

Review

Building Climate-Resilient Food Systems Through the Water–Energy–Food–Environment Nexus

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Abstract: Climate change disrupts global food systems by affecting water, energy, ecosystems, and agricultural productivity. Building climate resilience demands integrated approaches that recognize interdependencies among water, energy, food, and environmental (WEF-E) systems. This review synthesizes current research on how the WEF-E nexus can guide climate adaptation strategies. It highlights interdisciplinary solutions—such as solar-powered irrigation, agrivoltaics, agroforestry, conservation agriculture, and nature-based water management—that enhance resource efficiency, stabilize yields, and reduce environmental degradation. Effective implementation requires governance innovation, stakeholder participation, and coherent cross-sector policies. The paper also outlines research priorities, including the development of resilience metrics, modeling tools, and inclusive decision-making mechanisms. Emphasizing both adaptation and mitigation, the WEF-E nexus offers a transformative lens for sustainable, equitable, and climate-resilient food systems. As climate pressures intensify, advancing this integrated framework presents both an urgent necessity and a strategic opportunity to align food security with environmental stewardship.

Keywords: water–energy–food–environment nexus; climate resilience; sustainable food systems; integrated resource management; adaptation strategies



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1. Introduction

Climate change and environmental degradation pose unprecedented challenges to global food security. The 21st century’s grand challenge is to provide water, energy, and food for a growing population while staying within planetary boundaries in a changing climate [1,2]. Food systems worldwide are already experiencing climate impacts—rising temperatures, shifting precipitation, and more frequent extreme events—which threaten crop yields and supply stability. For example, each 1 °C increase in global temperature is projected to reduce average global yields of staple crops by several percent (e.g., wheat −6.0%, maize −7.4% per degree) [3–5], exacerbating the risk of hunger and food insecurity, especially in low-income regions [6].

At the same time, agriculture and food production are major consumers of water and energy and contribute significantly to environmental change. Food systems—defined in this review as the entire value chain from agricultural production through processing, distribution, and consumption—account for roughly one-quarter to one-third of global greenhouse gas emissions, including emissions from on-farm activities as well as pre- and post-production processes [7–9]. They have also driven widespread land-use change, biodiversity loss, and freshwater depletion [10,11]. These feedback loops make food systems both contributors to and victims of climate change. Ensuring food security under climate change thus requires enhancing the resilience of food systems—their ability to

withstand, adapt to, and recover from climate shocks—through more sustainable and integrated resource management [12,13]

In this context, the Water–Energy–Food–Environment (WEF-E) nexus has emerged as a promising framework for addressing the interlinked nature of resource systems. The Water–Energy–Food (WEF) nexus concept recognizes that water, energy, and food systems are deeply interconnected, and that sustainability challenges must be tackled through an integrated approach rather than in sectoral silos [14,15]. Increasingly, the nexus framework explicitly incorporates the environmental dimension (sometimes termed the water–energy–food–ecosystem nexus) to account for the ecosystems and natural processes that underpin these resources [16]. A nexus approach provides a platform to manage synergies and trade-offs among water, energy, food, and environment goals simultaneously [17–19].

This integrated perspective is vital for climate-resilient development, as effective adaptation strategies must span multiple sectors to avoid simply shifting vulnerabilities from one domain to another [20,21]. Indeed, pursuing single-sector solutions in isolation can lead to maladaptation—actions that inadvertently undermine resilience elsewhere. For instance, efforts to boost food production resilience (e.g., drought-proofing agriculture) can, if performed in isolation, erode the resilience of water systems through over-extraction or pollution [1,22]. Avoiding such unintended consequences calls for cross-sectoral planning and an interdisciplinary lens [23,24].

This review examines how an interdisciplinary WEF-E nexus approach can build climate-resilient food systems by synthesizing recent research (primarily peer-reviewed studies from the past decade) on the global challenges at the Water–Energy–Food–Environment nexus and highlighting integrated strategies for adaptation. This study maintains a broad geographic scope, recognizing that climate resilience in food systems is a global concern requiring context-specific solutions and knowledge exchange across regions. Key climate-resilient strategies and innovations are discussed—spanning technological interventions, ecosystem-based approaches, and governance mechanisms—with an emphasis on how they jointly address water, energy, food security, and environmental sustainability. This paper also identifies barriers to implementing nexus approaches and outlines actionable research directions to inform policy and practice. By leveraging the WEF-E nexus, stakeholders can better harmonize objectives like agricultural productivity, water conservation, clean energy access, and ecosystem health, thereby strengthening the capacity of food systems to endure and thrive under climate stress.

2. Methods

This review adopts a qualitative narrative synthesis approach to analyze and integrate the growing body of knowledge at the intersection of climate-resilient food systems and the WEF-E nexus. The aim was to provide a comprehensive, interdisciplinary overview of how nexus-based strategies can support food system resilience in the face of climate change. The methodological process followed five interlinked stages: conceptual framing, systematic literature search, source screening and selection, thematic synthesis, and gap identification and integration.

The first stage involved conceptual framing and formulation of guiding questions. This review was grounded in the broader discourse on planetary boundaries, socio-ecological resilience, and integrated resource governance. Seminal literature on the WEF nexus, Intergovernmental Panel on Climate Change (IPCC) assessments, and recent advances in food systems research was used to delineate the scope of inquiry. The review was driven by four core questions: (i) How does the WEF-E nexus inform strategies for climate adaptation in food systems? (ii) What synergies and trade-offs exist across water, energy, food, and

environmental sectors? (iii) What governance and institutional mechanisms enable nexus resilience? (iv) Where are the most critical knowledge and implementation gaps?

A structured and comprehensive literature search was conducted across major academic databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar. To capture high-impact grey literature and policy insights, institutional repositories from the Food and Agriculture Organization of the United Nations (FAO), Asian Development Bank (ADB), IPCC, United Nations Environment Programme (UNEP), International Water Management Institute (IWMI), Consultative Group on International Agricultural Research (CGIAR), and International Renewable Energy Agency (IRENA) were also consulted. The search employed Boolean combinations of key terms such as “WEF nexus”, “climate resilience”, “food systems”, “sustainability”, “governance”, and “nature-based solutions”. While the core publication window targeted recent research from 2012 to 2024, especially to reflect developments aligned with the post-Paris Agreement and Sustainable Development Goals (SDGs), seminal pre-2012 works were also included where conceptually or historically relevant. These earlier studies were particularly important in establishing theoretical frameworks on integrated resource management, ecological resilience, and foundational WEF nexus thinking. Priority was given to systematic reviews, interdisciplinary studies, and regionally diverse case analyses to ensure comprehensive coverage across multiple geographies and scales. Although this was not a formal systematic review, the search strategy was iteratively expanded by exploring additional relevant keywords and synonyms (e.g., “climate adaptation agriculture”, “water-energy-food security”, “climate-smart agriculture”, etc.) to broaden the scope. References cited in key papers were also cross-checked to identify any significant studies that may have been missed by the initial queries. This approach helped mitigate potential bias from the initial keyword set and ensured inclusion of literature from a variety of climatic and regional contexts.

Eligibility criteria were applied to screen and select sources. Peer-reviewed journal articles, systematic reviews, modeling studies, and empirical case studies that examined at least two components of the WEF-E nexus in the context of climate resilience were prioritized. Conceptual frameworks and transdisciplinary publications were also included to enrich the synthesis. Articles in languages other than English, opinion pieces lacking methodological clarity, and single-sector studies unrelated to food system adaptation were excluded. Select grey literature from international organizations was used only when peer-reviewed alternatives were unavailable, ensuring the scientific robustness and policy relevance of the synthesis.

The fourth stage involved thematic analysis and synthesis of the literature. A total of 330 documents were reviewed in full, of which 225 peer-reviewed sources were cited in the manuscript. Thematic coding was performed inductively to identify recurring patterns, interventions, and barriers across five nexus domains: (1) water security and efficiency, (2) sustainable energy integration, (3) climate-smart agricultural practices, (4) ecosystem-based approaches, and (5) integrated governance and policy. Comparative regional insights, especially from the Global South, were highlighted to contextualize findings and strengthen the relevance of the review to diverse geographies. Patterns were synthesized within each domain and across sectors to distill cross-cutting strategies and identify context-specific approaches.

The final stage focused on integrating findings to identify overarching lessons and research gaps. Insights from the literature were triangulated with knowledge from empirical case studies, conceptual models, and global assessment reports to ensure robustness. Key knowledge gaps were noted in the development of WEF-E resilience metrics, cross-sectoral policy alignment, stakeholder engagement frameworks, and socioeconomic dimensions

such as equity and justice in nexus implementation. These gaps informed the future directions and forward-looking research agenda for policy and practice.

Bibliometric Analysis and Literature Selection Summary

To provide additional transparency on the literature base of this review, a brief bibliometric analysis was conducted on the references. The studies cited span a wide temporal range and global geographic coverage, reflecting the broad scope of nexus research. Figure 1 maps the country or regional focus of the cited case studies and analyses. As shown, the literature encompasses all inhabited continents, with case studies from North and Sub-Saharan Africa, South and East Asia, Latin America, Europe, and North America. This illustrates a globally distributed evidence base, albeit with a concentration of examples in climate-vulnerable regions of Africa and Asia. In terms of publication years, Figure 2 shows the temporal distribution of referenced works. Research on the WEF-E nexus and climate resilience has grown markedly in the past decade, with over two-thirds of the sources being published after 2015, reflecting the surge of interest following the Paris Agreement. Early influential works (pre-2012) are also cited for foundational context.

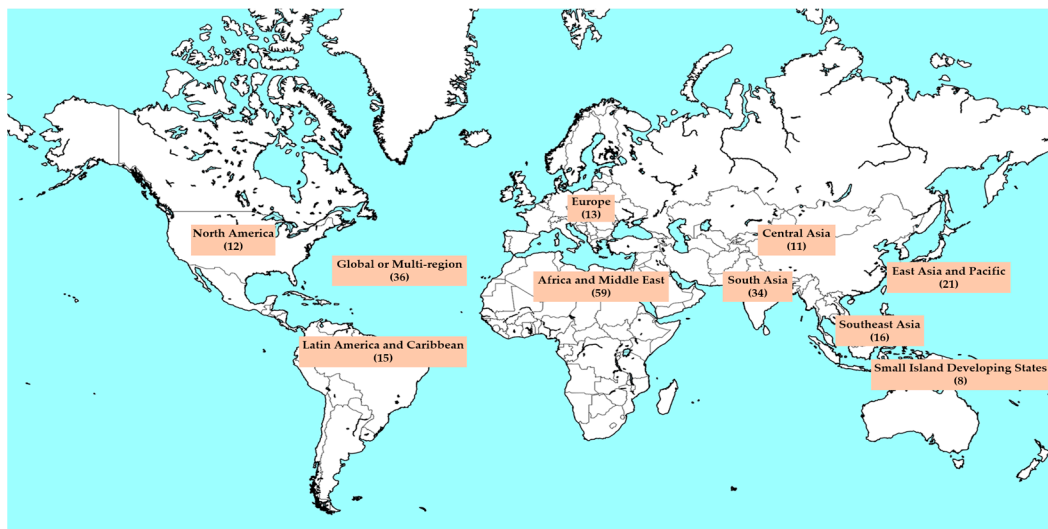


Figure 1. Spatial distribution of the reviewed studies. Note: the numbers in parentheses indicate the count of peer-reviewed studies reviewed from major world regions.

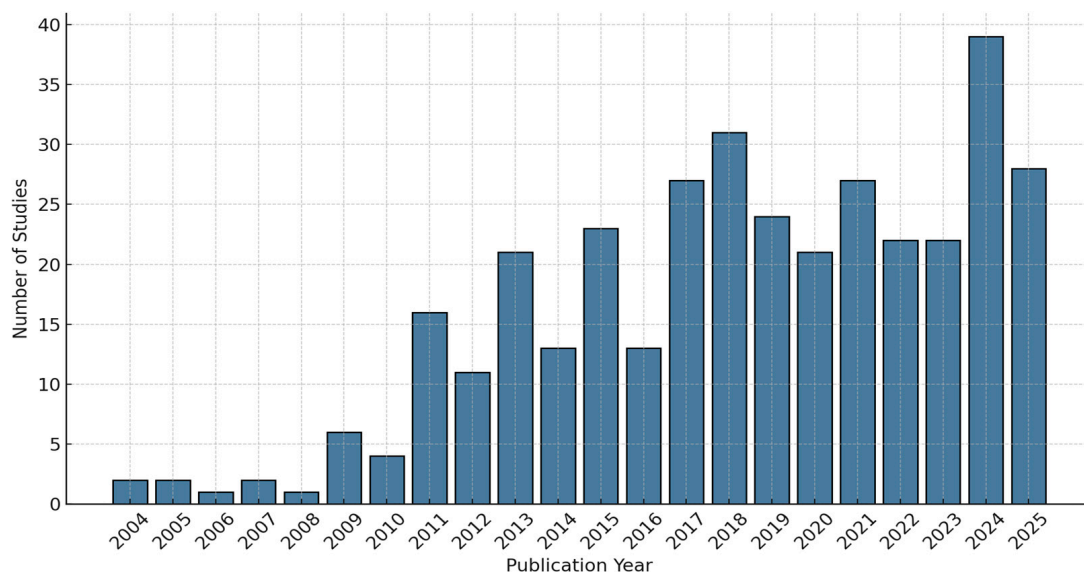


Figure 2. Temporal distribution of the reviewed studies.

To make the selection process explicit, Figure 3 presents a flowchart of the literature search and screening procedure, including inclusion/exclusion criteria applied at each stage. Initially, 895 records were identified via database and organizational searches. After removing duplicates and screening titles/abstracts for relevance to the WEF-E nexus and climate resilience, 330 articles remained for full-text review. Of these, 225 met the eligibility criteria and were included in the qualitative synthesis (the remainder were excluded for being outside scope or lacking sufficient nexus integration, as per the criteria noted above). This screening process ensured that the review focused on high-quality sources directly pertinent to the research questions. The flow diagram underscores the semi-systematic approach used to enhance rigor in what is fundamentally a narrative review.

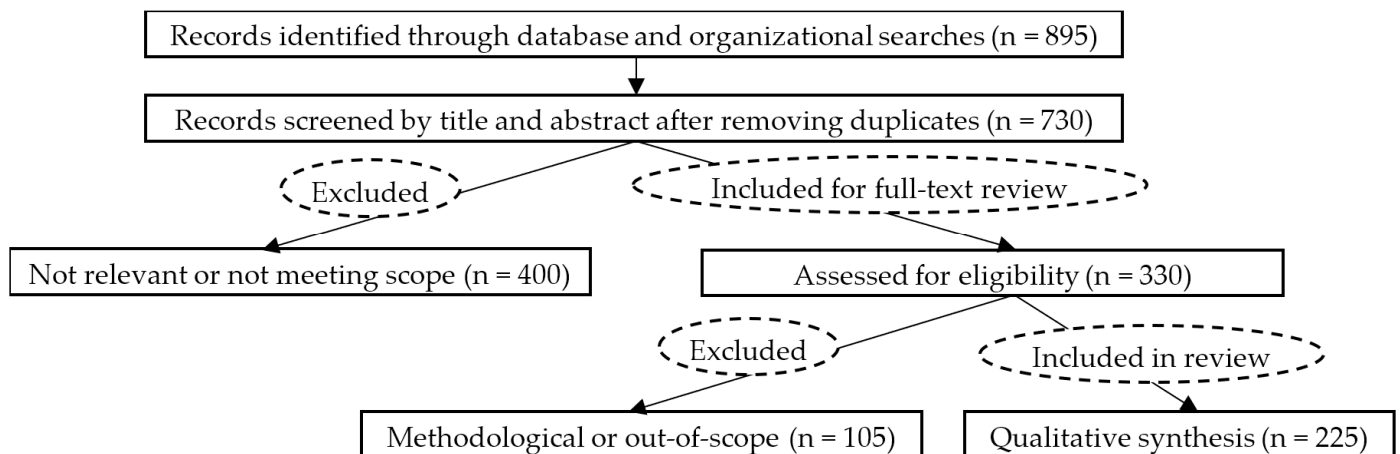


Figure 3. Flowchart of literature search and screening process with inclusion/exclusion criteria.

3. The Water–Energy–Food–Environment Nexus as a Framework for Resilience

The WEF nexus is fundamentally an integrated resource management approach that seeks to balance competing demands and maximize synergies among water, energy, and food systems. It has been described as “an adaptive approach that increases the resilience of energy, water, and food resources in conditions of climate change and population growth” [25]. Rather than treating water, energy, and food security in isolation, the nexus framework emphasizes their interdependence—water is essential for food production and energy generation; energy is required for pumping, treating, and distributing water as well as for agriculture; and food production impacts water availability and energy demand [20,22]. The environment underpins all three pillars by providing critical ecosystem services—such as climate regulation, soil fertility, and water cycling—and is in turn affected by how resources are managed [26]. Expanding the nexus to include the environment acknowledges that ecological integrity is not peripheral but central to achieving sustainability. The WEF-E nexus approach thus aligns with the principles of sustainable development and offers a systems-thinking lens for addressing trade-offs and synergies across sectors [27]. Effective nexus management can simultaneously advance several SDGs, such as ensuring access to clean water and energy (SDG 6 and 7), promoting sustainable agriculture and food security (SDG 2), and protecting ecosystems (SDG 14 and 15) [21,23].

A core strength of the nexus framework lies in its ability to identify and assess interlinkages among sectors. For instance, irrigation water withdrawals can conflict with hydropower generation or environmental flow needs, while bioenergy crop expansion may compete with land and water resources needed for food production [28,29]. The nexus approach enables decision-makers to anticipate such tensions and design interventions

that optimize co-benefits across sectors. Integrated strategies—such as powering irrigation systems with solar energy or using treated wastewater in agriculture—offer “win-win” solutions that support both sustainability and resilience [14,17]. At the same time, the framework highlights the risks of uncoordinated policies. For example, subsidizing electricity for groundwater pumping may increase food output in the short term but can lead to groundwater depletion and long-term water insecurity [30].

Climate change magnifies the importance of nexus-based approaches. Climate hazards—droughts, floods, heatwaves—typically affect multiple sectors simultaneously. A prolonged drought can depress crop yields (food), reduce reservoir levels and hydropower output (energy), and stress freshwater ecosystems (environment) [31,32]. Siloed adaptation—such as expanding irrigation without considering energy or ecosystem constraints—can inadvertently increase vulnerabilities elsewhere. For example, irrigation expansion may intensify groundwater depletion or increase energy demands in areas with unreliable power supply [1]. By contrast, integrated adaptation—e.g., increasing irrigation efficiency, promoting drought-resilient crops, and shifting to solar-powered water pumping—can enhance resilience across the WEF-E system simultaneously [33,34]. In Southern Africa, for example, the fragmented nature of sectoral planning has constrained adaptation, while nexus-oriented programs under the Southern African Development Community (SADC) have demonstrated potential for managing interlinked climate risks more effectively [18,35].

The WEF-E nexus also aligns with social-ecological systems thinking, recognizing the dynamic feedbacks between human development and environmental health. Ecosystem-based approaches such as watershed conservation, agroforestry, or wetland restoration can simultaneously improve water availability, soil health, and carbon sequestration while enhancing adaptive capacity [24,36]. This interdisciplinary lens requires bridging natural sciences (e.g., hydrology, ecology, climatology) with social sciences (e.g., governance, policy, and behavioral economics), making the nexus framework well-suited to tackle complex, multi-sector climate challenges [20,37]. Furthermore, the nexus approach facilitates the understanding of how climate shocks propagate across sectors and helps to identify leverage points for systemic interventions. For instance, the failure of energy infrastructure during a heatwave may disrupt water supply for irrigation and food preservation, leading to cascading failures. Nexus-informed modeling and early warning systems can aid in anticipating such risks and designing more robust adaptation strategies [24,38].

In summary, the WEF-E nexus offers a compelling framework for building climate-resilient food systems. It encourages an integrated, systems-level view of sustainability that accounts for interdependencies, mitigates trade-offs, and fosters synergies across critical sectors. By aligning resource governance with climate resilience objectives, societies can strengthen their ability to cope with complex and compounding environmental stresses while promoting long-term sustainability and equity.

4. Climate Change Impacts and Interconnected Challenges at the WEF-E Nexus

Climate change is altering each component of the Water–Energy–Food–Environment (WEF-E) nexus in profound and interconnected ways, making integrated adaptation strategies imperative. Water resources are particularly sensitive to climate variability as higher global temperatures accelerate snowmelt, shift precipitation patterns, and increase evapotranspiration, often resulting in more erratic water availability [39,40]. Droughts are becoming more prolonged and severe in many agricultural regions, stressing irrigation systems and depleting groundwater, while more intense rainfall events increase flood risks and degrade water quality [41]. Energy systems are likewise climate-sensitive. Hydropower

is vulnerable to reduced river flows, bioenergy crops are susceptible to weather extremes, and rising temperatures increase cooling demands, straining electricity grids [42,43]. When these disruptions co-occur with agricultural stress—such as heatwaves or pest outbreaks that lower crop yields—the cascading effects on food systems and livelihoods can be severe [6,44]. For instance, a major drought may reduce irrigation water availability (affecting crops), limit hydropower production (affecting energy), and trigger forest fires (affecting ecosystems), while simultaneously raising food and energy prices.

Notably, such compound risks are no longer confined to arid or tropical areas—temperate and colder regions are also facing distinct seasonal climate stresses that challenge agricultural resilience [45]. Harsh winters, for example, increasingly demand substantial energy inputs to maintain temperatures in livestock barns, greenhouses, and food storage facilities. These heating needs tightly link food production to energy systems and emissions profiles [46,47]. Emerging innovations—such as biomass boilers fueled by agricultural or forest residues, geothermal heat pumps, and high-efficiency insulation—offer promising mitigation–adaptation co-benefits [48–50]. By reducing reliance on fossil fuels, these technologies not only lower greenhouse gas emissions but also help stabilize food output and energy security in cold climates.

Global assessments have confirmed the growing vulnerability of food systems under climate change. The IPCC’s Sixth Assessment Report emphasizes that climate change has already reduced the yield growth of major crops in several regions and poses serious risks to food security, especially in low-income and tropical countries [51]. Studies project that without adaptation, cereal yields in some African and South Asian countries may decline by 10–30% by 2050 [4,5]. Climate-induced shifts in water availability could place an additional 500 million people under water stress by mid-century [52], threatening irrigated agriculture. Simultaneously, thermal power plants, which require cooling water, are increasingly at risk of operational curtailments during heatwaves and droughts [53]. Moreover, as energy demands rise—for cooling during increasingly hot summers and heating during harsher winters—the competition for limited water resources intensifies [54]. Thermal power plants and irrigated agriculture both depend heavily on water, making their coexistence increasingly precarious in water-stressed regions. In critical river basins such as the Indus and the Colorado, competing water withdrawals by cities, farms, and energy facilities present complex governance challenges [55,56]. These conflicts underscore the urgent need for integrated resource planning and cross-sector coordination to assess and manage water–energy trade-offs effectively.

Critically, these challenges are not isolated but interlinked through complex feedbacks. An adaptive intervention in one domain—such as expanding irrigation—can have positive or negative effects on energy use, groundwater levels, and ecosystem services, depending on implementation [37,57]. Conversely, renewable energy investments like solar-powered irrigation can enhance cross-sector resilience by reducing both fossil fuel use and water stress [58,59]. The WEF-E nexus perspective emphasizes these cross-cutting dependencies, urging a shift from sectoral adaptation to systemic resilience strategies [22]. Climate shocks can also disrupt food systems indirectly through infrastructure and service pathways. Extreme weather events may damage roads, electricity grids, and storage facilities, interrupting supply chains and market access [60]. For example, heavy storms in coastal regions often destroy both food crops and the electricity infrastructure required for processing and refrigeration. Thus, food system resilience must be understood as a function not only of crop performance but also of stable access to water, energy, and transport—each of which is increasingly affected by climate change [11,12].

Addressing these indirect risks also requires strengthening ecosystem-based adaptation alongside resilient infrastructure. Natural systems such as mangroves, wetlands, and

floodplains act as buffers against floodwaters, protecting both rural and urban communities while supporting biodiversity. At the same time, diversified cropping systems and decentralized energy solutions—such as solar mini-grids or bioenergy platforms—enhance adaptive capacity by reducing dependence on centralized infrastructure [61,62]. Investing in climate-resilient infrastructure, including elevated grain storage, all-weather roads, and modular microgrids, can further reduce cascading failures across the supply chain, especially during extreme weather events [63]. Together, these nature-based and engineered approaches form complementary pillars of systemic resilience.

An illustrative case is the 2020–2022 multi-year drought in East Africa, where failed rains triggered widespread crop and livestock losses. Simultaneously, depleted reservoirs reduced hydropower generation, leading to rolling blackouts. In response, some communities overpumped aquifers and reverted to diesel generators—actions that temporarily met demand but deepened long-term vulnerability by accelerating groundwater depletion and increasing emissions [18,35]. This underscores the pitfalls of reactive and siloed responses. A more proactive, nexus-based strategy would involve coordinated deployment of drought-resilient crop varieties (food), solar-powered irrigation (energy-water), aquifer monitoring and recharge efforts (environment), and regional trade or storage mechanisms (policy) to buffer supply shocks. These integrated measures align with climate-resilient development pathways advocated in global frameworks like the Paris Agreement and the SDGs [21,24]. These examples also underscore the critical importance of equitable access to nexus solutions. Poorer communities and smallholder farmers often face structural barriers—such as limited access to credit, inadequate infrastructure, and weak institutional support—that hinder their ability to adopt clean technologies or diversify resource inputs [64]. As a result, they remain disproportionately vulnerable to climate shocks. Without inclusive governance frameworks, targeted subsidies, and accessible financing mechanisms, the benefits of nexus-based resilience strategies risk being unevenly distributed [65]. Ensuring equity in adaptation efforts is therefore not only a matter of social justice but also essential for building systemic resilience across the WEF-E nexus.

In summary, climate change increases both the vulnerability of and interdependence within the WEF-E nexus. Its compound impacts—heat, drought, floods, infrastructure damage—can undermine resilience across multiple sectors simultaneously. Addressing these risks requires moving beyond fragmented interventions to systemic approaches that enhance the resilience of the entire nexus. This calls for deeper integration of knowledge, planning, and resources across domains, a theme the following section explores through specific adaptation strategies. Additionally, integrating mitigation with adaptation through the WEF-E lens—such as using biogas to manage manure, reduce methane, and generate clean energy—offers dual benefits. Climate-resilient development must therefore recognize and leverage such synergies.

5. Strategies for Climate-Resilient Food Systems via the WEF-E Nexus

Building climate resilience in food systems requires deploying a portfolio of strategies that span water management, energy innovation, agricultural practice, and ecosystem stewardship—and crucially, tying these together. This paper reviews key interdisciplinary strategies that operationalize the WEF-E nexus approach. These strategies illustrate how interventions can generate co-benefits across multiple sectors, thereby reinforcing the overall resilience of the food system.

5.1. Enhancing Water Security and Efficiency in Agriculture

Water management is central to climate adaptation in food systems, as agriculture is the largest consumer of freshwater globally [66]. To safeguard food production against

droughts and erratic rainfall, a shift toward water-efficient and diversified water sources is imperative. One widely adopted practice is precision irrigation—using technologies like drip irrigation and smart sensors to deliver water only when and where needed. These systems can significantly enhance water use efficiency and crop yields while reducing environmental footprints [67–69]. Drip and sprinkler systems integrated with soil moisture and weather-based sensors are increasingly deployed not only in horticulture but also in staple crops, with notable adoption in semi-arid regions of India, Morocco, and southern Spain [70–72]. These systems help farmers reduce water application by 30–50%, while increasing yields by minimizing water stress during critical crop growth stages [73].

When powered by renewable energy, such systems address water and energy efficiency simultaneously. For instance, solar-powered drip irrigation has shown remarkable benefits, with case studies reporting reductions in water usage by nearly half and a 90% decrease in diesel fuel use through the replacement of diesel pump engines with solar photovoltaic technology [74,75]. This not only conserves scarce water supplies but also cuts greenhouse gas emissions and operating costs, improving farmers' resilience to both drought and fuel price shocks. Programs in regions such as the Sahel and the Indo-Gangetic Plain are promoting solar-based irrigation through public–private partnerships and subsidies, helping smallholder farmers access clean energy while stabilizing water use [76,77]. However, governance is critical—without proper regulation, solar-powered groundwater pumping may lead to aquifer over-extraction [78], highlighting the need for groundwater monitoring and user guidelines to accompany solar pump scale-up.

Similarly, rainwater harvesting and on-farm water storage (small ponds, tanks) enable farmers to capture and utilize rainfall in wet periods to bridge dry spells, reducing dependence on irregular rains [79]. In many arid regions, treated wastewater reuse for agriculture is emerging as a strategic adaptation because it provides a reliable water source for irrigation while recycling nutrients [80,81]. A notable example is Israel, which has implemented policies to treat all reclaimed wastewater to a degree suitable for unrestricted agricultural irrigation, recycling over 85% of its domestic wastewater [82]. By closing the water loop, such approaches alleviate pressure on freshwater ecosystems during droughts and maintain food production even as climate variability increases [83]. Other countries—including Spain, Tunisia, as well as subnational areas such as California in the United States—are increasingly adopting municipal-to-agricultural water reuse systems, particularly to support peri-urban vegetable production [84–86]. These schemes help stabilize irrigation supplies amid growing freshwater scarcity and reduce the discharge of nutrients and contaminants into rivers and coastal ecosystems. By recycling treated wastewater for productive use, they contribute to both climate adaptation and resource circularity, aligning with broader circular economy and integrated water management goals. In some cases, these systems are also paired with nutrient recovery technologies, offering additional benefits for soil fertility and reducing reliance on synthetic fertilizers.

Another critical strategy is integrated water resources management that considers basin-wide water allocations across sectors and ecosystems [87]. Under climate stress, coordinated management of surface water, groundwater, and ecological flows becomes essential. Policies that promote conjunctive use of groundwater and surface water, for example, can buffer irrigation needs in dry years (using groundwater storage) and recharge aquifers in wet years, enhancing overall system resilience [88,89]. Protecting and restoring natural water infrastructures—such as wetlands, floodplains, and watershed forests—is equally important. These ecosystems act as sponges and buffers (storing water and regulating flow), thereby reducing flood risks and sustaining streamflows during dry periods [90,91]. Nature-based approaches—such as restoring riparian vegetation, de-siltation of village ponds, and rewetting peatlands—are gaining attention not just for hydrological regulation

but also for biodiversity and carbon sequestration benefits [92–94]. In Rwanda and Nepal, community-led watershed restoration programs have improved both water availability and soil productivity while generating employment [95,96]. Integrating such nature-based solutions (e.g., wetland conservation or reforestation in upstream catchments) into water management plans provides cost-effective climate adaptation while yielding co-benefits like biodiversity habitat and water quality improvement [97,98]. Recent evidence suggests that blending nature-based and grey infrastructure—such as combining upstream forest buffers with downstream reservoirs or integrating green roofs into irrigation system design—can optimize water capture and delivery while minimizing ecological harm [99].

The nexus approach highlights that ensuring water security for food production must go hand in hand with sustainable energy use and environmental conservation. For example, where large-scale irrigation is expanded as an adaptation measure, the energy source for pumping should be low-carbon (to avoid amplifying climate change) and water withdrawals must be balanced with ecosystem needs to prevent long-term degradation [24]. These trade-offs are especially visible in regions with seasonal electricity shortages—such as parts of Sub-Saharan Africa or Central Asia—where irrigation demands during dry seasons coincide with peak power usage. In these contexts, demand-responsive solar irrigation or time-of-use incentives can balance water-energy loads [100,101]. Cross-sector initiatives like solar irrigation programs with groundwater governance guidelines are being piloted in parts of South Asia and Sub-Saharan Africa to achieve this balance [102]. These initiatives underscore the importance of coupling technology adoption with institutional reforms—such as water user associations, aquifer recharge planning, and digital monitoring tools—to ensure long-term sustainability. Ultimately, the success of agricultural water adaptation lies in integrating diverse technologies, ecosystems, and governance innovations under a cohesive nexus framework.

5.2. Sustainable Energy Integration for Food Systems

Reliable and sustainable energy access is increasingly recognized as a pillar of climate-resilient agriculture. Farms and agri-food enterprises need energy for irrigation, mechanization, processing, and cold storage—needs that can spike during climate extremes (e.g., more pumping in droughts, more drying or cooling of produce in heat). Integrating renewable energy technologies into food systems boosts resilience by reducing dependence on fossil fuels and centralized grids, which may be vulnerable during crises [103,104]. For example, during heatwaves or storms, grid outages can halt irrigation and spoil perishable produce in storage. Decentralized energy options like solar mini-grids, battery storage, and hybrid renewable-diesel systems provide critical backup, particularly in remote rural areas [105].

One innovative synergy at the WEF nexus is agrivoltaics—the co-location of solar photovoltaic panels with crops on the same land. Studies have found that this dual-use approach can create mutual benefits, as the solar panels provide partial shade that reduces heat and drought stress on crops, while the cooler microclimate under the panels improves their power generation efficiency. In dryland trials, agrivoltaic systems yielded more electricity and higher crop output compared to separate installations, as the shading cut crop water demand and enhanced plant growth [106]. Recent trials in India, Japan, and the U.S. have shown yield improvements of 10–20% in shade-tolerant crops like lettuce, spinach, and chilies under agrivoltaic arrays, while also reducing soil evaporation [107–109]. Additionally, rotating panel designs are being developed to optimize both solar tracking and light transmission to crops. Such systems exemplify a win-win nexus solution, producing clean energy and food concurrently and increasing overall land and water productivity. They also diversify farmers' income (energy sales plus crops), which is a resilience boon

if one source is hit by climate events. In some cases, farmers lease part of their land for solar development while continuing to cultivate lower-growing crops or graze livestock underneath—creating a multi-use revenue model that enhances financial resilience [110].

Beyond agrivoltaics, small-scale biogas and bioenergy systems offer another nexus strategy. By converting agricultural residues, manure, and other organic wastes into biogas (through anaerobic digesters), farms can generate renewable energy for cooking, heating, or electricity, while also producing a nutrient-rich slurry that can be returned to fields as fertilizer. This closes resource loops—waste becomes input—and reduces reliance on external energy and chemical fertilizers [111,112]. Many smallholder communities in regions like East Africa and South Asia have adopted biodigesters as a climate-smart practice, as the biogas provides a stable energy supply that is not impacted by fuel shortages or price volatility, and the biofertilizer improves soil health, thereby boosting crop resilience to drought and reducing fertilizer costs [113,114]. Moreover, biodigesters help reduce indoor air pollution and deforestation by replacing firewood for cooking, contributing to health and environmental co-benefits, especially for women and children in rural households. On larger scales, energy recovery from food industry waste and municipal organic waste can similarly contribute to a more resilient and circular food system, while cutting methane emissions (a potent greenhouse gas) from waste decomposition [115]. Examples include breweries, sugar mills, and dairy plants that use waste-to-energy systems to power processing operations, lowering operational costs while decarbonizing industrial food production.

Crucially, sustainable energy integration also means decarbonizing food supply chains, which has mitigation benefits that help limit future climate change. For example, solar-powered cold storage units allow farmers to preserve produce post-harvest without diesel generators, maintaining food supply and quality during heat waves or transport disruptions [116]. Likewise, replacing diesel water pumps with solar or wind-powered pumps, as noted earlier, eliminates fuel dependency and pollution [74]. Renewable energy mini-grids can keep rural agro-processing facilities running when main grids fail during storms [117]. In Bangladesh and Nigeria, solar cold rooms and mobile solar chillers have helped reduce post-harvest losses by 25–40%, significantly extending the shelf life of perishables such as fruits, vegetables, and dairy in off-grid or energy-insecure regions [118,119]. These technologies not only preserve food quality during transport delays or heatwaves but also enhance farmers' market access and bargaining power by allowing them to store produce longer and sell at more favorable prices. In many cases, farmer cooperatives and women's groups have operated these systems collectively, further strengthening local value chains and income resilience [120,121].

These improvements not only directly aid farmers during climate stresses but also reduce the long-term climate footprint of agriculture, aligning resilience with sustainability. However, scaling such solutions requires supportive policies, financing mechanisms, and capacity building—areas this review discusses later as part of the enabling environment for nexus strategies. For instance, pay-as-you-go (PAYG) solar technologies, carbon finance mechanisms, and public–private partnerships are increasingly lowering the entry barrier for smallholders to adopt clean energy solutions. PAYG models allow farmers to access solar pumps or lighting systems with minimal upfront costs, paying gradually from their agricultural earnings [122]. Carbon credit schemes offer additional revenue streams for projects that reduce emissions, such as biodigesters or solar cold storage, enhancing financial viability [123]. Meanwhile, training programs and digital platforms—such as mobile apps for troubleshooting or performance tracking—are supporting long-term system maintenance, user engagement, and data-driven decision-making [124]. These

enablers collectively strengthen both adoption and sustained use, particularly in remote or underserved regions.

5.3. Climate-Smart Agricultural Practices and Diversification

Transforming agricultural practices is at the heart of climate-resilient food systems. A suite of climate-smart agriculture practices has been developed to increase productivity, enhance adaptation, and reduce emissions. Many of these practices inherently operate at the nexus of water–food–environment, and sometimes energy [125,126]. One key principle is agrobiodiversity and diversification: diversified farming systems (e.g., growing a variety of crops and integrating crop–livestock or crop–fish systems) tend to be more resilient to climate shocks than monocultures [127,128]. Diverse cropping can spread risk (if one crop fails, others may succeed) and make better use of resources year-round, while mixed crop–livestock systems allow resource recycling (e.g., crop residues feed animals, manure fertilizes fields, reducing external inputs needed). Additionally, planting hardy or stress-tolerant crop varieties—such as drought-tolerant cereals, submergence-tolerant rice, or heat-resistant horticultural crops—directly improves the capacity to withstand climate extremes. Breeding and disseminating such varieties (often through international research networks and local seed systems) is a major focus of adaptation efforts in food security [129,130].

A particularly powerful nexus strategy in agriculture is the adoption of agroforestry and other ecosystem-based farming approaches. Agroforestry—the intentional integration of trees or shrubs with crops and/or livestock—has been identified as a “no-regrets” climate adaptation, offering multiple benefits [131]. Trees in farmlands can shade crops and reduce heat stress, break harsh winds, and improve soil moisture by reducing evaporation and improving infiltration, thereby buffering both drought and heavy rainfall impacts. Research syntheses indicate that well-designed agroforestry systems moderate microclimate extremes (lowering under-story crop temperatures by 2–4 °C in hot conditions) and can reduce runoff and erosion during intense rains by 20–50%, thus protecting yields [132,133]. During droughts, deeper-rooted trees can access soil moisture and maintain some level of productivity or provide fodder/fruit when annual crops fail. By maintaining year-round ground cover and root systems, agroforestry also improves soil structure and fertility (through leaf litter and nitrogen-fixing species), enhancing longer-term agricultural sustainability. Notably, a recent global assessment found that agroforestry practices increased crop yields by 5–15% on average under extreme weather conditions, compared to conventional monocultures [134]. Beyond these direct resilience gains for food production, agroforestry sequesters carbon in biomass and soil, contributing to climate change mitigation, and supports biodiversity by creating habitat corridors—demonstrating the intertwined benefits for the environment. Many traditional farming communities have practiced forms of agroforestry for centuries (such as home gardens, shade-grown coffee/cacao, or silvopasture with trees in grazing lands), and revitalizing these practices with modern knowledge is a key adaptation strategy in regions from Sub-Saharan Africa to Southeast Asia and Latin America [135,136].

Other sustainable land and water management practices also bolster resilience. Conservation agriculture techniques—minimal soil tillage, maintaining soil cover with mulch or cover crops, and crop rotations—help build soil organic matter, which improves water retention and reduces erosion, thereby stabilizing yields under weather extremes [137–139]. Similarly, integrated soil fertility management (combining organic and inorganic fertilizers) and efficient nutrient management can keep crops healthier and more tolerant to stress while preventing environmental pollution [140–142]. In pastoral and rangeland systems, sustainable grazing management and reseeded of degraded lands can restore vegetation cover, improving the resilience of livestock food supply during droughts [143]. Urban and

peri-urban agriculture (e.g., controlled environment horticulture, vertical farms, hydroponics) present another resilient strategy, as they can be less dependent on natural rainfall and use resources in a highly controlled, efficient manner—though their energy footprint must be managed via renewables to be sustainable [144–146].

Importantly, blending traditional knowledge with innovation often yields the best results. Indigenous agricultural systems have long optimized for variability (through polycultures, terraced irrigation, etc.), and these approaches are being revisited and validated by science [147,148]. For instance, in small island states, communities are reviving traditional crop varieties and wild food gathering as buffers against climate-induced crop failure [149]. Coupling these time-tested strategies with modern tools—such as weather forecasting services, crop insurance, and mobile-based advisories—can greatly enhance adaptive capacity. Ultimately, climate-smart agriculture is not one single practice but a context-specific combination of practices that together strengthen the food production system’s robustness to climate stress, while also tending to use water, soil, and other inputs more sustainably (aligning with the nexus approach of efficiency and environmental stewardship).

5.4. Ecosystem Conservation and Landscape Approaches

Protecting and leveraging natural ecosystems is a cost-effective way to build resilience into the water–energy–food nexus. Healthy ecosystems provide services that buffer climate impacts, such as forests regulating hydrological cycles and climate, wetlands absorbing floodwaters, mangroves and reefs shielding coasts from storms, and biodiversity supporting pollination and pest control crucial for agriculture [90,150]. Thus, conservation and restoration efforts yield resilience dividends for food systems. For example, conserving upstream forests in a watershed can stabilize dry-season water flows for downstream irrigation and hydropower, and reduce sedimentation in reservoirs, thereby sustaining energy and agricultural productivity in a changing climate [98,151]. Likewise, restoring coastal mangroves can protect brackish fisheries and coastal farmlands from storm surge and salinization [152,153]. These approaches exemplify the food–environment nexus in action by investing in nature to safeguard food and water security. In many regions, the cost of ecosystem restoration is lower than the economic damages avoided from disasters such as floods or coastal erosion, making nature-based solutions not only ecologically sound but fiscally prudent [154,155]. Initiatives like the Bonn Challenge and the United Nations Decade on Ecosystem Restoration have brought global attention to these benefits, with large-scale efforts now underway to restore forests, wetlands, and degraded lands in over 70 countries [156,157].

One area of growing interest is the integration of biodiversity conservation goals with the WEF nexus. Modern agriculture has been a major driver of biodiversity loss, yet long-term food security may depend on halting and reversing this trend [10,158]. A recent systematic review highlighted the need for a “Water–Energy–Food–Biodiversity” nexus approach to foster sustainable transitions in agricultural landscapes [159]. By explicitly including biodiversity (or environment) in nexus assessments, policymakers can design interventions that support both productivity and conservation. For instance, a nexus analysis might reveal opportunities to set aside or restore portions of agricultural land that are marginal for production but critical for habitat connectivity or water quality, compensating farmers via payment for ecosystem services [160]. Such integrated approaches are gaining traction in programs like the European Union’s Biodiversity Strategy and Costa Rica’s national Payments for Ecosystem Services schemes, where farmers are rewarded not only for carbon sequestration but also for maintaining forest corridors and riparian zones that benefit downstream users [161,162].

The whole landscape can be made more resilient with these actions, as biodiversity-rich systems often recover faster from disturbances, and maintaining wild crop relatives or diverse gene pools can provide traits for breeding climate-hardy crops in the future [163,164]. In sum, treating ecosystem health as an integral component of food system resilience leads to strategies that are multifaceted—ranging from sustainable fisheries management (balancing energy use of fleets with fish stock regeneration) to agroecological practices that mimic natural ecosystems [135,165]. For instance, intercropping, agroforestry, and integrated pest management enhance on-farm biodiversity while reducing reliance on synthetic inputs such as chemical fertilizers and pesticides. These nature-based practices not only lower input costs and environmental pollution but also improve soil health, water retention, and pest regulation—key components of climate resilience. Over time, such diversified systems are better able to buffer climate shocks, sustain yields under variable conditions, and support broader landscape-level ecological functions [166–168].

On a policy level, adopting a landscape or watershed approach to planning allows for these synergies to be realized. Rather than managing forest conservation, agriculture, water use, and energy generation separately, a landscape approach looks at the mosaic of land uses and optimizes them collectively under climate considerations [169]. For example, in a drought-prone region, this could mean jointly planning reforestation in upper catchments, terracing and rainwater harvesting in mid-hills for farming communities, and solar pump irrigation schemes in downstream plains, ensuring each intervention complements the others. Community-based natural resource management is often a key element, as local stakeholders have intimate knowledge of environmental changes and can implement adaptive practices when empowered with secure resource rights and knowledge [170]. Participatory land-use planning and multi-stakeholder governance platforms—such as watershed committees or district-level resilience task forces—can facilitate coordination and resolve competing claims across sectors. These governance innovations are especially important where land tenure is insecure or fragmented.

There are numerous case studies—from community forest management in Nepal's hills reducing landslide risk, to farmer-managed natural regeneration in Niger's farmlands restoring tree cover and raising crop yields—that demonstrate the resilience gains from local stewardship of resources under a supportive institutional framework [171,172]. Evidence also includes Brazil's Atlantic Forest Restoration Pact and Kenya's Water Towers program, which combine local community efforts with national-level targets to conserve critical ecosystems that underpin both agricultural productivity and hydropower reliability [173,174].

By aligning agricultural development with environmental conservation, the WEF-E nexus approach seeks coherence between human and natural systems in the face of climate change. This not only reduces competition over resources (for instance, avoiding scenarios where agriculture and ecosystems compete destructively for water in a drought) but also fosters innovative solutions (such as using agroforestry as mentioned, or integrated fish–rice farming that enhances water use efficiency and biodiversity) [175]. Such approaches can make food systems more flexible and adaptive, capable of re-organizing after disturbances in ways that preserve functionality. As climate change accelerates, the ability of food systems to reorganize and recover (a key aspect of resilience) will hinge on maintaining the underlying environmental support systems and diversity that confer adaptability. In this sense, ecosystem conservation is not peripheral but central to food system resilience—functioning as natural insurance that maintains essential services such as water filtration, microclimate regulation, nutrient cycling, and pollination. Therefore, investing in nature is increasingly seen not as a luxury but as foundational to resilient agriculture and water management.

5.5. Integrated Governance and Policy for Nexus Resilience

While the above technological and land-management strategies are crucial, enabling them at scale requires supportive governance, institutions, and policies that embody nexus thinking. One of the persistent barriers to implementing WEF-E nexus solutions is the fragmented nature of governance, where water, energy, agriculture, and environment are often managed by separate ministries or departments with distinct, and sometimes conflicting, policies. Overcoming these silos is a priority for climate-resilient planning [176,177]. Governments and regional bodies are experimenting with integrated policy frameworks that encourage cross-sector collaboration. For instance, the European Union's Green Deal and related policies are increasingly referencing the WEF nexus to harmonize water, energy, and agricultural goals in the move towards a circular, low-carbon economy [178]. Similarly, Thailand's National Committee on Climate Change includes cross-sectoral participation and ensures coordinated adaptation strategies across water, energy, and agricultural ministries during seasonal drought planning. Kenya's National Climate Change Action Plan explicitly adopts a nexus lens in aligning mitigation and adaptation priorities across food, water, and energy sectors [179,180]. Some countries have set up inter-ministerial nexus task forces or commissions to ensure climate adaptation plans are coordinated across sectors. These institutional innovations aim to prevent situations where, say, an agriculture subsidy undermines water conservation targets or an energy policy ignores food security impacts [31]. Joint planning tools such as shared climate risk maps, basin-scale scenario models, and integrated investment platforms are increasingly used to support this alignment. In Rwanda and Peru, cross-sectoral data platforms have improved the consistency and transparency of decisions involving competing water users [181,182].

Land use planning and water allocation laws offer concrete entry points for nexus governance. By incorporating climate change projections and multi-sector needs into spatial planning, authorities can designate zones for different uses (conservation, agriculture, energy infrastructure) in a way that anticipates future resource constraints [22]. Similarly, water laws can be reformed to prioritize critical needs during drought (e.g., drinking water and key ecological flows) while incentivizing less water-intensive crop choices or technologies via pricing and tradable permits. In many regions, updating outdated irrigation and power supply policies—which often encourage wasteful use—is essential to promote efficiency measures that increase resilience. For example, electricity subsidies for farmers in India have historically led to groundwater overuse, but pilot reforms in states like Gujarat and Punjab now link subsidies to efficient irrigation practices, including solar pump adoption and smart metering [183]. Transitioning from flat electricity tariffs for farmers to metered tariffs or solar pump incentive programs can reduce groundwater over-extraction and encourage efficient irrigation practices, thus safeguarding aquifers against climate-induced declines [58,184].

Another vital aspect is engaging stakeholders at all levels in participatory governance. Resilience is context-specific, so local knowledge and preferences must shape solutions. In some cases, what experts view as an optimal nexus solution may not align with local priorities. The Morocco drylands case is illustrative, as farmers there prioritized income-generating innovations like crop diversification (integrating olive trees with cereals), whereas external stakeholders emphasized water-saving technologies like rain-water harvesting [16]. Both perspectives are valid for resilience, and reconciling them requires dialogue and co-design of interventions. Multi-stakeholder platforms—bringing together farmers, water users, energy providers, conservationists, and policymakers—are increasingly used to negotiate trade-offs and co-create adaptation plans [17,185]. Such platforms, whether formal (e.g., river basin councils) or informal, build trust and help in aligning incentives. In Bolivia, participatory watershed councils have been instrumental

in designing upstream–downstream compensation schemes that account for both agricultural water needs and environmental flow preservation [186]. For instance, if farmers are expected to adopt water-saving practices that benefit downstream users and ecosystems, there may need to be compensation or support (such as technical aid or secure land rights) to make it worthwhile for them. Approaches like Payment for Ecosystem Services or community benefit-sharing from hydropower projects can encourage cooperative behavior across sectors [187].

Furthermore, aligning financial mechanisms with nexus objectives is part of the governance challenge. Climate finance and development aid are gradually shifting to favor integrated projects—for example, funding a program that simultaneously improves irrigation efficiency, installs renewable energy, and restores watersheds, rather than siloed investments [14]. The Global Environment Facility and Green Climate Fund has recently supported integrated WEF projects in Africa and Southeast Asia, combining solar infrastructure with land restoration and efficient water use technologies [188]. National budgets and economic plans also need to reflect the cross-sector nature of resilience-building; this could mean joint funding of projects by agriculture and water ministries, or creating budget lines for nexus initiatives. Innovative insurance products and contingency funds that address multiple hazards (such as an index insurance that pays out for drought to cover both crop losses and hydropower revenue shortfalls) are another tool to manage systemic risk [189]. Some financial instruments now use composite indices (e.g., rainfall plus reservoir levels) to trigger payouts across multiple sectors, reflecting the interdependencies in climate risk exposure [190].

In summary, effective governance for a climate-resilient WEF-E nexus entails breaking down silos, fostering collaboration, and creating policies that incentivize integrated resource management. It also means embracing adaptive management—policies need to be flexible and responsive to new information, given the uncertainty in climate projections. Successful examples often involve polycentric governance, which entails cooperation between national, regional, and local institutions, as well as among public, private, and civil society actors, to manage the complex nexus [191]. In Ethiopia’s Tana Basin, nested institutions—from village-level water committees to regional river basin agencies—coordinate land, water, and energy planning, exemplifying polycentric governance in practice [192]. Developing human and institutional capacity to understand nexus interdependencies is a precursor to all these efforts. Thus, training programs, joint research, and pilot projects play a role in demonstrating the value of nexus approaches to decision-makers. Initiatives like the Nexus Regional Dialogues and the FAO’s Water-Energy-Food Nexus Capacity Building Modules are being deployed in multiple countries to support institutional learning [28,193]. Ultimately, governance that is inclusive and integrative will be better positioned to handle the multi-dimensional challenges climate change poses to food systems and resource security.

6. Future Directions and Actionable Research Agenda

While progress has been made in conceptualizing and implementing WEF-E nexus strategies, significant knowledge and implementation gaps remain. Advancing climate-resilient food systems through the nexus approach will require targeted research and innovation efforts in the coming years. The key actionable research directions and emerging areas of focus are as follows:

6.1. Developing Metrics and Tools to Measure Nexus Resilience

There is a need for robust indicators and models that can quantify the resilience of WEF systems and capture cross-sector dynamics [1,17]. Currently, resilience is often assessed qualitatively or within individual sectors. Research should aim to create composite indices

(e.g., a WEF security index) [194] and simulation tools that decision-makers can use to evaluate how a given policy or technology will affect water, energy, and food outcomes under climate scenarios. Advances in data analytics, remote sensing, and system modeling (such as integrated assessment models or agent-based models) can be harnessed to analyze complex interactions and optimize interventions across the nexus [23,195].

For example, dynamic system models could simulate how a drought affects not just irrigation supply but also electricity generation (through hydropower), crop yields, and downstream food prices—enabling more comprehensive policy evaluation [196,197]. Developing such tools requires cross-disciplinary datasets and algorithms that reflect feedback loops, thresholds, and time-lagged responses. Researchers are also working on creating modular toolkits that allow local governments or non-governmental organizations (NGOs) to assess nexus risks and resilience in real time using satellite data, mobile inputs, and locally calibrated indicators [198]. These can inform land-use zoning, emergency response, or adaptation investment decisions. In parallel, participatory modeling approaches that involve stakeholders in co-developing resilience metrics can increase the legitimacy and usability of tools. For instance, farmers may value flexibility or diversity more than technical efficiency—so metrics should reflect local priorities alongside scientific rigor [199]. Ultimately, operationalizing nexus resilience will require tools that are context-sensitive, accessible, and designed to support both long-term planning and short-term decision-making under uncertainty.

6.2. Improving Understanding of Systemic Nexus Dynamics and Thresholds

Fundamental research is needed on the behavior of coupled WEF-E systems under stress. For instance, what are the critical thresholds (tipping points) beyond which a water shortage cascades into food and energy crises? How do feedback loops operate? For example, how does agricultural collapse lead to energy shortfalls that further constrain agriculture? Studies examining past multi-sector climate disasters could yield insights into vulnerability points [26,88]. For example, during the 2015–2016 El Niño event in Southern Africa, reduced rainfall caused a sharp decline in hydropower output, which in turn limited irrigation and food processing capacities—highlighting the compound effects of single-sector shocks [200]. Research in Central Asia found that seemingly unrelated interventions (like upstream land-use change causing ecosystem loss) can significantly impact water availability for food and energy downstream [1]. Similar findings have emerged from the Amazon and Mekong basins, where deforestation in headwater regions has altered evapotranspiration and rainfall patterns with cross-border implications for agriculture and energy generation [201,202].

Mapping out such interdependencies in various regions (perhaps via network analysis or stress testing models) will help anticipate problems and design buffers. Emerging approaches like dynamic Bayesian networks, agent-based modeling, and multi-layer network theory offer promising tools to identify vulnerability nodes, critical dependencies, and cascading risks in WEF-E systems [203–205]. This also includes incorporating cross-scale interactions—understanding how local actions aggregate to global impacts and vice versa (for instance, global trade as a buffer or transmitter of shocks in the nexus) [206]. For instance, disruptions in fertilizer supply chains due to regional droughts or geopolitical conflict can reverberate globally, affecting energy-intensive food production and prices [207]. Research linking trade flows with biophysical risk data can enhance preparedness and inform diversification strategies.

6.3. Bridging the Implementation Gap Between Nexus Plans and Practice

Many nexus ideas remain on paper due to governance and complexity challenges [1,177]. Research in social sciences and policy is required to translate nexus assessments into actual policy shifts and investments. Case studies of successful nexus interventions (and failures) can illuminate enabling conditions [28]. For example, in Jordan, integrated water–energy–food projects supported by the Ministry of Planning and International Cooperation have shown that strong inter-ministerial collaboration, donor alignment, and early community engagement are critical for success [208]. Conversely, failed implementations in parts of Sub-Saharan Africa have highlighted the risks of inadequate coordination between agriculture and energy ministries [209]. Participatory action research, where scientists work with communities and officials to pilot nexus-based projects, can demonstrate feasibility and refine methods [210]. In Kenya, collaborative pilot programs have helped design agro-solar irrigation systems that reflect both local water needs and financial constraints, leading to higher uptake than top-down infrastructure schemes [211].

There is also a call for transdisciplinary approaches, involving stakeholders in co-producing knowledge so that research outputs are directly usable [212]. Such approaches build trust and ensure that interventions account for cultural norms, gender roles, and existing local strategies for resilience. Tools like stakeholder mapping, participatory scenario planning, and visioning exercises have been used effectively to co-design nexus solutions in Southeast Asia and Latin America [213,214]. Addressing socioeconomic barriers—such as property rights, financing, and equity concerns—is part of this agenda. For instance, how can we ensure that smallholder farmers benefit from integrated solutions and are not left behind in large infrastructure-focused nexus projects? This includes ensuring that access to solar irrigation or wastewater reuse is not limited to wealthier farmers with formal land titles, and that mechanisms such as land tenure security, microfinance, or targeted subsidies are embedded in implementation plans. Answering such questions will make implementation more inclusive and effective [26]. Ultimately, bridging this gap requires governance innovations, local capacity building, and alignment of funding flows with nexus priorities, so that integrated solutions become the norm rather than the exception.

6.4. Integrating Resilience Thinking with Other Development Frameworks

While resilience is a key goal, it should be pursued alongside sustainability, efficiency, and equity [177]. Research should explore how the nexus approach can incorporate principles of justice and equity, ensuring that resilience-building does not marginalize any group [215]. For example, without inclusive design, irrigation or energy projects may disproportionately benefit large landowners, exacerbating inequality. This includes gender dimensions (women often manage water and food at the household level and need to be empowered in decision-making) and the needs of indigenous and marginalized communities. Gender-sensitive planning is essential, as women often bear the responsibility for household water and food management but are underrepresented in governance and resource allocation processes [216]. Incorporating the traditional ecological knowledge of indigenous communities can enhance resilience by aligning interventions with local ecosystems and long-standing resource stewardship practices [217].

Additionally, linking the nexus to emerging frameworks like the circular economy (which emphasizes resource reuse and waste minimization) could yield innovative solutions [218]. For instance, integrating food–energy–waste loops—such as converting food processing residues into biogas and compost—can support low-emission, resource-efficient food systems. This is increasingly being implemented in peri-urban settings where waste generation and food demand intersect [219]. The nexus approach can also benefit from economic analysis—evaluating the costs, benefits, and trade-offs of interventions to guide

investments. Full-cost accounting and life cycle assessment methods can help quantify externalities, co-benefits, and distributional impacts of proposed interventions, improving transparency and investment targeting. Multi-criteria decision analysis and nexus scenario planning under different climate futures are tools that researchers can refine and offer to policymakers [14,195,220]. By combining social, environmental, and economic criteria in decision-making, these tools can support more balanced choices—especially when navigating trade-offs between short-term gains and long-term system resilience.

6.5. Exploring Novel Technologies and Nature-Based Solutions

Continued innovation is crucial. On the technology front, areas like desalination powered by renewables, advanced water recycling, gene editing for stress-resilient crops, carbon capture in agriculture (soil carbon sequestration and biochar), and internet of things for resource monitoring all have nexus implications that warrant study [36,221]. For instance, integrating smart sensor systems for soil moisture and automated irrigation controls has shown significant water and energy savings in pilot farms across India and Israel, but scaling these technologies to smallholder settings requires affordability, training, and robust data governance frameworks [222]. Large-scale solar desalination could open new water sources for farming but raises questions about brine disposal (environment) and energy use. Life cycle assessments and policy safeguards are needed to ensure that the environmental costs of new technologies do not offset their intended resilience or sustainability gains [223].

On the nature-based side, concepts such as regenerative agriculture, rewilding, and climate-smart landscape restoration deserve research into their multi-sector benefits [224]. Evidence from Latin America and Sub-Saharan Africa shows that regenerative practices—like no-till farming, agroecology, and integrated livestock–forestry systems—can improve soil carbon, water retention, and yield stability under climate stress [225,226]. However, adoption depends on localized technical support, access to markets, and enabling institutions. One emerging idea is the use of “green infrastructure” in tandem with “gray infrastructure”—for instance, combining levees with restored mangroves for coastal protection, or agroforestry with irrigation schemes—and developing guidelines for such hybrid approaches [97]. Designing performance metrics and cost–benefit models for these hybrid systems will help integrate them into infrastructure investment plans, especially in coastal and flood-prone regions. Researchers can also investigate carbon finance or ecosystem service payments as mechanisms to fund resilience-enhancing conservation on farmland [160].

6.6. Geographic and Context-Specific Research

Much of the nexus literature has global or national scope; more granular studies are needed in diverse contexts (e.g., small island developing states, conflict-affected regions, megacities, etc.) [31]. Each context may have unique nexus challenges—consider small islands where freshwater is limited, energy is imported, and space for food production is constrained, all under severe climate threat; they require tailored solutions like rainwater harvesting, ocean energy, and protected hydroponics. Similarly, high-altitude farming regions (e.g., the Andes, Himalayas) face fragile ecosystems, limited market access, and seasonally variable water flows [227,228]—factors that require bespoke water–energy–food solutions like gravity-fed irrigation, micro-hydropower, and resilient cropping systems.

Sharing knowledge across contexts (south–south learning, for instance) can accelerate adaptation. Platforms for peer learning among municipal planners, water utilities, or farmer cooperatives across regions could help scale best practices and avoid repeating mistakes. In particular, the Global South, where climate impacts are most acute and resources are

limited, should be a focus of applied nexus research, to support development pathways that are resilient and sustainable [229]. Donor agencies and international organizations can play a role by incentivizing regionally grounded research and supporting interdisciplinary teams that include local scholars and practitioners.

Lastly, improving the monitoring and evaluation of implemented nexus projects will feed back into research and learning. By rigorously tracking outcomes of nexus-based initiatives (using indicators for water, energy, food security, ecosystem health, and socioeconomic well-being), an evidence base of what works and what does not under real-world conditions can be built. Such evaluations should go beyond technical performance to assess social equity, long-term cost-effectiveness, and institutional resilience—providing a holistic understanding of success. This evidence can refine theories and models, creating a virtuous cycle between practice and research [23]. Building open-access databases of documented nexus interventions and their measured outcomes could accelerate learning and inform replication in similar contexts.

6.7. Integrating the WEF-E Nexus into Education and Capacity Building

Embedding WEF-E nexus thinking into education and training is essential for fostering a systems-oriented mindset across generations [230]. At primary and secondary levels, age-appropriate modules and activities—such as tracing a meal’s journey, exploring links between home energy use and water conservation, or managing school gardens with solar irrigation—can make resource interconnections tangible. These approaches align with STEM education goals and help students appreciate the social dimensions of the nexus, including equity in access to water, food, and energy [231]. At the tertiary level, universities are increasingly offering nexus-focused courses within engineering, environmental science, public policy, and business programs [232]. Projects on integrated food–energy systems or climate adaptation can train future leaders to plan holistically. Open online courses and certifications—offered by organizations like FAO and ADB—are expanding access globally [233–236]. Initiatives such as summer schools, hackathons, and interdisciplinary exchanges help cultivate “nexus champions” by connecting young professionals from diverse sectors.

For current decision-makers and communities, targeted capacity-building efforts are critical. Policymakers, NGO workers, local officials, and farmers alike benefit from training programs that use real-world planning scenarios to teach integrated thinking [237,238]. Programs like the Nexus Regional Dialogues have developed manuals and workshops that introduce accessible analytical tools and simulate decision-making for cross-sector planning [239]. However, feedback shows that nexus thinking can initially be challenging, requiring ongoing coaching and institutional support. Including nexus principles in job descriptions and performance metrics can reinforce adoption. Crucially, capacity building must be inclusive—extension services should support farmers in evaluating how new practices affect ecosystems or market resilience [240]. Outreach at the local government level, where resource departments are often co-located, can foster habits of integrated planning from the ground up [241]. In sum, education and capacity building are long-term investments that yield high returns by creating an informed, systems-literate society equipped to design and support climate-resilient solutions across the WEF-E nexus.

7. Conclusions

Climate change compels a rethinking of how resources are managed for food production and livelihoods. This review has argued that adopting a WEF-E nexus approach is essential for building food systems resilient to climate stress. The nexus framework highlights resources’ interdependence and encourages holistic strategies that strengthen

the entire system's capacity to cope with shocks. Interventions ranging from technological innovations like solar-powered irrigation and agrivoltaics, to agroecological practices like agroforestry, to institutional reforms for integrated governance can yield synergistic benefits across water, energy, food, and environmental objectives. Such integrated solutions outperform siloed measures by avoiding trade-offs that undermine long-term sustainability. They also align resilience with sustainability and equity, ensuring that efforts to adapt to climate change also support climate mitigation and social well-being. The WEF-E nexus also promotes proactive planning, encouraging interventions that deliver benefits across sectors. Policies can be crafted to support both farmer incomes and resource conservation, infrastructure designed for multipurpose use, and adaptation projects evaluated for cross-sector impacts.

To realize the potential of the WEF-E nexus for climate-resilient development, stakeholders at all levels must embrace an interdisciplinary and collaborative mindset. Governments need to break down sectoral barriers in planning and create enabling policies that reward resource-use efficiency and cross-sector collaboration. Research and education should equip practitioners with systems-thinking tools and a deep understanding of nexus dynamics. Critically, communities and local actors should be engaged as co-designers of solutions, leveraging local knowledge and ensuring that resilience initiatives address ground realities and justice considerations. When farmers, energy producers, water managers, and conservationists find common cause, the resulting partnerships can drive innovative actions—for example, community solar irrigation schemes that sustain both farming and ecosystems, or watershed committees that allocate water in equitable, climate-smart ways. Embedding nexus thinking in national strategies and planning processes can help align mitigation and adaptation. Supported governance platforms enable coordination across sectors, ministries, and levels of decision-making.

The road ahead is not without challenges. Climate change will continue to test the resilience of food systems with unprecedented extremes and uncertainties. However, the examples and evidence highlighted here demonstrate that proactive, integrated approaches can markedly improve outcomes. Countries and regions that have started to implement nexus-based adaptations (from SADC's cross-sector climate plans, to Europe's policy integration, to local projects across Asia, Africa, and the Americas) provide valuable lessons. Scaling up these successes, and learning from setbacks, will be vital. This will likely involve mobilizing significant investments—but ones that yield multiple dividends, including improved food security, safer water and energy access, protected ecosystems, and communities better buffered against climate shocks.

In moving forward, a summary of key climate impacts, nexus strategies, and future priorities (Table 1) can serve as a reference. This summary underscores that each major climate risk to food systems has corresponding nexus-based responses and areas for further work. By systematically addressing these, stakeholders from local to global levels can collaboratively enhance resilience.

Table 1. Summary of main climate change impacts on food systems, corresponding WEF-E nexus strategies to address them, and future directions for research and action.

Climate Challenge/Impact	Nexus-Based Adaptation/Mitigation Strategies	Future Priorities/Research Directions
Drought and water scarcity—Reduced water availability for crops and livestock; drying of rivers and reservoirs, affecting irrigation and hydropower.	- Precision irrigation (drip/smart systems) to maximize water productivity. - Rainwater harvesting, water reuse, and aquifer recharge to buffer dry spells. - Drought-tolerant crop varieties and diversified cropping to maintain yields with less water. - Integrated drought management plans (agriculture–water–energy coordination).	- Improve drought forecasting and early warning integration with farm advisories. - Develop drought insurance and safety nets linked to water availability indices. - Research optimal allocation policies that balance water use between agriculture, energy (hydropower/thermal cooling), and ecosystems under scarcity.
Temperature extremes (heatwaves and cold spells)—Heat stress on crops/animals; increased evapotranspiration and cooling needs. In cold regions, need for heating greenhouses and barns.	- Agroforestry and shade provision to reduce field temperatures. - Heat-tolerant crop breeds and adjusted planting calendars to avoid hottest periods. - Renewable-based cooling (e.g., solar-powered fans, evaporative cooling) for livestock. - Biomass or geothermal heating for greenhouses/livestock in cold climates; insulation and energy efficiency improvements in facilities.	- Breeding programs for crops and livestock focused on heat tolerance without yield penalties. - Innovations in passive cooling/heating designs for farm structures (e.g., earth-sheltered greenhouses, thermal energy storage). - Region-specific studies on nexus impacts of shifting growing seasons (e.g., energy demands of extended seasons, water needs under warming).
Extreme rainfall and flooding—Crop damage, soil erosion, infrastructure (roads, power lines) damage; waterlogging of fields.	- Landscape-based water management that involves restoration of wetlands, floodplains to absorb floods; drainage management in farms. - Protective infrastructure that supports multiple uses (e.g., small reservoirs that catch floods and later supply irrigation). - Storm-resistant food storage and energy systems (e.g., elevating grain stores, flood-proof power units). - Coastal mangrove restoration to shield agricultural land from storm surges.	- Climate-proofing rural infrastructure at scale (roads, bridges, electrical grids) to maintain market access post-disaster. - Breeding/developing water-logging tolerant crop varieties for flood-prone areas. - Enhance community-based flood management plans linking farmers, water managers, and energy providers (e.g., coordinated dam releases and farm warnings).
High greenhouse gas (GHG) emissions from food systems—Agriculture’s contribution to climate change (carbon dioxide from fuel and deforestation, methane from livestock, nitrous oxide from soils) exacerbates future climate risks.	- Climate-smart agriculture practices that reduce emissions (e.g., efficient fertilizer use, agroforestry carbon sinks, rice management to cut methane). - Biogas digesters turning manure into renewable energy, lowering methane emissions and providing fuel. - Solar, wind, and other renewables replacing diesel in farm operations (pumping, machinery) to cut carbon dioxide. - Sustainable intensification to produce more food on less land, avoiding deforestation.	- Develop better measurement and verification for farm-level GHG reductions (to include agriculture in carbon markets/incentives). - Explore novel methane mitigation (e.g., feed additives for livestock, paddy rice microbiome management). - Integrate emission reduction goals into national food security plans (e.g., set targets for fertilizer efficiency, renewable energy in agriculture).

Table 1. Cont.

Climate Challenge/Impact	Nexus-Based Adaptation/Mitigation Strategies	Future Priorities/Research Directions
Ecosystem degradation and biodiversity loss—Climate stress on ecosystems (wildfires, habitat shifts) combined with unsustainable farming undermines services (pollination, water regulation).	• Expansion of nature-based solutions that includes agroecology, conservation agriculture, organic farming to reduce chemical load and improve soil biodiversity. • Protecting forests, wetlands, and grasslands that support the water cycle and provide habitat refuges (ecological corridors in agricultural landscapes). • Community-based natural resource management to align farming practices with ecosystem health (e.g., rotational grazing, community forestry). • Pollinator-friendly practices (flower strips, reduced pesticide use) to support crop pollination under climate stress.	• Research on “climate-smart conservation”—how to make ecosystems more resilient to climate while conserving them (e.g., assisted species migration, selecting genotypes adapted to future climate). • Payment for ecosystem services schemes to reward farmers for practices that enhance carbon sequestration, water quality, and biodiversity. • Cross-disciplinary monitoring of landscapes (agronomic and ecological indicators) to detect early warning signs of ecological decline affecting production.

In conclusion, building climate-resilient food systems through the WEF-E nexus is both an urgent necessity and an opportunity. It is a necessity because the complex risks of the Anthropocene cannot be managed in isolation; safeguarding any one of water, energy, food, or the environment requires addressing them together. It is an opportunity because it opens pathways for innovation, enabling the transformation of agriculture and resource use into forms that are not only shock-resistant but also more sustainable and just. Pursuing nexus-based solutions represents a significant step toward a future in which humanity can sustain itself without depleting the very resources and ecosystems upon which food production depends, even amid a changing climate. Realizing this integrated resilience vision will require sustained commitment and collaboration across disciplines and sectors. The benefits include a stable food supply and a healthier planet for future generations. The urgency to act is clear, as climate change continues to outpace current response capacities. With the necessary knowledge and tools increasingly available, the task ahead lies in their effective implementation and continuous refinement—bridging science, policy, and practice to build a sustainable, climate-resilient food system. Embracing the nexus approach offers not only a way to navigate the complexities of climate change but also an avenue to transform food systems into engines of sustainability and equity.

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Abbreviations

The following abbreviations are used in this manuscript:

ADB	Asian Development Bank
CGIAR	Consultative Group on International Agricultural Research
e.g.,	exempli gratia (for example)
etc.	et cetera (and others)
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
NGO	Non-governmental organization
PAYG	Pay-as-you-go
SADC	Southern African Development Community
SDGs	Sustainable Development Goals
UNEP	United Nations Environment Programme
WEF	Water–Energy–Food
WEF-E	Water–Energy–Food–Environment
°C	Degree Celsius

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