

The Water-Energy-Food Nexus: Concepts, Methods, Regional Applications, and Governance—A Review

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Abstract

The water-energy-food (WEF) nexus has become an influential framework for analysing the interdependencies among three essential resources for sustainable development. Since the Bonn 2011 conference, WEF research has expanded from conceptual discussion to quantitative assessment, coupling coordination analysis, scenario simulation, optimisation, and governance analysis. This review synthesises conceptual definitions, methodological approaches, regional applications, and governance implications. It uses a narrative critical review with systematic elements based on a Web of Science Core Collection export. The review defines key constructs—coupling coordination, WEF efficiency, security, and resilience—and compares major methods according to decision purpose, system boundary, spatial and temporal suitability, data needs, and ability to represent physical flows versus composite indices. Regional evidence is synthesised comparatively rather than study by study. The literature shows growing attention to China, Africa, Central Asia, Europe, and the Middle East and North Africa. Despite progress, WEF research still faces challenges related to data scarcity, scale mismatches, institutional fragmentation, complex trade-offs, climate uncertainty, pollution, health, and social equity. Future research should strengthen interdisciplinary integration, multi-scale modelling, stakeholder engagement, policy coherence, and the incorporation of ecological, carbon, land, health, justice, and gender dimensions into the WEF framework.

Keywords

Water-Energy-Food Nexus, Coupling Coordination, Resource Security, Resilience, Governance, Review

1. Introduction

Population growth, urbanisation, climate change, and economic development are intensifying competition for water, energy, and food. Traditional sectoral management often treats these resources separately, overlooking their interdependencies. The WEF nexus emphasises that water, energy, and food are linked through irrigation, energy production, water allocation, food trade, land use, and carbon emissions. Understanding these synergies and trade-offs is therefore essential for achieving the Sustainable Development Goals.

Recent reviews have examined the WEF nexus from multiple perspectives. Holmatov *et al.* [1] categorised more than 900 documents to characterise approaches, outcomes, and variables supporting on-the-ground change. Jones-Crank [2] proposed a typology of WEF nexus research based on the level of integration and the weighting of sectors. Javan *et al.* [3] reviewed pollution within the WEF nexus and highlighted the need for integrated cross-sector policies. Bamgboye *et al.* [4] reviewed WEF research in Central Asia's transboundary basins and identified gaps in smaller-scale analyses and stakeholder participation. These reviews show that WEF research is growing rapidly, but conceptual clarity, methodological integration, and practical implementation remain uneven.

This review asks: How have WEF concepts and frameworks evolved? What methods dominate? What themes and regions are most studied? What governance and policy insights have emerged? What challenges and future directions remain?

2. Review Methodology

This study is a narrative critical review with systematic elements. It draws on a Web of Science Core Collection export supplied as WEFsavedrecs.txt. The search logic combined the core WEF nexus terms: TS = ("water-energy-food" OR "water energy food" OR "WEF nexus" OR "water-energy-food nexus"). The export date was 25 July 2026. The eligibility criteria were: peer-reviewed journal articles; English language; publication between 2022 and 2026; and explicit or implicit engagement with water-energy-food interactions, nexus governance, or WEF-related methods. Records were excluded when "WEF" referred only to unrelated meanings such as wave energy flux, Weierstrass elliptic function, or weight evolving frequency, or when the study did not address resource nexus interactions. Screening proceeded from title and abstract to full-record assessment. After removing clearly irrelevant records, 40 studies were retained for this concise review. The synthesis was thematic and comparative, organised around concepts, methods, regional applications, governance, challenges, and future directions. Because the review is concise, it does not claim to be a systematic review with exhaustive coverage; rather, it provides a transparent and reproducible synthesis of the selected WEF nexus literature.

3. Key Concepts and Definitions

Coupling coordination refers to the degree to which water, energy, and food sub-

systems are both strongly interconnected and jointly developing. High coupling coordination does not simply mean that the subsystems are linked; it means that their interactions support balanced and mutually reinforcing development [5] [6]. Studies often measure coupling coordination to identify whether resource systems are merely coupled or are also coordinated in a sustainable direction [7].

WEF efficiency refers to the input-output performance of water, energy, and food systems. It assesses how well these systems produce resource services while minimizing resource inputs and environmental costs [8] [9]. Efficiency studies differ in whether they treat environmental pollution as an undesirable output, whether they consider only physical flows or also economic values, and whether they measure single subsystems or the whole nexus [10].

Security in the WEF context means reliable availability, access, affordability, and stability of water, energy, and food under normal conditions and shocks. Security is broader than efficiency because it includes distributional, institutional, and vulnerability dimensions [11] [12].

Resilience refers to the capacity of WEF systems to absorb disturbances, adapt to changing conditions, and transform when necessary. Resilience is closely related to security but focuses more on disturbance response, recovery, and adaptive capacity [13]. Institutional fragmentation and weak governance can limit resilience even when resource endowments are adequate [14].

4. Methodological Approaches: Comparative Assessment

WEF studies use diverse methods, and each method has a different decision purpose, system boundary, spatial and temporal suitability, data requirement, and capacity to represent physical flows or composite indices.

Indicator and index approaches are useful for broad comparison and communication. They can integrate physical, economic, social, and environmental variables into composite scores. However, they depend heavily on weighting choices and may obscure underlying physical flows. Han *et al.* [9] constructed a WEF indicator system and used coupling coordination and spatial equilibrium measurement for China. Deng *et al.* [13] and Kou *et al.* [14] used related indicator approaches to assess regional coordination.

Coupling coordination degree models are suitable for analysing interaction and balance among subsystems. They are often applied at provincial, basin, and city scales. Their strengths include simplicity and comparability. Their limitations include sensitivity to indicator selection and difficulty in capturing nonlinear feedbacks. Han *et al.* [15] used a Lotka-Volterra model to assess water competition and synergy in the Yellow River Basin, which offers a more dynamic view than standard coupling coordination models.

Efficiency methods, especially data envelopment analysis and slack-based measures, are suitable for benchmarking and identifying inefficiency. Huang *et al.* [10] employed a three-stage DEA model to measure provincial WEF efficiency in China. Gao *et al.* [11] used a dynamic slack-based measure to evaluate WEF ef-

efficiency across 31 Chinese provinces. Guan *et al.* [12] developed a framework that considers negative environmental impacts and clarified interactions within the WEF system to evaluate coupling efficiency in the Yellow River Basin. These methods represent physical and economic inputs and outputs well, but they are less suited to capturing governance or equity dimensions.

System dynamics and simulation models are suitable for policy simulation and long-term prediction. They can represent feedback loops, delays, and nonlinear relationships. Barati *et al.* [5] used system dynamics to analyse water scarcity in Iran. Jonsson *et al.* [16] explored dynamic mode decomposition for WEF modelling and policy impact prediction. Dias *et al.* [17] used WEAP to simulate Brazilian watersheds and analyse governance actions. These methods require substantial data and calibration, and their results depend on model assumptions.

Machine learning and artificial intelligence methods are increasingly used for prediction, pattern recognition, and driver analysis. Fu *et al.* [18] developed an integrated XGBoost-LSTM model for WEF efficiency simulation in the Yellow River Basin. Cheng *et al.* [19] used explainable machine learning to evaluate WEF system security. Huang *et al.* [20] examined the impact of artificial intelligence on WEF technical efficiency in China. These methods can handle large datasets and nonlinearity, but they often lack transparency and may not represent causal mechanisms unless carefully designed.

Optimisation models are suitable for resource allocation and trade-off analysis. Feng *et al.* [21] constructed a multi-objective nonlinear optimisation method for sustainable agriculture in the Tarim River Basin. Darboei *et al.* [22] used a multi-objective grey wolf optimiser for water resource exploitation under climate change. Iqbal *et al.* [23] optimized the WEF Nexus for sustainable agriculture in Pakistan. Khalili *et al.* [24] validated WEF nexus indicators for sustainable organic saffron production. These methods can identify Pareto-optimal solutions but require clear objective functions and constraints.

Life cycle assessment and footprint methods are suitable for quantifying environmental pressures along supply chains. Ceballos-Santos *et al.* [25] applied a WEF nexus approach to seafood products. Entrena-Barbero *et al.* [26] proposed a WEF nexus index for dairy farms. These methods represent physical flows well but often require extensive inventory data and may not capture governance or equity.

Governance and policy analysis methods include institutional analysis, policy coherence assessment, stakeholder engagement, and participatory approaches. Jones-Crank [27] conducted a multi-case institutional analysis of WEF governance. Ballo *et al.* [28] developed a multi-criteria policy coherence index for sub-Saharan Africa. Djenontin *et al.* [29] introduced Collaborative Learning Schools for stakeholder engagement. Al-Zu'bi *et al.* [30] investigated household WEF practices in Amman, Jordan. Dearden *et al.* [31] reviewed pathways linking WEF insecurity and health in South Africa. These methods are essential for understanding implementation, power, and equity, but they are often qualitative and context-

specific.

5. Regional Applications: A Comparative Synthesis

5.1. China

Chinese WEF research focuses on water scarcity, energy transition, food security, and spatial imbalance. The Yellow River Basin is a major hotspot. Recurrent trade-offs include water for agriculture versus water for energy and ecosystems, and economic growth versus environmental protection. Common methods include coupling coordination, DEA, system dynamics, machine learning, and optimisation. Governance constraints include fragmented sectoral responsibilities and uneven implementation. Policy responses discussed in the literature include water resource fee-to-tax reform, water rights reform, and ecological security planning [32] [33]. Han *et al.* [34] proposed a multi-level symbiosis framework for WEF synergies in the Yellow River Basin. Chen *et al.* [32] found that water resource fee-to-tax reform and water rights reform promote WEF coordination. Ding *et al.* [33] identified and optimised ecological security patterns from a WEF perspective. Han *et al.* [9], Huang *et al.* [10], Gao *et al.* [11], Kou *et al.* [14], and Deng *et al.* [13] provide provincial and regional evidence on coupling coordination and efficiency. Fu *et al.* [18] and Cheng *et al.* [19] show the growing use of machine learning for prediction and security assessment.

5.2. Africa

African WEF research emphasises data scarcity, infrastructure gaps, institutional fragmentation, and social vulnerability. Recurrent trade-offs include agricultural expansion versus water and energy security, and resource extraction versus local livelihoods. Methods include index-based assessment, system dynamics, policy coherence analysis, and participatory approaches. Governance constraints include weak cross-sectoral coordination, limited local capacity, and uneven service delivery [14] [28]. Ballo *et al.* [28] evaluated WEF governance and energy transition pathways in Mali, South Africa, Malawi, and Tanzania. Dlamini *et al.* [35] evaluated climate change adaptation in the Buffalo River catchment, South Africa. Dalla Dearden *et al.* [31] reviewed WEF insecurity and health in South Africa. Djenontin *et al.* [29] reported lessons from a collaborative learning school in Uganda.

5.3. Central Asia and the Middle East

Central Asian and Middle Eastern WEF research focuses on transboundary water, climate stress, energy production, and food imports. Recurrent trade-offs include upstream hydropower versus downstream irrigation, and water-intensive agriculture versus urban and industrial demand. Methods include system dynamics, scenario analysis, and integrated assessment. Governance constraints include transboundary coordination failures and geopolitical uncertainty. Bamgboye *et al.* [4] reviewed WEF research in Central Asia's transboundary basins. Barati *et al.* [5] analysed water scarcity in Iran. Hejazi *et al.* [36] analysed water scarcity impacts on

agriculture and electricity in the Middle East and North Africa. Iqbal *et al.* [23] optimized the WEF Nexus for sustainable agriculture in Pakistan.

5.4. Europe and South America

European and South American WEF research emphasises ecosystem services, climate adaptation, urban systems, and supply chains. Recurrent trade-offs include agricultural intensification versus water quality and biodiversity, and energy demand versus land use. Methods include life cycle assessment, footprint analysis, system dynamics, and spatial modelling. Governance constraints include policy coherence and multi-level coordination. Carrasco-Astudillo *et al.* [8] integrated the WEF nexus into resilient cooling strategies for buildings. Ceballos-Santos *et al.* [25] applied a WEF nexus approach to seafood products in the European Atlantic area. Javan *et al.* [3] reviewed pollution within the WEF nexus. Dias *et al.* [17] studied watershed governance and sustainability indices in Brazil. Abdelatif and Djiar [7] linked WEF indicators with urban carrying capacity for Algiers.

6. Governance and Policy Progress

WEF governance research calls for a shift from sectoral management to cross-sectoral coordination. Jones-Crank [27] compared WEF governance in Phoenix, Cape Town, and Singapore and identified horizontal coordination, scalar fit, and bottom-up participation as key themes. Ballo *et al.* [28] found strong structural policy alignment but limited functional integration in sub-Saharan Africa. Djenontin *et al.* [29] emphasised participatory co-creation of actionable knowledge. Al-Zu'bi *et al.* [30] highlighted the importance of household-level WEF dynamics and inclusive decision-making. Dearden *et al.* [31] called for integrated research and policy approaches addressing the WEF-health nexus.

Policy tools directly examined in the reviewed literature include water resource fee-to-tax reform and water rights reform [32], green financing risk assessment [37], policy coherence assessment [28], participatory learning and stakeholder engagement [29], household-level inclusive policy development [30], health-oriented integrated policy [31], and ecological security planning [33]. These tools are not universally applicable; their effectiveness depends on institutional capacity, data availability, and political context.

7. Key Challenges

1) Data scarcity: Long-term, high-resolution WEF data are often unavailable. Bamgboye *et al.* [4] and Djenontin *et al.* [29] highlighted data and capacity constraints in Central Asia and Uganda.

2) Scale mismatches: Administrative boundaries rarely align with river basins or ecological processes. Ding *et al.* [33] developed a framework for ecological security patterns from a WEF perspective.

3) Institutional fragmentation: Water, energy, and food are managed by different agencies with conflicting goals. Ballo *et al.* [28] found limited functional inte-

gration in sub-Saharan Africa.

4) Complex trade-offs: WEF systems are nonlinear and dynamic. Han *et al.* [15] found that including grey water footprint intensified water competition between food and energy industries in the Yellow River Basin.

5) Climate uncertainty: Precipitation, temperature, and extreme events affect water, energy, and food production. Barati *et al.* [5] projected worsening water scarcity in Iran. Hejazi *et al.* [36] projected that agricultural production could drop by 60% by 2050 in some MENA countries.

6) Pollution and health: Water, air, food-chain, and emerging pollutants increase WEF risks. Javan *et al.* [3] reviewed pollution within the WEF nexus. Dearden *et al.* [31] identified pathways linking WEF insecurity and health in South Africa.

7) Social equity and gender: Vulnerable groups, women, Indigenous peoples, and rural households are often marginalised. Al-Zu'bi *et al.* [30] found gender-related differences in household WEF decisions.

8) Abbreviation ambiguity: "WEF" may also refer to wave energy flux, Weierstrass elliptic function, or weight evolving frequency, requiring careful literature screening. Javan *et al.* [3] and Jones-Crank [2] noted the need for clear definitions.

8. Future Research Directions

The following are research priorities proposed by this review, not established findings of the selected studies.

1) Interdisciplinary integration: Linking natural science, engineering, economics, sociology, law, and governance. Jones-Crank [2] proposed a typology to clarify integration levels.

2) Multi-scale dynamic modelling: Connecting global, national, basin, city, and household scales. Ding *et al.* [33] developed a multi-scale framework for ecological security patterns. Dias *et al.* [17] simulated watershed governance across scales.

3) AI and big data: Using machine learning, remote sensing, and large datasets. Fu *et al.* [18] used XGBoost-LSTM. Cheng *et al.* [19] used explainable machine learning. Huang *et al.* [20] examined AI development and WEF technical efficiency.

4) Participatory governance: Stakeholder engagement, co-design, and policy coherence. Djenontin *et al.* [29] introduced Collaborative Learning Schools. Al-Zu'bi *et al.* [30] emphasised bottom-up policy development.

5) Equity and justice: Incorporating gender, poverty, Indigenous rights, health, and environmental justice. Al-Zu'bi *et al.* [30], and Dearden *et al.* [31] provide foundations.

6) Carbon neutrality and circular economy: Integrating carbon footprints, carbon taxes, green finance, and circular supply chains. Gutman *et al.* [37] assessed green financing risks. Chen *et al.* [32] analysed water policy and WEF coordination.

7) Ecology and planetary boundaries: Treating ecosystem services and biodiversity as WEF constraints. Ding *et al.* [33] and Han *et al.* [34] provide ecological and

symbiosis perspectives.

8) Policy implementation evaluation: Moving from policy design to implementation, accountability, and impact assessment. Ballo *et al.* [28] developed a policy coherence index.

9. Conclusions

The WEF nexus has become an important framework for understanding water, energy, and food interlinkages. Recent literature shows a shift from conceptual advocacy to quantitative assessment, dynamic simulation, optimisation, and governance practice. China, Africa, Central Asia, Europe, and the Middle East and North Africa are key research regions. Coupling coordination degree models, DEA, system dynamics, machine learning, and multi-objective optimisation are now mainstream methods. Policy research increasingly addresses water rights, water taxes, green finance, policy coherence, participatory governance, and ecological security.

Nevertheless, WEF research still faces challenges related to data, scale, governance, equity, and uncertainty. Future work should be more interdisciplinary, multi-scale, participatory, and policy-oriented, integrating ecology, carbon, land, health, gender, and justice into a unified analytical framework to support resource security, sustainable development, and the SDGs.

Declaration of AI-Assisted Technology Use

During manuscript preparation, large language models were used for language polishing and grammar revision to improve readability. All AI suggestions were reviewed and edited by the author. The author hold full responsibility for the paper. AI was not used for data generation, analysis or core academic writing.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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