and household-level dynamics that are critical for understanding vulnerability, inequality, and resilience. Methodologically, studies relied heavily on quantitative modelling. While these methods effectively evaluate resource flows and efficiencies, they often fail to capture the social, institutional, and adaptive dimensions necessary for resilient agrifood systems. Consequently, environmental and economic pillars were consistently emphasized, whereas social and governance dimensions remained comparatively underdeveloped.

Although current applications of the WEF nexus have substantially improved understanding of resource interdependencies and enhanced efficiency in water, energy, and agricultural production, the framework must move beyond its predominantly production-centered orientation to function as a truly transformative tool. Advancing sustainable, nutrition-sensitive, and resilient agrifood systems requires broadening the analytical lens beyond cereals and caloric sufficiency to include diversified food systems involving livestock, legumes, fruits, vegetables, and oilseeds. Equally,

water assessments must move beyond physical availability to incorporate water quality and equitable access, while the energy dimension must extend beyond fuel inputs to address energy reliability and renewable transitions. Relative to the SARAS framework, current WEF nexus applications remain insufficiently holistic, as environmental and economic dimensions dominate assessments while social and governance dimensions critical for adaptive, equitable, and resilient agrifood systems are comparatively underrepresented.

Strengthening the transformative capacity of the WEF nexus also requires a shift away from the current “data-driven bias,” where easily quantifiable biophysical indicators are prioritized over complex socio-institutional realities. Future nexus research should increasingly adopt locally grounded, people-centered, and hybrid methodological approaches that integrate physics-based simulations with participatory and systems-based methods. Such approaches can better capture feedback loops, adaptive capacity, governance dynamics, and recovery trajectories under conditions of uncertainty and shock. Through these shifts, the WEF nexus can evolve from a framework focused primarily on resource flow into a more comprehensive pathway towards sustainable and resilient agrifood systems.

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