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Review

Water–energy–food nexus in the circular economy: implications for climate mitigation

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The Water–Energy–Food (W-E-F) nexus creates difficulties for policy makers, public and private organisations seeking to define a clear pathway towards a sustainable economy. Since the beginning of the industrial revolution, global consumption and resource use have followed a 'linear economy model'. This review examines recent developments in circular W-E-F innovations, sustainable design tools, life-cycle methodologies and policy developments.

Evidence from recent technological studies, optimisation frameworks and empirical assessments demonstrates the potential for substantially reduced greenhouse gas emissions, integrated resource planning and circular value creation within agriculture, water management and energy production. The review finds that integrating circular economy (CE) principles into the W-E-F nexus remains crucial for climate mitigation and advancing sustainable resource management. Greater efficiency and reduced emissions across interconnected systems are essential to achieving these goals. Recent developments, technological advances and new policies can support efforts in redesigning the resource flow, improving socio-economic outputs and achieving the Sustainable Development Goals (SDG).

This review paper contributes to the knowledge by highlighting the conceptual and methodological gaps on the W-E-F nexus, while recommending a framework that links CE approaches with climate mitigation.

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Introduction

Nowadays, pressure on water availability, food and energy security and environmental quality is increasing due to population growth and rising consumption. Water, energy and food are closely interrelated and are commonly referred to as the 'water-food- energy' nexus (W-E-F). According to Ghosh et al. [1], the theoretical framework of the W-E-F nexus put emphasis on the four critical links. The first association is the water for food, as agriculture accounts for 70% of the total global freshwater [2,3]. The second link is the water for energy, as water is required for the extraction, mining, processing, as well as for generating electricity [4–14]. The third component is the water–energy interface, where substantial energy inputs are needed to pump, transport, distribute and treat water across different stages of the supply chain [15–23]. Lastly, the fourth link is the energy for food interface, as energy is required to produce, transport and distribute food [24–33]

The W-E-F nexus creates challenges for policymakers, public institutions and private organisations in defining a clear path towards a sustainable economy. Since the onset of the industrial revolution, patterns of global consumption and resource utilisation have increased dramatically, driving significant pressure on natural systems, followed a 'linear economy model'. While this approach has enhanced vast economic and social growth, it has also resulted in enormous overconsumption and the loss of resources. A clear need

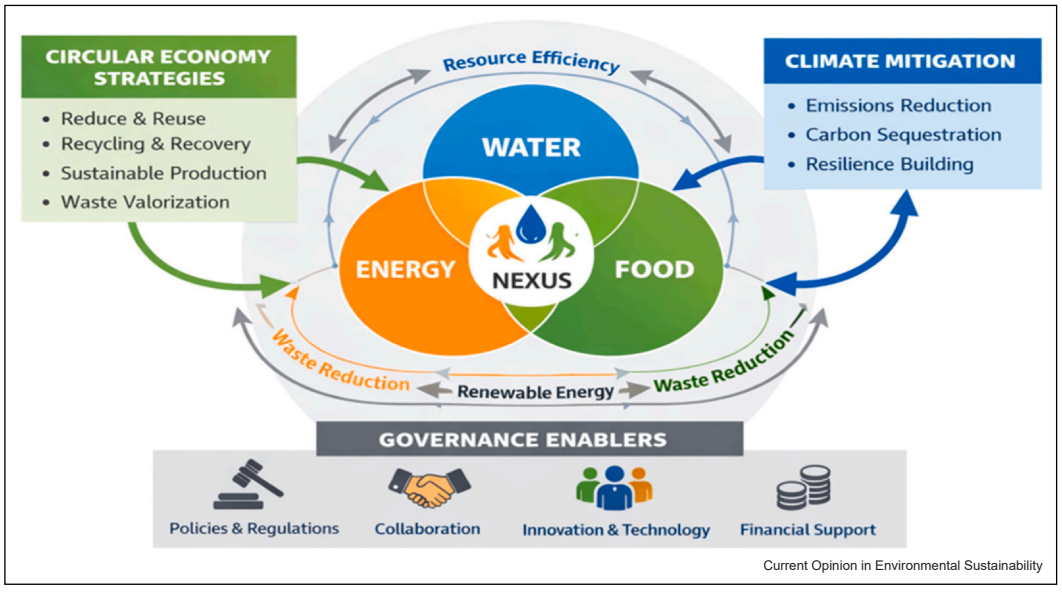
exists for a new economic model — the circular economy (CE), which has been proposed for a long period as an alternative to our current linear economy.

This review paper examines recent developments in circular W-E-F innovations, sustainable design tools, life-cycle methodologies and policy developments and adopts a concept-driven and forward-looking perspective, focusing on emerging insights rather than exhaustive coverage of the water–energy–food nexus literature. Evidence from recent technological studies, optimisation frameworks and empirical assessments demonstrates the potential for low-carbon and near-neutral emission pathways, as reported in the reviewed studies, integrated resource planning and circular value creation within agriculture, water management and energy production. Governance and policy analysis show growing alignment with sustainability agendas such as the European Green Deal, while also revealing persistent gaps in coordination, data availability and institutional alignment. The review further highlights evolving considerations of equity and justice, emphasising the need for inclusive and socially responsive nexus transitions.

Despite the swift growth of studies centered on the (W-E-F) nexus, on-going research is still hindered by three interconnected conceptual gaps. First, although CE concepts are frequently mentioned in nexus-related literature, they are typically viewed as mere operational instruments or niche technical fixes. There is a lack of focus on CE as a comprehensive theoretical framework that can fundamentally reconfigure nexus interactions for climate action. Current scholarship tends to prioritise isolated technological advancements or specific resource cycles, failing to explain how circularity can structurally alter cross-sectoral dependencies and carbon emission trajectories. Second, much of the existing W-E-F discourse suffers from methodological isolation. Analytical approaches — such as life-cycle assessments, governance studies and socio-economic reviews — often progress independently rather than through integrated dialogue. This lack of synergy prevents current literature from clearly defining exactly how and under what circumstances circular models produce tangible climate mitigation results across the entire nexus. Third, while issues of equity, social justice and a 'just transition' have become central to sustainability discussions over the last few years, these elements are not yet deeply embedded in nexus-based CE research. This is particularly evident regarding the creation and execution of climate-related policies. This review fills these voids by offering a structured, forward-looking integration of modern literature. It frames the CE as a central pillar for climate mitigation within the W-E-F nexus. Instead of simply listing technologies or individual case studies, this paper categorises evidence through the lenses of design, governance, fairness and macroeconomics. The goal is to illustrate how circular initiatives transform nexus dynamics, lower emissions and foster development paths that are resilient to climate change.

Figure 1 displays the conceptual framework connecting CE approaches with the W-E-F nexus and climate-

Figure 1



Conceptual framework linking CE strategies with the W–E–F nexus and climate-mitigation pathways, illustrating resource loops, emissions reduction mechanisms and governance enablers.

mitigation pathways. The framework demonstrates how resource efficiency, waste reduction and circular resource loops across water, energy and food systems contribute to emissions reduction and climate resilience. Governance, innovation and policy coordination act as enabling mechanisms supporting this transition.

Methodology

Since there is methodological heterogeneity in all those studies and quantitative meta-analysis is not possible, we adopt a structured thematic review, organised around analytically defined domains, in order to synthesise interdisciplinary literature. It is based on an epistemological perspective and combines positivist evidence from quantitative assessments and interpretive insights from equity, justice, governance and policy assessments. Studies identified through a targeted search in major academic databases, and selected based on relevance, methodological transparency and contribution to the W-E-F nexus.

The paper adopts an analytical approach and classifies the studies into six domains: recent advances, Sustainable Design & Life-Cycle Approaches, Policy and Governance, Equity and justice, Macro-Economic and Sustainability Implications and Case studies. There is a comparison across methods, geographical contexts and outcomes. This approach addresses the identified conceptual gap while enhancing the analytical synthesis rather than descriptive analysis.

Recent advances in circular water–food–energy nexus

Samberger [34] examines the importance of enhancing water circularity within the food–water–energy nexus as a means of supporting climate-mitigation efforts. This paper reviewed the recent studies about the W-F-E nexus and climate change, trying to explain why water circularity is one of the most important factors to accelerate the transition from a linear model of the economic system to circularity. According to this study, water circularity initiatives should follow the waste hierarchy logic, beginning with reducing water consumption and progressing towards recovering materials and energy from residual streams. Pollutants in wastewater can be converted into inputs for other processes. Thus, the most effective approach to mitigating climate change and the shortage of resources is to control the value of water as much as possible. Vahedi et al. [35] focus on the optimisation models and decarbonisation. They showed a transformative method to achieving substantially reduced greenhouse gas emissions in a fossil fuel-based industrial region by incorporating circularity principles with W-E-F nexus optimisation. Sei et al. [36] integrate the wastewater treatment process into the W-E-F nexus. Empirical results showed that the wastewater treatment process has progressed from eliminating and disposing of organic matter and nutrients to regaining resources, proposing an environmental and ecological approach. The W-E-F nexus incorporates the climatical impacts of wastewater management via greenhouse gas emissions and other socio-economic considerations [37]. This subsection critically analyses how recent advances and interventions operationalise the W-E-F nexus in terms of climate mitigation.

Sustainable design and life-cycle approaches

Del Borghi [38] explains the CE frameworks and, more specifically, how circular strategies are applied in the food-water-energy nexus. This study is a review of recent studies in this field and tries to explain the interdependencies among water-energy and food. More specifically, this study focused on how important factor is the application of life cycle assessment into this nexus. From A LCA perspective this study highlights that the biggest challenge is the reduction, managing and reuse the waste from food. The author concluded that it is very important to transfer the concept from a theoretical perspective to an integrated approach policy to pave the way to a W-E-F nexus reduction. Similarly, Segovia-Hernández et al. [39] to investigate the status of the Water–Energy–Food Nexus (WEF) in European countries made a review to discuss design principles. This review verified that most of the W-E-F findings concentrated mostly on energy production. From a methodological view, authors showed that there is no commonly accepted method for W-E-F evaluations, implying the necessity to plan a standard and holistic approach. A new holistic framework is required with the objective of developing the efficiency of future nexus methods by considering all of the resources/ sectors, incorporating water (quantity and quality), energy, food, land and climate nexus. Andersson [40] examined on how applying the W-E-F nexus to initiate interactions and decrease trade-offs amongst the SDG. Paper supports the view that the nexus is a paradigm-shifting method that transfers away from 'siloed' resource management and practices incorporation and holistic planning amongst W-E-F governance. The author describes a method for a W-E-F nexus that can map and quantify carbon footprints, making synergies. Important policy suggestions of the paper contain a criterion for what it means to 'optimise' the 'output' of an algae cultivation system. This criterion is an instrument for resolution between stakeholders' conflicting priorities. Thus, this subsection critically analyses how Sustainable Design & Life-Cycle Approaches are linked to the W-E-F nexus and evaluates the environmental performance while quantifying climate mitigation potential.

Policy and governance

Adamos et al. [41] explored the nexus policy insights for W-E-F resilient communities. Authors delivered an overview of the main policies of the European Green

Deal from the standpoint of the W-E-F nexus, seeking connections, improvements and actions. The study specified the necessity for combined and sustainable methods to address the shared challenges of safeguarding energy security, endorsing agricultural productivity and reaching food system resilience in the face of major changes. Hejnowicz et al. [42] highlighted the governance challenges and made an integration across different sectors. In their critical appraisal of the W-E-F, involving different approaches, drivers, enablers and applications, they give emphasis to the situation across the Global South (Africa, Asia, Latin America and the Caribbean). Finally, Naidoo et al. [43] tried to operationalise the nexus and explained the stakeholder processes and interactive governance. The implementation of the W-E-F can enhance resource security and sustainable development. The paper made a review of existing literature and applied a systemic analysis of a W-E-F-nexus analytical framework, where empirical findings were used to construct a Theory of Change that guides the practical implementation of the approach in Southern Africa. This section critically examines the policy and governance influence on the effectiveness of CE in addressing challenges under climate mitigation.

Equity, justice and just transition

Li and Zhang [44] applied the just energy transition perspective and explained why social equity matters in the relationship of the nexus and circularity. The research examined how the WEF-nexus concept has evolved and how it can support a socially equitable, environmentally responsible and economically viable energy transition. It emphasises that inclusive policies — particularly for vulnerable groups — are essential to ensure access to clean energy, secure water and food supplies and reduce inequalities. Hoosain et al. [45] examined how the shift to a CE and the usage of new technologies can impact the relationship of W-E-F and climate and achieve the SDGs. Authors support the view that the cooperation of CE with new technologies leads to a new model of natural resource management aimed at achieving sustainability. This section highlights the importance of social inclusion, distributive justice and access to resources in shaping the sustainable future.

Macro-economic and sustainability implications

Morales-García and Rubio [46] made an attempt to link the nexus with a wide economic sustainability. Authors highlighted that the W-E-F serves as an effective framework for assessing economic risks linked to resource scarcity, informing investment decisions and evaluating how policy choices or shocks, including climate change, affect sectoral performance and future resource availability. Farmandeh et al. [47] tried to examine the validity of several internal and external factors that can explain the interconnectedness of the W-E-F and the climate. They focused on socioeconomic, climate and demographic indicators that have implications for the W-E-F and sustainable use of essential resources in agricultural societies. They deployed a mixed-method and their results emphasise the need for integrated advanced strategies that integrate the W-E-F. This section critically analyses the macroeconomic implications of the W-E-F nexus under climate and resource limitations.

Case studies/illustrative examples

Mashaal et al. [48] paper is an excellent case study and illustrative example of an ecovillage that shows the circular WEF nexus circular design This paper's deployed a systematic modelling to achieve sustainable development objectives and mitigate resource stress in Ferdaws village in Western Dessert in Egypt. The ecovillage model integrates coordinated management of groundwater resources, agricultural production, energy generation and community needs to address local water, food and energy demands sustainably. The empirical results were promising and indicated a low environmental risk and aligned with the W-E-F nexus and sustainable development goals. Ibrahim and Shirazi [49] investigated the nexus between W-E-F and the Transition Towards a CE in Qatar. The empirical results indicate that energy, agriculture and water supply systems of Qatar present a prospect by enabling processes such as regeneration, virtualisation, exchange, optimisation, sharing and loop-closure that collectively support the expansion of the CE. Finally, Brandoni and Bosnjakovic [50] examined the nexus in the EU countries, concentrating on energy and investigated how CE can address future challenges. Authors found that several prospects can be applied within the nexus, including heat recovery, food-waste valorisation, electricity production and the extraction of energy and nutrients from wastewater streams. However, differences emerge in scalability, governance capacity and climate-mitigation effectiveness, particularly between Global North and Global South contexts. This subsection critically evaluates applied case studies of the W-E-F nexus, assessing their effectiveness and outcomes.

Conclusion

This review paper highlights that the relationship of the nexus and circularity constitutes a powerful structural lever for climate mitigation. The reviewed literature demonstrates the crucial importance of design, governance and equity. The findings underline the need for coordinated action across researchers, practitioners and policy makers. Beyond summarising existing literature, this paper contributes analytically by clarifying where CE strategies deliver measurable climate-mitigation benefits within the W-E-F nexus and where evidence remains insufficient or fragmented.

We found that the integration of CE within the W-E-F nexus is crucial for climate mitigation and achieving sustainable resource management. Increasing efficiency and reducing emissions across those integrated systems remain central priorities. Recent developments, technological advances and new policies can provide support in redesigning the resource flow, improving socio-economic outputs and achieving the SDGs. Several studies highlighted the importance of bridging the continual gaps between design, governance and equity. Successful applications should move beyond theoretical models towards integrated, practical solutions supported by inclusive policy processes, cross-sectoral coordination and strong community engagement.

Key limitations in investigating the nexus remain in the methodological integration, model harmonisation, data availability and uncertainty assessment. More multi-scale models, methods and LCA metrics are needed to further examine the interventions and evidence-based decision making. Policy barriers, including lack of integrated governance and institutional fragmentation, further constrain implementation. Most countries do not have an integrated governance framework to be able to support CE solutions. Limited financing and stakeholders' involvement further hinder implementation. There is a need for more case studies and evaluation metrics for the long-term performance of circular WEF interventions. More empirical studies are needed to measure benefits and trade-offs. Future research should prioritise multi-scale modelling approaches, standardised life-cycle metrics and long-term empirical validation. Policymakers should strengthen integrated governance frameworks and investment incentives, while practitioners should scale pilot initiatives supported by digital monitoring of cross-sector collaboration.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

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.

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- •• of outstanding interest

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