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Integrated Assessment of the Water–Energy–Food–Ecosystem Nexus in the Jordan Valley: A Mixed-Methods Empirical Study

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Abstract

Jordan is among the most water-stressed countries globally, with renewable freshwater availability falling below 100 m^3 per capita per year. The Jordan Valley (JV), the country's primary irrigated agricultural corridor, faces interconnected pressures across water, energy, food, and ecosystem (WEFE) systems under intensifying climatic and demographic stressors. This study evaluates the integrated performance of the WEFE nexus in the Jordan Valley using updated evidence (2018–2023) to quantify cross-sector interactions, performance gaps, and intervention priorities. A mixed-methods empirical assessment integrated quantitative sectoral data on water supply–demand and quality, electricity supply–demand and renewable deployment, agricultural productivity, and ecosystem pressure indicators, complemented by Living Lab–based stakeholder interviews. Sectoral indices were calculated based on supply–demand adequacy and aggregated into an overall WEFE Nexus Index. Results indicate persistent water scarcity, with a domestic supply of 23.48 MCM yr^{-1} versus demand of 26.00 MCM yr^{-1} (deficit -2.52 MCM yr^{-1}) and irrigation supply of 206 MCM yr^{-1} relative to approximately 400 MCM yr^{-1} demand (deficit -194 MCM yr^{-1}). Water services account for 14% of national electricity consumption, while solar pumping provides approximately 40% of daytime irrigation energy. Agricultural productivity is constrained by salinity and water quality, resulting in yield gaps (e.g., greenhouse vegetables: 4.7 vs. 10.0 t/dunum). Sectoral performance is uneven (Water 0.71; Energy 1.00; Food 0.45; Ecosystem 0.50), yielding an overall WEFE Nexus Index of 0.63 (0.50 after efficiency adjustment). Climate projections indicate continued warming (+1.8 °C) and declining precipitation (-11%) by 2060. Water harvesting, integrated renewable-powered water services, wastewater reuse, salinity management, climate-smart agriculture, and ecosystem restoration are critical to enhancing climate-resilient resource security in the Jordan Valley. The WEFE index developed here offers a tool for integrated planning and underscores that achieving climate-resilient resource security in the Jordan Valley will require strategic, cross-sector interventions and adaptive governance rather than sector-specific fixes.

Keywords: Jordan Valley; water–energy–food–ecosystem (WEFE) nexus; sustainability; renewable energy; climate change; irrigated agriculture

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1. Introduction

Jordan ranks among the world's most water-stressed countries, with renewable freshwater resources of approximately 61 m^3 per capita per year [1]. Chronic water scarcity, high energy requirements for water pumping and treatment, and a heavy reliance on food imports together exert interlinked pressures on the country's resource base. These challenges are further intensified by environmental degradation, including groundwater depletion, soil salinization, and ecosystem loss [2,3].

The Jordan Valley (JV) extends from Lake Tiberias in the north to the northern Dead Sea and represents the country's primary agricultural corridor (Figure 1). It sustains most of Jordan's irrigated agriculture and contributes substantially to national fruit and vegetable production [3–5]. However, the valley's semi-arid climate, characterized by low rainfall, high evapotranspiration, and rising temperatures, has exacerbated water scarcity and increased dependence on energy-intensive pumping systems. The once-abundant Jordan River has been reduced to a fraction of its historical flow due to upstream diversions and over-extraction. As a result, agricultural production has become increasingly dependent on non-conventional water sources, particularly treated wastewater blended with freshwater, which currently supplies approximately 60–65% of irrigation demand [6].

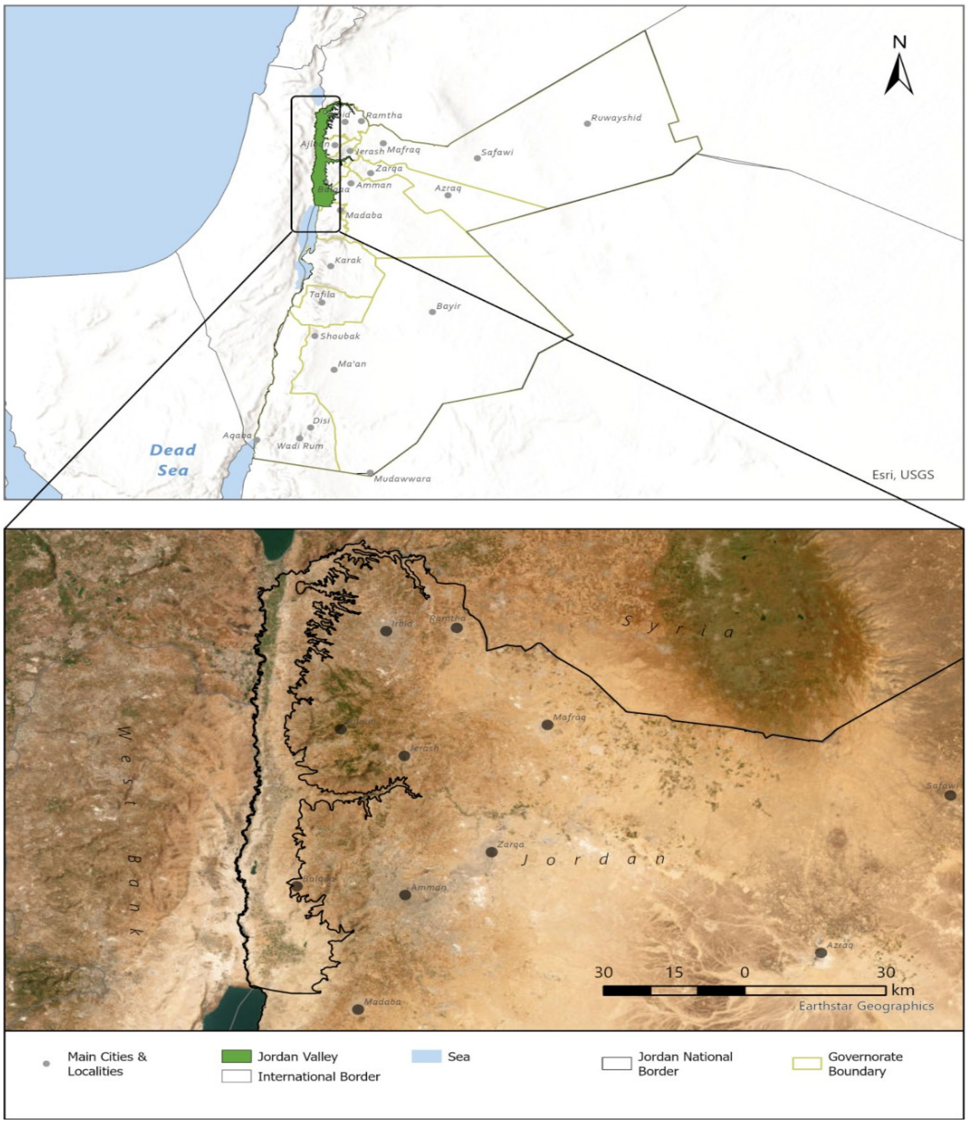

Figure 1. Location of Jordan Valley as part of Jordan rift valley.

Within this coupled system, water, energy, food, and ecosystem components are tightly interconnected. Renewable energy, particularly solar power, which accounts for more than 15% of Jordan's electricity generation, offers opportunities to reduce the energy burden associated with water services and agricultural production [7,8]. At the same time, ecosystem degradation, pollution pressures, and the spread of invasive species undermine long-term system sustainability and resilience [9]. Addressing these challenges, therefore, requires moving beyond siloed, sector-specific interventions toward integrated resource management approaches [10]. The Water–Energy–Food–Ecosystem (WEFE) nexus provides a holistic framework for balancing competing demands, enhancing climate resilience, and safeguarding critical ecosystem services [10–12].

Despite a growing body of WEFE nexus studies applied to Jordan and other arid and semi-arid regions, existing assessments remain largely conceptual, sector-specific, or reliant on fragmented and outdated datasets. In particular, there is a lack of valley-scale analyses that quantitatively integrate water, energy, food, and ecosystem indicators for the Jordan Valley using a consistent and updated evidence base that reflects current biophysical conditions and policy contexts. Consequently, decision-makers continue to lack a harmonized, JV-specific WEFE baseline capable of supporting cross-sector prioritization, identifying dominant performance constraints, and guiding targeted interventions across sub-regions [13]. Applied diagnostic studies that combine empirical evidence with stakeholder engagement are increasingly used to translate findings into implementable strategy solutions. For example, FAO's 2024 "study and strategy solutions" [14] approach demonstrates how mixed qualitative and quantitative evidence can be organized into clear findings, gaps, and prioritized recommendations. Following a similar evidence-to-action logic, this study integrates sectoral WEFE indicators with Living Lab stakeholder inputs to identify cross-sector performance gaps and intervention priorities for the Jordan Valley.

To address this gap, the present study develops an integrated WEFE assessment for the Jordan Valley by synthesizing and analyzing sectoral indicators using updated datasets for the period 2018–2023, and by complementing quantitative analysis with qualitative insights from stakeholders to capture local constraints, trade-offs, and implementation considerations. The analysis generates sector-specific nexus indices and an aggregated WEFE performance profile, providing an evidence-based platform to support integrated resource planning and policy development. Guided by this objective, the study addresses the following research question: How do water, energy, food, and ecosystem indicators interact within the Jordan Valley, and which priority areas emerge for integrated sustainability interventions under increasing climatic and resource pressures?

2. Materials and Methods

2.1. Study Design

This study adopted a mixed-methods empirical design integrating quantitative sectoral indicators with qualitative stakeholder perspectives. Quantitative data on water, energy, food, and ecosystem variables were compiled from national agencies, technical reports, and international databases for the period 2018–2023. These data were used to construct sector-specific performance indices and an aggregated WEFE Nexus Index to evaluate system dynamics and cross-sector interactions in the Jordan Valley. To contextualize and enrich the quantitative findings, qualitative data were generated through a structured Living Lab process. The Living Labs functioned as participatory, multi-stakeholder co-creation platforms that facilitated collaborative learning, deliberation on trade-offs, and joint problem-solving within the WEFE framework.

Five in-person Living Lab sessions were conducted throughout the project, enabling iterative dialogue, validation of interim findings, and refinement of proposed interventions.

A purposive sampling strategy was employed at the inception of the EU-funded EcoFuture project to ensure representation of key institutional and operational actors shaping WEFE outcomes. Twenty-five participants were selected to reflect the core landscape of decision-making and implementation in the Jordan Valley. The cohort included representatives from the Ministries of Water and Irrigation, Energy and Mineral Resources, Agriculture, and Environment; farmers cultivating strategic crops across the northern, central, and southern Jordan Valley; academic researchers with domain expertise; private sector actors; and participants from two transnational sessions involving stakeholders from Palestine to capture cross-border dimensions of resource governance. Participants were selected based on their formal decision-making authority, regulatory responsibility, technical expertise, or direct engagement in resource management and agricultural production, as well as agricultural cooperatives and water users' associations. Women farmers have also participated in the living labs. Although the sample size was intentionally limited, it encompassed the principal institutional and practitioner groups influencing WEFE system performance, thereby providing analytically robust and policy-relevant qualitative insights. Informed consent was obtained from all participants, and confidentiality protocols were strictly observed throughout the research process.

Mixed-methods design and integration. We used a convergent mixed-methods design in which quantitative WEFE indicators and qualitative stakeholder evidence were developed in parallel and integrated at interpretation. Quantitative results identified sectoral deficits and performance gaps, while Living Lab engagement was used to (i) validate and contextualize indicator patterns, (ii) explain institutional and operational drivers of observed gaps, and (iii) prioritize intervention options based on feasibility and cross-sector co-benefits.

2.2. Study Area and Scope

The analysis focuses on the Jordanian portion of the JV, a low-lying agricultural corridor within the Jordan Rift Valley. The valley's sub-sea-level topography creates a distinctive micro-climate with mild winters, hot summers and a steep rainfall gradient, from about 400 mm yr^{-1} in the north to less than 50 mm yr^{-1} in the south [5,13]. These climatic contrasts define three sub-regions (Northern, Middle and Southern JV) with distinct resource conditions. The JV supports more than 30,000 ha of irrigated farmland and roughly 260,000 residents, making it a critical site for examining nexus interactions [13]. The study was conducted in the Jordan Valley (JV), Jordan's primary irrigated agricultural corridor, extending along the Jordan Rift Valley from the northern reaches near Lake Tiberias/Yarmouk confluence toward the southern areas adjacent to the Dead Sea. The JV lies along Jordan's western border and is hydrologically linked to the Jordan River system. To provide geographic context at regional and national scales, a study area map showing international and administrative boundaries and the spatial extent of the JV is provided (Figure 1).

2.3. Data Sources and Analytical Approach

The study integrated multiple national and international datasets to develop a comprehensive and up-to-date evidence base for assessing the WEFE nexus in the Jordan Valley over the period 2018–2023. Water-sector data, including domestic and agricultural supply–demand balances, were obtained from official water budget reports and annual statistical bulletins issued by the Ministry of Water and Irrigation (MWI). Water-quality parameters for surface water, blended treated wastewater, and groundwater were referenced from the Third National Water Master Plan (NWMP-3, 2023) [15] and associated technical documentation on water reuse.

Energy-sector data were compiled from the Ministry of Energy and Mineral Resources (MEMR), the National Energy Research Center, and related technical reports. These datasets included electricity generation and consumption by source, renewable energy deployment trends, pumping-station energy requirements, and performance indicators for solar-powered irrigation systems. Agricultural statistics (2018–2023) were obtained from the Department of Statistics (DoS), encompassing cultivated area by crop type, yield data, import dependency ratios, farm-level production indicators, and the spatial distribution of agricultural systems across the northern, central, and southern Jordan Valley.

Climate projections were derived from CMIP6 General Circulation Models (GCMs), including EC-Earth3-CC, HadGEM3-GC31-LL, and MPI-ESM1-2-LR, under SSP1-2.6, SSP2-4.5, and SSP5-8.5 pathways. Bias-corrected temperature and precipitation time series were analyzed to evaluate historical variability and mid-century climate change projections. Additional ecosystem and environmental indicators were synthesized from the Jordan Environment Monitor, peer-reviewed scientific literature, EU-funded project deliverables, and national monitoring reports. These sources provided data on soil salinity, biodiversity status, pollution pressures, trace element distribution, and habitat conditions.

All secondary datasets were cross-validated across multiple institutional and technical sources wherever feasible to ensure internal consistency and enhance reliability. The consolidated quantitative database, together with qualitative evidence generated through the Living Lab process, constituted the analytical foundation for calculating sector-specific performance indices and the aggregated WEFE Nexus Index. To enhance transparency and methodological rigor, the demographic distribution and institutional representation of Living Lab stakeholders are presented in Supplementary Material (Table S1), which summarizes participant roles, sectoral affiliation, and regional representation across the 25 participants engaged in the participatory process.

2.4. Variables and Indicators

To assess the performance of the WEFE sectors in the Jordan Valley, a set of quantitative indicators was developed based on available data from 2018–2023. These indicators were selected to represent supply–demand balances, resource quality, productivity constraints, and environmental conditions relevant to the WEFE nexus. Water indicators captured volumetric supply and demand for domestic and agricultural uses, as well as water-quality parameters influencing irrigation suitability. Energy indicators included electricity generation and consumption, solar pumping capacity, and renewable energy integration in water services. Food indicators were based on actual versus potential yields for key crops, cultivated area distribution, and production performance. Ecosystem indicators represented soil salinity, biodiversity loss, pollution pressures, and degradation of natural habitats. These variables were suggested to serve as inputs to the sectoral nexus indices and the overall WEFE Nexus Index. The indicators presented in Table 1 were proposed during the Living Lab consultations to support the development of a comprehensive WEFE Nexus Index reflecting stakeholder priorities. However, not all suggested indicators were included in the index calculated in this study due to limitations in the availability and consistency of quantitative data for the assessment period (2018–2023). Therefore, only indicators with reliable and comparable datasets were retained in the WEFE index calculation to ensure methodological robustness and consistency of the analysis. The remaining indicators are presented as part of the stakeholder-driven framework to inform future monitoring and policy evaluation efforts.

Table 1. WEFE Variables and Indicators Used in the Study.

WEFE Domain	Variable	Indicator Description	Unit	Purpose/Use
Water	Domestic water supply	Annual drinking water supplied to JV residents	MCM/yr	Quantify supply–demand balance
	Domestic water demand	Estimated annual drinking water needs	MCM/yr	Identify deficits/surpluses
	Agricultural water supply	Irrigation water available from King Abdullah Canal (KAC), King Talal Dam (KTD), and groundwater	MCM/yr	Assess irrigation sufficiency
	Agricultural water demand	Total irrigation requirement based on cultivated area	MCM/yr	Evaluate gap relative to supply
	Water quality (EC)	Electrical conductivity of irrigation water (fresh, blended, groundwater)	dS/m	Assess salinity risk for crops
	Water quality (TDS)	Total dissolved solids	mg/L	Evaluate irrigation suitability
	Nitrate concentration	NO_3^- levels in irrigation water	mg/L	Assess nutrient pollution risk
	Boron concentration	B levels in irrigation water	mg/L	Determine toxicity constraints
	SAR	Sodium adsorption ratio	–	Evaluate soil sodicity hazard
Energy	Electricity supply	Annual electricity generated in the JV	GWh/yr	Determine energy availability
	Electricity demand	Annual electricity consumption in the JV	GWh/yr	Identify energy gaps
	Solar pumping capacity	Installed solar capacity for irrigation pumps	MW	Measure renewable energy integration
	Solar energy generation	Annual generation from solar pumping systems	GWh/yr	Evaluate contribution to water services
	Renewables share	Share of total energy supplied by solar	%	Assess energy transition progress
Food (Agriculture)	Actual crop yield	Observed yield for vegetables, citrus, etc.	t/dunum	Identify productivity levels
	Potential/attainable yield	Demonstrated maximum under optimal practices	t/dunum	Calculate yield gaps
	Cultivated area	Area under vegetables, fruits, and greenhouses	Dunum	Understand cropping patterns
	Food import ratios	Proportion of national food supplied by imports	%	Assess contribution to food security
Ecosystems	Soil salinity	Percentage of cultivated soils affected by salinity	% area	Evaluate soil degradation
	Biodiversity condition	Estimated biodiversity loss relative to natural baseline	% loss	Assess ecological health

Table 1. *Cont.*

WEFE Domain	Variable	Indicator Description	Unit	Purpose/Use
	River flow levels	Jordan River discharge reaching JV	MCM/yr	Indicator of riparian ecosystem status
	Pollution load	Nutrient and pesticide levels in water bodies	–	Assess environmental pressure
	Habitat degradation	Extent of riparian/wetland loss	Qualitative/ quantitative	Evaluate ecosystem functioning

2.5. WEFE Index Calculation

The construction of the WEFE Nexus Index builds on established composite indicator methodologies and integrated WEFE assessment frameworks [16–18], adapted to the biophysical and institutional context of the Jordan Valley. To quantify integrated WEFE performance in the Jordan Valley, four sectoral indices (Water (W), Energy (E), Food (F), and Ecosystem (Eco)) were calculated and then aggregated into an overall WEFE Nexus Index. The index construction followed a transparent, stepwise procedure designed to (i) standardize indicators with different units, (ii) express sector performance relative to system needs, and (iii) enable comparison and integration across domains.

Step 1. Define sector performance metrics

For each WEFE domain, a primary performance metric was defined based on the most policy-relevant and consistently available indicators:

- Water domain: domestic and agricultural supply–demand adequacy, supported by irrigation water-quality constraints (e.g., salinity risk).
- Energy domain: electricity supply–demand adequacy for the Jordan Valley, including the contribution of renewable energy.
- Food domain: agricultural productivity adequacy represented by the ratio of actual to attainable yields for key crop systems (greenhouse vegetables, open-field summer vegetables, citrus).
- Ecosystem domain: ecosystem condition represented by degradation pressure indicators, with emphasis on biodiversity status and soil salinity constraints.

Step 2. Compute sector adequacy ratios

Each sector index was expressed as an adequacy ratio bounded between 0 and 1, where 1 indicates that the system meets or exceeds the sector requirement. Ratios were calculated as follows:

(a) Water Index (W):

Water adequacy was calculated separately for domestic and agricultural uses as Equation (1):

$$\boldsymbol{Adom} = \boldsymbol{min}\left(\mathbf{1}, \frac{\boldsymbol{Sdom}}{\boldsymbol{Ddom}}\right), \boldsymbol{Aagr} = \left(\mathbf{1}, \frac{\boldsymbol{Sagr}}{\boldsymbol{Dagr}}\right) \tag{1}$$

where $\boldsymbol{S}$ is annual supply and $\boldsymbol{D}$ is annual demand. Because agricultural water dominates total withdrawals and is the principal constraint in the Jordan Valley, the Water Index was calculated as a weighted composite Equation (2):

$$\boldsymbol{W} = \boldsymbol{\alpha}\ \boldsymbol{Adom} + (\mathbf{1} - \boldsymbol{\alpha})\boldsymbol{Aagr} \tag{2}$$

The Water Index was computed as a weighted composite of domestic and agricultural adequacy, where α represents the policy-informed weight assigned to domestic water relative to sectoral dependence. Sensitivity analysis demonstrates the robustness of the results: varying α between 0.3 and 0.5 changes the Water Index by approximately ± 0.02

and the overall WEFE score by about ±0.01, while even an extreme shift of α from 0 to 1 alters the WEFE Index by only ~0.10 and does not change the relative ranking of sectoral constraints. Water-quality indicators (EC, TDS, SAR) were used to contextualize irrigation constraints and interpret agricultural adequacy in areas affected by salinity (see Supplementary Table S2).

(b) Energy Index (E):

Energy adequacy was calculated as Equation (3):

$$\boldsymbol{E = \min\left(1, \frac{Sen}{Den}\right)} \tag{3}$$

where $\boldsymbol{S_{en}}$ and $\boldsymbol{D_{en}}$ represent annual electricity supply and demand in the Jordan Valley. To avoid overestimating performance when nominal supply exceeds demand but network losses and operational constraints persist, the energy index was conservatively capped at unity (E = 1.00) when $\boldsymbol{S_{en} \geq D_{en}}$. Renewable energy indicators (e.g., installed solar pumping capacity and annual PV generation) were reported as enabling variables that support the water–energy linkage and reduce pumping costs/emissions.

(c) Food Index (F):

Food-sector performance was represented by the yield adequacy of key crop systems, computed as Equation (4):

$$\boldsymbol{Yi = \min\left(1, \frac{Yact, i}{Ypot, i}\right)} \tag{4}$$

where $\boldsymbol{Y_{act,i}}$ is the observed yield and $\boldsymbol{Y_{pot,i}}$ is the attainable (best-practice) yield for crop system $\boldsymbol{i}$. The Food Index was then calculated as the weighted mean across crop systems, Equation (5):

$$\boldsymbol{F = \sum_{i=1}^{n} \omega i Yi} \tag{5}$$

where $\boldsymbol{w_i}$ reflects the relative importance of each crop system (e.g., area share or production relevance) and $\boldsymbol{\sum w_i = 1}$. Weights were primarily based on cultivated area shares, with robustness checks using alternative weighting schemes (e.g., production-based weights) yielding comparable index values. This approach captures productivity limitations driven by water deficit, salinity, and climate stress.

(d) Ecosystem Index (Eco):

The ecosystem index summarized ecological condition using available, measurable degradation indicators (e.g., biodiversity loss, salinization extent, habitat degradation). Indicators were normalized to a 0–1 scale so that higher values indicate healthier ecosystem conditions. When biodiversity loss ($\boldsymbol{L_{bio}}$) was used as the primary metric, ecosystem condition was computed as Equation (6):

$$\boldsymbol{Eco = 1 - Lbio} \tag{6}$$

with $\boldsymbol{L_{bio}}$ expressed as a fraction (0–1). Where multiple ecosystem indicators were available, a composite ecosystem condition score was calculated as a weighted average of normalized indicators (e.g., biodiversity condition, soil salinity pressure), with weights selected to reflect ecological relevance and data availability constraints in arid and semi-arid environments. It is acknowledged that ecosystem indicators reflect pressure and condition proxies rather than a full valuation of ecosystem services, given data limitations typical of water-scarce regions.

Step 3. Aggregate sector indices into the WEFE Nexus Index

The overall WEFE Nexus Index was calculated as the arithmetic mean of the four sector indices Equation (7):

$$\boldsymbol{WEFE} = \frac{\boldsymbol{W} + \boldsymbol{E} + \boldsymbol{F} + \boldsymbol{Eco}}{\boldsymbol{4}} \tag{7}$$

This produces a single integrated performance score (0–1) representing the proportion of the system's WEFE potential currently achieved. This aggregation approach ensures transparency, comparability, and interpretability for policy-oriented applications [19]. Uncertainty was quantified by computing 95% confidence intervals for each sector index and propagating them to the combined WEFE index under the independence assumption (variance additivity).

Step 4. Adjustment for system inefficiencies (optional)

Because sectoral adequacy can be overestimated when substantial losses occur (particularly non-revenue water and conveyance losses), an adjusted WEFE score was also reported by applying an efficiency correction factor (η) to the relevant domain(s), primarily water Equation (8):

$$\boldsymbol{WEFE\ adj} = \frac{(\boldsymbol{\eta W}) + \boldsymbol{E} + \boldsymbol{F} + \boldsymbol{Eco}}{\boldsymbol{4}} \tag{8}$$

where $\boldsymbol{\eta}$ represents the fraction of effective water service after losses. This adjustment is intended to provide a more conservative estimate of integrated WEFE performance under real operational conditions in water-scarce systems.

Step 5. Reporting and interpretation

The theoretical contribution of the WEFE Index lies in its ability to integrate disparate sectoral metrics into a single, transparent composite indicator. Following established composite indicator methodologies [18,19], the index applies normalization and equal weighting to ensure comparability across dimensions and highlights trade-offs and synergies across the water, energy, food, and ecosystem domains. By providing a harmonized baseline, the index supports integrated planning, facilitates scenario and sensitivity analysis, and enables comparisons with other arid regions using the same framework.

All sector indices (W, E, F, Eco) and the aggregated WEFE score were reported alongside the underlying indicators (supply, demand, yields, ecosystem condition metrics) to ensure transparency and reproducibility. The indices were interpreted comparatively to identify the primary constraints (lowest-performing sectors) and to highlight leverage points where cross-sector interventions (e.g., renewable-powered pumping, wastewater reuse with improved quality management, soil salinity mitigation, ecosystem restoration) may generate co-benefits across the WEFE nexus.

2.6. Qualitative Interviews

Qualitative data were collected through semi-structured interviews with living labs participants, conducted within the framework of the Living Lab meetings, to complement the quantitative sectoral indicators and contextualize WEFE interactions in the Jordan Valley. A purposive sampling strategy was applied to ensure representation across the three subregions (Northern, Middle, and Southern JV) and across different farming systems and irrigation conditions. The interviews captured variation in irrigation sources (freshwater, blended water, and groundwater) and exposure to water-quality and salinity constraints.

The interviews conducted within the living labs followed a semi-structured format covering the four main components of the WEFE nexus (water, energy, food, and ecosystems). The questions were designed to capture stakeholders' perceptions regarding resource availability, system stability, and emerging challenges in the Jordan Valley. Table 2 presents examples of the interview questions used to guide the discussions with participants. The synthesized findings are documented in publicly available project reports accessible at https://ecofuture-prima.eu/ (accessed on 10 March 2026). All participants were informed about the purpose of the study and the voluntary nature of their involvement prior to data collection. Informed consent was obtained from all interviewees, and confidentiality and anonymity were ensured throughout the research process. The study protocol adhered to relevant institutional and national ethical guidelines for research involving human participants. (The detailed Living Lab reports are provided in the Supplementary Excel Sheet (Table S5)).

Table 2. Example questions from the semi-structured interview guide used in the living labs.

Indicator	Questions Discussed in the Living Labs
Water security (quantity & quality)	"From your perspective—whether as a producer, policymaker, researcher or community representative—what are the main sources of water in the Jordan Valley, and how reliable are they throughout the year? What trends have you observed in water quality or salinity, and how do these changes influence agricultural productivity, environmental management and policy priorities in your work?"
Energy availability & stability	"Considering the energy supply that supports water delivery and agricultural operations, what energy sources are currently used in the Jordan Valley and how stable and affordable are they? What opportunities and barriers do you see for integrating renewable energy into the water–energy–food–ecosystem nexus?"
Food security (quantity & quality)	"Looking at food production and quality in the Jordan Valley, have you observed changes in productivity, crop quality or market access? What strategies or innovations are being employed—in policy, research or practice—to enhance food security under water and energy constraints?"
Ecosystems and biodiversity conservation	"What changes in ecosystems (such as soil health, pest outbreaks or pollinator decline) have you observed, and how do these affect farming practices, resource management and research agendas? Are there conservation or restoration initiatives you are involved in or would like to see implemented?"

2.7. Analytical Methods

Analytical procedures were designed to integrate quantitative sectoral indicators, climate projections, and qualitative evidence within a unified assessment framework. Quantitative analyses focused on deriving sector-specific adequacy metrics and composite indices as described in Section 2.5, while qualitative findings were used to contextualize and interpret observed system dynamics. Supply–demand gaps for water and energy were quantified by comparing annual volumetric supply with documented sectoral demand, and temporal trends were examined to identify structural constraints and emerging pressures. Climate model outputs were analyzed to assess long-term shifts in temperature and precipitation relevant to water availability and agricultural productivity under alternative emissions pathways.

A sensitivity analysis was conducted to evaluate the robustness of the WEFE index and to identify the parameters that exert the greatest influence on the aggregated nexus score. Because the WEFE index integrates multiple sectoral indicators (water, energy, food, and ecosystem) through a composite formulation, it is important to assess how uncertainties or variations in individual inputs may affect the overall index. The sensitivity analysis was conducted using a local perturbation approach, where key parameters of the WEFE index formulation were varied by ±10% while keeping all other variables constant. The resulting change in the WEFE index was then calculated to quantify the sensitivity of the index to each parameter. This approach allows identification of the parameters that most strongly influence the composite WEFE index.

The integrated analytical workflow followed a sequential explanatory mixed-methods approach, in which quantitative results guided qualitative interpretation and qualitative insights informed the synthesis of system-level interactions. This approach ensured consistency, transparency, and reproducibility of the WEFE assessment.

3. Results

3.1. Water and Energy: Scarcity and Interdependence

Water scarcity defines the JV's resource landscape. Drinking water supply is estimated at 23.48 MCM yr^{-1} for about 260,000 inhabitants, while demand is 26 MCM yr^{-1}, leaving a deficit of −2.52 MCM. The agricultural sector is under significantly greater pressure, with irrigation water supply limited to 206 MCM, compared to an estimated demand of approximately 400 MCM, which accounts for land preparation and leaching requirements across the valley. resulting in a shortfall of −194 MCM. Much of the irrigation water—about 61%—comes from surface water and blended treated wastewater (BTWW), highlighting the reliance on non-conventional sources [1,20]. This structural dependence on marginal and non-conventional water resources represents one of the defining constraints shaping agricultural and environmental performance across the JV. Table 3 summarizes water supply, demand and deficits for drinking and agricultural use.

Table 3. Water supply, demand and deficits in the JV.

Category	Supply (MCM yr^{-1})	Demand (MCM yr^{-1})	Deficit (MCM yr^{-1})	Source
Drinking water	23.48	26.00	−2.52	MWI (Water Budget report, 2018–2023) [20]
Agricultural water	206.00	400.00	−194.00	MWI (National Water Strategy, 2023–2030) [1]

The quality of irrigation water exhibits marked spatial variability across the Jordan Valley (Table 4). Surface water conveyed through the northern section of the King Abdullah Canal (KAC) remains relatively fresh, with total dissolved solids (TDS) concentrations of approximately 500–750 mg L^{-1}, and is predominantly used for irrigating citrus orchards in the northern Jordan Valley. In contrast, blended irrigation water derived from the King Talal Dam (KTD)—a mixture of freshwater and treated wastewater (BTWW)—shows substantially higher salinity levels (≈1200–1500 mg L^{-1} TDS) and is primarily applied in the central and southern parts of the valley, where vegetable crops and date palms dominate the prevailing production systems. Due to chronic irrigation water deficits, farmers in the southern Jordan Valley intermittently supplement surface supplies with groundwater; however, groundwater in the southern basins is frequently brackish (1500–5000 mg L^{-1} TDS) and commonly exhibits elevated nitrate and boron concentrations [21,22]. The spatial gradients in irrigation water quality translate into differentiated agronomic risks, constraining crop selection, yield stability, and long-term soil health across the valley. These constraints often necessitate water blending or desalination measures and substantially influence irrigation management practices and overall agricultural productivity [23].

Table 4. Selected water-quality parameters for irrigation water in the JV.

Parameter	Freshwater (KAC North)	Blended (KAC + TWW Mid)	Groundwater (South)	Jordanian Irrigation Water Standard (JS 1766:2014) [24]	Source
Electrical conductivity (dS m^{-1})	~1.1	~1.9	2–5	<1.7 (no restriction); 1.7–3.0 (slight–moderate restriction); >3.0 (severe restriction)	W. Management of Water Resources Project/Third National Water Master Plan (NWMP-3); Ministry of Water and Irrigation (MWI); Ministry of Environment (MoEnv); Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Jordan, 2023 [15].
Total dissolved solids (mg L^{-1})	500–750	1200–1500	1500–5000	1088 (no restriction); 1088–2000 (slight–moderate restriction); >2000 (severe restriction)	
Nitrate (mg L^{-1})	<20	40–60	>50	<5 (no restriction); 5–30 (slight–moderate restriction); >30 (severe restriction)	
Phosphate (mg L^{-1})	<1	2–4	1–3	<6 (no restriction); 6–20 (slight–moderate restriction); >20 (severe restriction)	
Boron (mg L^{-1})	<0.2	0.5–0.8	0.8–1.5	<0.7 (no restriction); 0.7–3.0 (slight–moderate restriction); > 3.0 (severe restriction)	
Sodium adsorption ratio (SAR)	2–4	5–7	6–10	SAR limits depend on ECw; higher SAR acceptable only with higher salinity (Table 1, JS 1766:2014 [24])	

Energy and water are closely linked: pumping, treatment and distribution of water consume roughly 14% of Jordan's total electricity [25]. The energy demand of water utilities has outpaced tariff revenues, threatening financial sustainability. Solar resources in the JV are abundant (annual global horizontal irradiation >2000 kWh m^{-2}), offering opportunities to reduce costs and emissions. Pilot projects have converted 214 irrigation pumps to solar-powered systems, adding approximately 7.65 MW of installed capacity and generating about 7.7 GWh yr^{-1} [25,26]. These initiatives demonstrate the technical feasibility of reducing the water sector's energy burden, although their current scale remains insufficient relative to total pumping demand. Most installations are grid-connected under Jordan's net-metering programme, whereby photovoltaic generation offsets electricity used for pumping, with surplus energy credited to the water utility's account. Despite these gains, night-time pumping continues to rely on grid electricity, as solar systems currently supply only about 40% of annual energy demand during daylight hours [25,26]. Further expansion of solar pumping and modernization of conveyance infrastructure could therefore contribute to reducing both energy consumption and water losses.

Based on the quantified domestic and agricultural supply–demand balances reported above, water-sector performance was translated subsequently into a normalized Water Index (W). Domestic water adequacy approached unity (Adom $\approx$ 0.90), whereas agricultural water adequacy was substantially lower (Aagr $\approx$ 0.52) due to the pronounced irrigation deficit. Applying the weighted aggregation described in the Section 2 resulted in an overall Water Index value of W = 0.71, indicating that water scarcity, particularly in agriculture, represents one of the primary constraints within the Jordan Valley WEFE system (α was estimated to be 0.51 for Aagr).

3.2. Energy Results

Based on national data and a population ratio of about 2.6%, the Jordanian side of the JV generated about 575.73 GWh in 2021 and 621.15 GWh in 2022, while demand was roughly 507 GWh and 540 GWh in the same years. Projections for 2030 estimate that supply will rise to around 705 GWh and demand to about 604 GWh. Almost all of this future supply is expected to come from solar power (around 412 GWh from transport-network photovoltaic systems and 292 GWh from distribution-network PV), with only a tiny contribution from biogas. Conventional steam, diesel, simple-cycle, combined-cycle, wind and hydro generation are negligible in the valley [27]. The following figure summarizes the electricity supply and demand for JV (Figure 2).

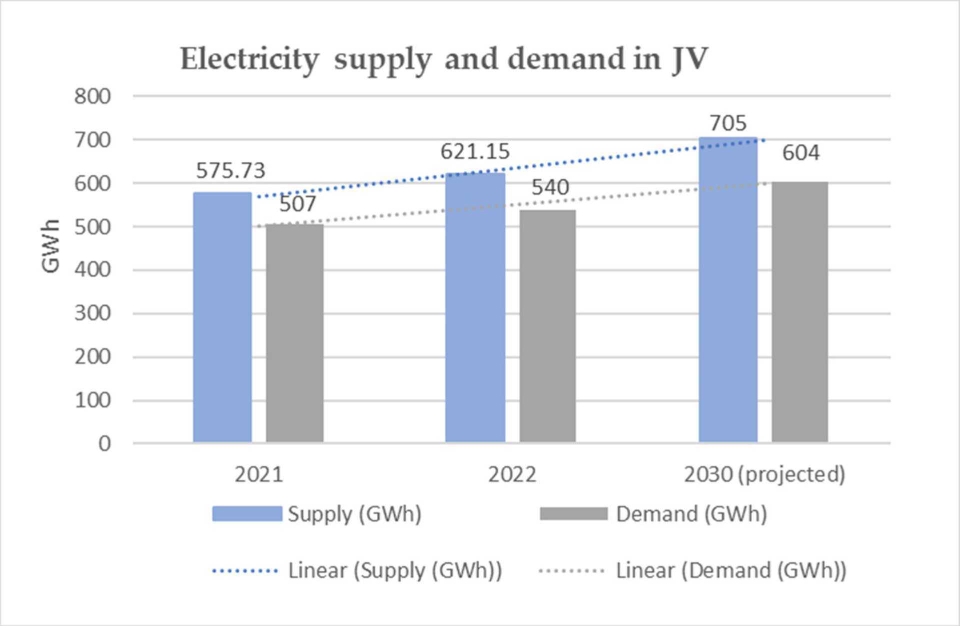

Figure 2. Electricity supply and demand in the JV in years 2021, 2022, and 2030 (projected).

The 2030 energy-demand projection was derived by extrapolating a 2018–2023 electricity consumption trend" using a linear growth model, with additional adjustments for planned irrigation expansion and population growth, and uncertainty bands were generated using ±10% variation around the trend line [27]. Electricity supply exceeded demand during the assessment years (2021–2022), and projections indicate continued adequacy toward 2030. Consequently, energy-sector performance was expressed as a normalized Energy Index capped at unity, yielding E = 1.00. This result indicates that energy availability (driven largely by solar generation) functions as an enabling rather than limiting factor within the Jordan Valley WEFE nexus, particularly in relation to water pumping and irrigation services. Nevertheless, operational constraints and temporal mismatches between energy generation and water-pumping demand may limit effective utilization.

3.3. Food and Agriculture: Production, Yields and Constraints

The Jordan Valley functions as Jordan's main horticultural production zone; however, substantial yield gaps persist between actual farm-level productivity and attainable yields under improved management. Although approximately 36,000 dunums of vegetables and 23,500 dunums of fruit trees are cultivated using water conveyed from the King Talal Dam and the King Abdullah Canal, national food security remains constrained, with imports accounting for about 87% of food by value, particularly for staple commodities such as wheat and rice. This contrast points to a structural disconnect between relatively high horticultural production in the Jordan Valley and the country's continued dependence on food imports, while also indicating unrealized production potential within existing irrigated systems [28]. Despite widespread adoption of drip irrigation and greenhouse technologies, actual crop yields remain substantially below attainable levels (Table 4). This yield gap reflects persistent water scarcity, elevated salinity, and low soil organic matter, which together constrain nutrient uptake and plant growth. Insights from the Living Lab meetings (conducted as participatory, multi-stakeholder meetings combining semi-structured interviews and facilitated group discussions) revealed that farmers frequently reduce irrigation during peak summer periods to cope with limited water availability and rising energy costs, resulting in intentional yield sacrifices. These short-term coping strategies mitigate immediate resource stress but reinforce longer-term productivity losses. Some farmers have shifted from citrus orchards toward more salt-tolerant crops such as date palms and herbs. Greenhouse farming is expanding as an adaptive response, enabling improved climate control and water-use efficiency; however, it requires substantial capital investment and additional energy for cooling. Across the Living Lab discussions, stakeholders consistently emphasized that closing the yield gap requires integrated, cross-sector measures, including improving irrigation water quality through blending or desalination, adopting soil amendments (e.g., compost and biochar), introducing salt- and heat-tolerant crop varieties, and enhancing farmers' access to renewable energy to offset pumping costs [29,30].

The maximum attainable yields reported in Table 5 reflect best-practice values observed in demonstration farms and experimental studies within the Jordan Valley rather than purely theoretical maxima [3,31,32].

Table 5. Actual and potential crop yields in the JV.

Crop Type	Actual Yield (t dunum^{-1})	Maximum Attainable Yield (t dunum^{-1})	Notes
Greenhouse vegetables	4.7	10.0	Tomatoes, cucumbers, eggplants; major greenhouse crops.
Summer vegetables	2.0	8.0	Open-field tomatoes and peppers.
Winter vegetables	4.2	—	Cabbage, lettuce; yield gap less documented.
Citrus trees	2.6	4.0	Oranges, mandarins and grapefruits.

The yield gaps observed across key crop systems (Table 5) were converted into a normalized Food Index using the ratio of actual to attainable yields. Yield adequacy values ranged from approximately 0.47 for greenhouse vegetables to about 0.33 for summer vegetables, with citrus systems exhibiting moderately higher performance. Food Index value of F = 0.45, identifying agricultural productivity as the weakest-performing WEFE domain in the Jordan Valley.

3.4. Ecosystems and Environmental Health

The JV's ecosystems—including riparian zones, wetlands, shrublands and agro-ecosystems have been severely degraded by water diversion, habitat loss and pollution. The Jordan River's discharge has plummeted from about 1300 MCM yr^{-1} historically to <50 MCM yr^{-1} at the Allenby Bridge, collapsing riparian habitats and accelerating biodiversity loss [33]. Soil salinization and erosion are widespread, fueled by the blended water irrigation from fresh and treated wastewater of relatively higher salinity, and insufficient drainage [34]. Table 6 summarizes the major ecosystem pressures.

Table 6. Major ecosystem pressures in the JV.

Category	Key Issues	Discussion
Water resources	Surface flow decline, groundwater depletion, salinity increase	River flow reduction from 1300 to <50 MCM yr^{-1}, over-pumping of aquifers leading to falling water tables and saline intrusion [33].
Soil	Degradation, salinization, erosion, nitrate pollution	Salinity affects 60–70% of cultivated soils; nitrate contamination stems from fertilizer leaching and wastewater reuse [35].
Biodiversity	Loss of native species, invasive plants, habitat conversion	Invasive species such as *Prosopis juliflora* out-compete native flora and deplete groundwater resources; wetland and riparian habitat loss reduces pollinators and natural predators [36].
Pollution	Fertilisers, pesticides, wastewater discharge	Agricultural runoff and untreated sewage elevate nutrient and pesticide loads in canals and aquifers [37].
Climate	Decreasing rainfall, rising temperature	Observed rainfall declines of 11–34% and temperature increases of ~1.9 °C between 1982 and 2021 exacerbate water scarcity and soil degradation [38,39].

Ecosystem degradation undermines the services that sustain agriculture and communities, such as: pollination, soil fertility, water purification and flood regulation. Interviewees noted a decline in wild pollinators and increased pest outbreaks, requiring more pesticide use [27]. Restoration efforts, such as riparian re-vegetation and constructed wetlands, have shown promise for improving water quality and biodiversity but remain limited in scale [40]. Strengthening ecosystem management through protected areas, agro-forestry and nature-based solutions could provide long-term resilience across the nexus [27].

The ecosystem domain achieved a normalized score of Eco = 0.50, reflecting moderate but declining ecological conditions that undermine regulating services essential for water quality and agricultural resilience. The index was estimated based on the rate of change in biodiversity and surface water availability, referring to literature reviews, reflecting data availability constraints typical of arid and semi-arid systems [33,36].

3.5. Climate Trends and Projections: Observed Changes and Future Risks

Future climate conditions in the Jordan Valley were assessed using CMIP6 projections from three General Circulation Models (GCMs): EC-Earth3-CC, HadGEM3-GC31-LL, and MPI-ESM1-2-LR, under SSP2-4.5 and SSP5-8.5 emission pathways. Bias-corrected temperature and precipitation time series reveal a continued drying and warming trend. As shown in Table 7, average annual precipitation has declined from ≈366 mm (1982) to ≈287 mm (2021) and is projected to decrease by an additional ≈11% by 2060, reflecting increasing aridity. Mean annual temperature has risen to ≈22.2 °C in 2021, with model projections indicating a further warming of ≈+1.8 °C by 2060. These changes indicate that the JV is moving toward a hotter and drier climate regime by mid-century [38,39]. Projections were used to contextualize medium-term pressures rather than to generate deterministic forecasts.

Table 7. Observed and projected climate trends in the JV.

Indicator	Historical (1982)	Recent (2021)	Projected 2060
Average annual Precipitation (mm)	366.35	287.4	−11% from the year (2021)
Mean annual temperature (°C)	-	22.15	+1.8% (from the year 2021)

These model-based projections underscore the urgency of climate adaptation. Reduced rainfall and hotter temperatures will compound existing water deficits, making efficient irrigation, drought-tolerant crops and ecosystem restoration even more critical [40]. The EU-funded EcoFuture project strategic plan emphasizes that climate-resilient practices—such as rainwater harvesting, mulching, shading and the use of climate-resilient seeds—must become mainstream to sustain agriculture under warming conditions [27,36,40].

Projected increases in temperature and continued precipitation decline are expected to intensify irrigation water deficits, exacerbate crop heat stress, and accelerate ecosystem degradation. These climate trends reinforce the low Food (F) and Ecosystem (Eco) index values and indicate that, without targeted adaptation measures, integrated WEFE performance in the Jordan Valley is likely to deteriorate further toward mid-century.

3.6. WEFE Index Results

To present the integrated performance of the water, energy, food, and ecosystem domains in a clear and comparable format, the sector-specific indices and the aggregated WEFE Nexus Index were summarized in a standardized format in Table 8. This table provides a quantitative snapshot of the relative strengths and weaknesses across the four nexus domains and highlights the sectors exerting the greatest constraints on overall system sustainability. By organizing the indices side by side, the table facilitates direct comparison of adequacy levels, reveals the imbalance between enabling (energy) and limiting (water, food, ecosystem) sectors, and supports evidence-based prioritization for policy and planning in the Jordan Valley.

Table 8. Sectoral WEFE indices and integrated performance in the Jordan Valley (assessment period: 2018–2023).

WEFE Domain	Index Value	What the Index Represents	Key Interpretation for the JV
Water (W)	0.71	Adequacy of water supply relative to domestic and agricultural demand (normalized 0–1)	Water is a primary constraint, driven mainly by large irrigation deficits and compounded by quality/salinity limitations.
Energy (E)	1.00	Adequacy of electricity supply relative to demand (capped at 1)	Energy is comparatively enabling; renewables (especially solar pumping) strengthen the water–energy linkage and reduce operating costs.
Food (F)	0.45	Agricultural productivity adequacy based on actual vs. attainable yields (normalized 0–1)	The lowest-performing domain, reflecting large yield gaps consistent with water shortages, salinity, and heat stress.
Ecosystem (Eco)	0.50	Ecosystem condition based on normalized degradation/condition indicators (0–1)	Moderate but declining ecological performance; ecosystem degradation undermines regulating services that support water quality and agriculture.

Table 8. *Cont.*

WEFE Domain	Index Value	What the Index Represents	Key Interpretation for the JV
Overall WEFE Index	0.63	Mean of W, E, F, Eco	The JV achieves ~63% of its integrated WEFE potential, with constraints dominated by water, food productivity, and ecosystem condition.
Adjusted WEFE Index (inefficiency-corrected)	~0.50	Overall index after accounting for major system inefficiencies (notably water losses)	Effective integrated performance is substantially lower when operational losses are considered, strengthening the case for efficiency-focused interventions.

Figure 3 summarizes sectoral performance indices for Water (0.71), Energy (1.00), Food (0.45), and Ecosystems (0.50) and the aggregated WEFE Nexus Index (~0.63). Indices are normalized to a 0–1 scale, where higher values indicate stronger sectoral performance or adequacy relative to needs. The framework illustrates key interlinkages across sectors and highlights that overall integrated performance is primarily constrained by water deficits, agricultural yield gaps, and ecosystem degradation, while energy availability, especially renewable energy, acts as a potential enabling factor for cross-sector improvements. An inefficiency-adjusted estimate (~0.50) is included to reflect the influence of major operational losses, particularly in the water system.

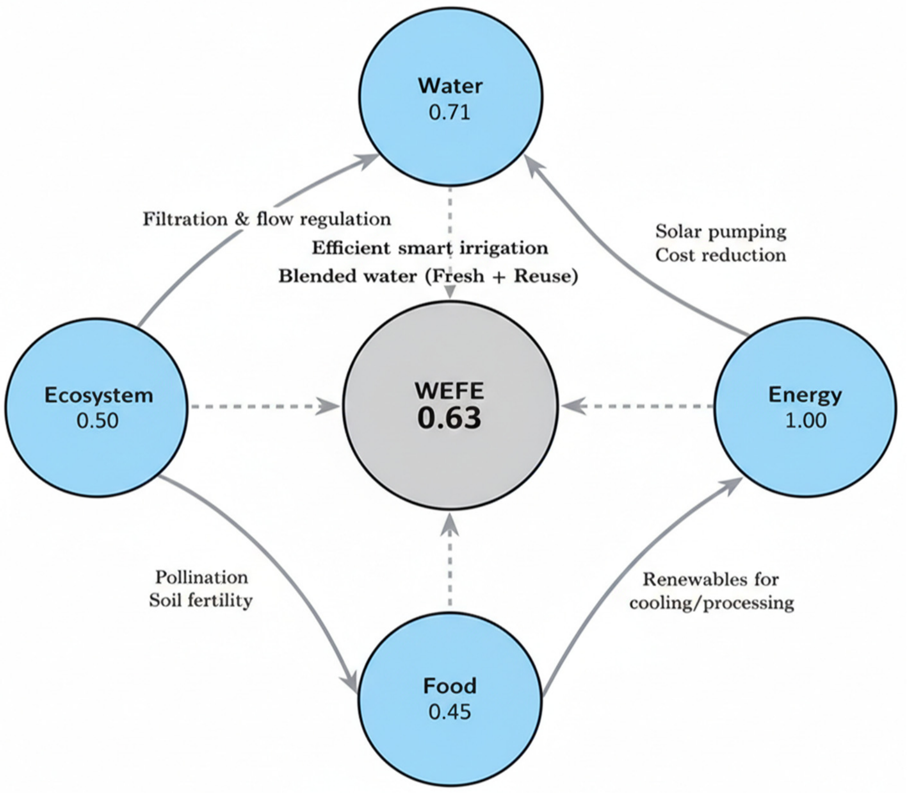

Figure 3. WEFE Nexus Framework for JV.

Sectoral indices were aggregated using equal weights across the four WEFE domains (Water, Energy, Food, and Ecosystems), reflecting their comparable importance in integrated resource sustainability. In addition, an inefficiency correction was applied to the water domain to account for non-revenue water and conveyance losses, resulting in an adjusted

WEFE Index of approximately 0.50. This adjustment highlights the sensitivity of overall nexus performance to operational inefficiencies, particularly within the water system. This adjusted value represents a conservative sensitivity estimate reflecting real operational conditions rather than an independently measured index.

Accounting for 2018–2023 variability, the sector indices are W = 0.71 (95% Confidence Interval (CI): 0.65–0.77), E = 1.00 (CI: 0.98–1.02), and F = 0.45 (CI: 0.40–0.50), giving an integrated WEFE ≈ 0.67 (CI: 0.64–0.69). These confidence intervals indicate that water and food indices have substantial variability year-to-year, whereas energy remains consistently high (Table S3).

3.7. Qualitative Analysis

The semi-structured interviews conducted across the five EcoFuture project living labs (n = 25 stakeholders) provided qualitative insights into the relative importance of WEFE nexus indicators and potential intervention strategies. As shown in Figure 4, stakeholders identified water security as the most critical component affecting sustainability in the Jordan Valley, followed by food security and energy availability, while ecosystem conservation received slightly lower but still significant importance ratings. These perceptions reflect the strong interdependence between water availability, agricultural productivity, and energy requirements for irrigation and water supply in the region. The intervention priorities emerging from the living lab discussions (Figure 5) further support these findings. Water harvesting, storage systems, renewable energy integration, and smart irrigation technologies received the highest levels of stakeholder support, highlighting the need to improve water-use efficiency and reduce energy costs associated with agricultural water management. Treated wastewater reuse and soil management practices such as composting were also recognized as important measures to enhance resource efficiency and soil fertility. In addition, stakeholders emphasized the relevance of ecosystem restoration and improved governance coordination as complementary strategies for maintaining long-term environmental sustainability and strengthening the resilience of the WEFE nexus in the Jordan Valley.

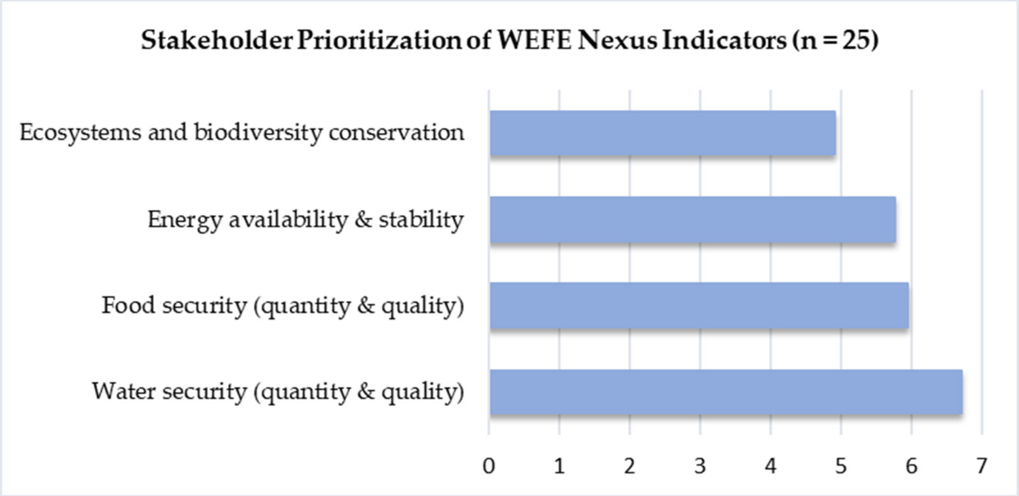

Figure 4. Stakeholder prioritization of WEFE indicators derived from semi-structured interviews conducted in five living labs of the EcoFuture project (n = 25 participants).

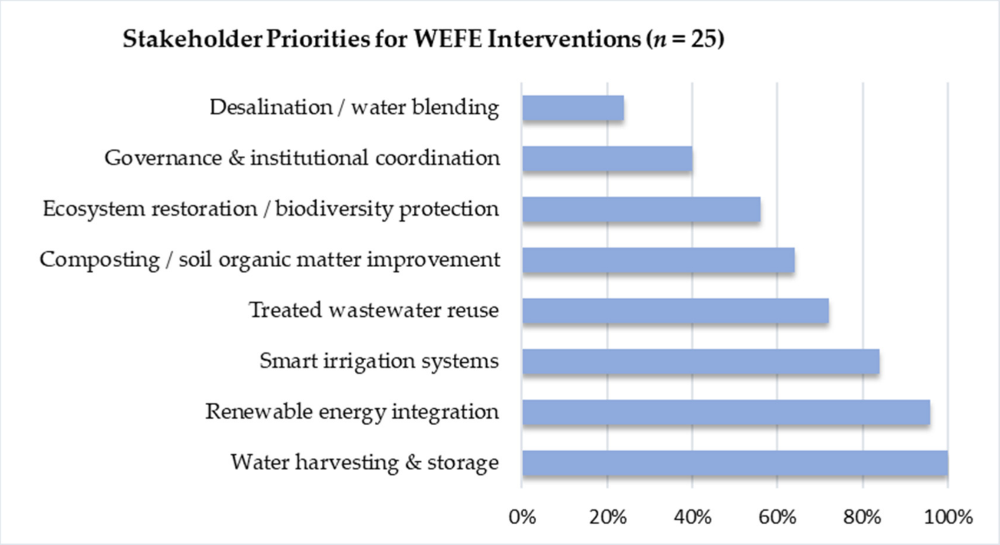

Figure 5. Stakeholder prioritization of WEFE nexus interventions based on semi-structured interviews conducted during the EcoFuture living labs (n = 25 participants).

3.8. Sensitivity Analysis

The sensitivity analysis results highlight how variations in key parameters influence the WEFE nexus index. The detailed results are presented in Supplementary Table S4, which reports the variation of the WEFE index under ±10% changes in each parameter. The results show that the WEFE index responds differently to perturbations across the four nexus components. Among all parameters, energy supply (S_en) and biodiversity loss (L_bio) exhibit the highest sensitivity. A ±10% increase in energy supply leads to an increase of approximately +0.025 in the WEFE index, while a similar change in biodiversity loss results in a decrease of approximately −0.025, indicating that both energy availability and ecosystem conditions strongly affect the overall WEFE performance. Water-related parameters also demonstrate relatively high sensitivity, particularly for domestic water supply (S_dom) and domestic water demand (D_dom). Changes in domestic water supply increase the WEFE index by approximately +0.023, while increased domestic water demand reduces the index by approximately −0.022. Agricultural water supply and demand show moderate effects (±0.013), while the parameter α controlling the water index results in a variation of approximately +0.02 in the WEFE index (Table S4).

Food-related parameters exhibit comparatively smaller effects on the WEFE index. Variations in actual and potential yields of greenhouse vegetables, summer vegetables, and citrus produce changes ranging between ±0.004 and ±0.011, indicating that short-term changes in crop productivity have a relatively limited impact on the aggregated WEFE index. To illustrate the sectoral influence, Figure 6 presents the average absolute sensitivity of the WEFE components. The figure shows that the energy and ecosystem components have the strongest average influence on the WEFE index, followed by the water component, while the food component exhibits the lowest sensitivity.

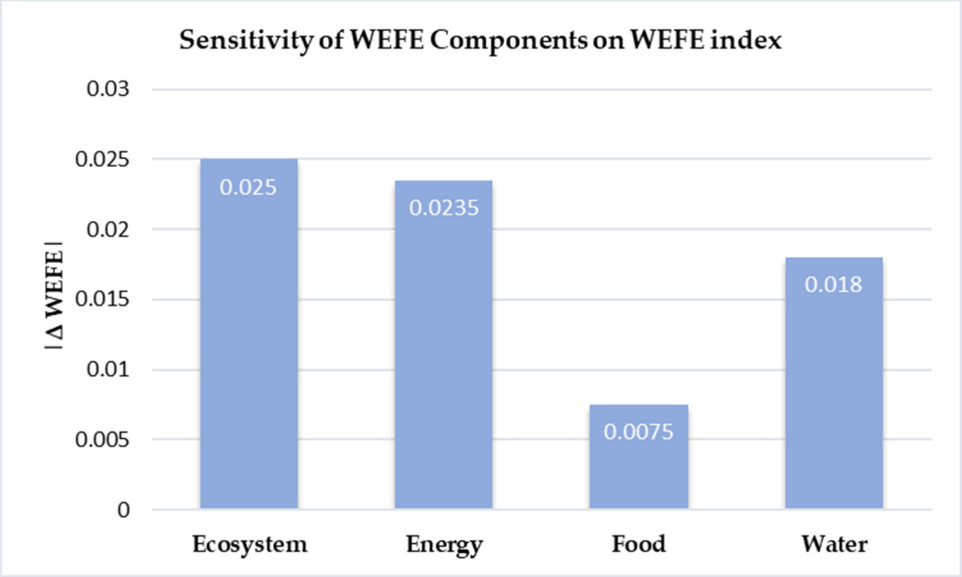

Figure 6. Average absolute sensitivity of the WEFE components on the WEFE index.

4. Discussion

The integrated assessment of the Jordan Valley highlights water scarcity as the dominant constraint shaping overall WEFE system performance. The Water Index score of 0.71 reflects a substantial mismatch between irrigation water supply and demand, consistent with national assessments reporting chronic deficits and declining freshwater availability in arid regions such as Jordan [27,41]. Agricultural water demand in the valley is nearly double the available supply, while water-quality challenges, particularly elevated salinity and nitrate concentrations, further reduce the effective usability of irrigation resources [40]. Together, these results indicate that water scarcity in the Jordan Valley is not solely a volumetric issue, but a compound constraint driven by interacting quantity and quality limitations, reinforcing its role as the primary bottleneck to sustainable resource management and agricultural productivity [41].

The strong performance of the energy sector, reflected in an Energy Index of 1.00, demonstrates the potential of renewable energy, particularly solar power, to function as an enabling factor within the WEFE nexus. Although electricity supply slightly exceeds demand, the increasing integration of solar pumping is especially significant given that water pumping and distribution account for approximately 14% of Jordan's total electricity consumption [42]. The results indicate that energy availability itself is not a limiting factor; rather, its strategic importance lies in reducing operational costs and the vulnerability of water service provision. The documented expansion of solar-powered irrigation systems [41,43] aligns with this finding, as the integration of renewable energy enhances the resilience of water services. Nevertheless, energy-related gains cannot be fully realized unless water governance, allocation efficiency, and loss reduction are addressed concurrently [43]. Integrating renewable energy into hydraulic infrastructure can improve both energy efficiency and water system performance. Recent work demonstrates that pressure-regulating turbines and micro-hydropower units can recover otherwise wasted hydraulic head in water distribution networks and convert it into usable electricity, with growing evidence of technical feasibility and positive techno-economic returns when properly sited [44–47].

In the context of the Jordan Valley, where irrigation pumping is energy-intensive and pressure zones vary sharply due to terrain, introducing solar-powered pumping alongside micro-hydropower energy recovery at pressure-reducing points could reduce operational costs, offset grid electricity consumption, and contribute to long-term sustainability. Such a hybrid approach aligns with regional solar resource availability and would allow water utilities to modernize irrigation conveyance while recovering energy that is currently dissipated as pressure loss [44–47].

In contrast, the Food Index (0.45) represents the weakest performance among the four domains, underscoring substantial yield gaps across major crop systems. Actual yields for vegetables and citrus remain well below attainable levels, reflecting the combined pressures of limited water availability, soil degradation, and heat-induced evapotranspiration [48,49]. Qualitative insights from the Living Lab process help explain this low performance, as farmers reported deliberately reducing irrigation during peak summer periods to cope with water scarcity and rising energy costs, often accompanied by shifts toward more salt-tolerant crops. While these strategies are rational short-term adaptations, they directly contribute to persistent yield gaps and reinforce the low Food Index values, highlighting the importance of addressing economic, institutional, and behavioral drivers alongside biophysical constraints [27].

The ecosystem domain, with an Ecosystem Index of 0.50, reflects moderately to severely degraded ecological conditions that directly affect water quality, soil fertility, and agricultural stability. This finding is consistent with documented habitat loss, biodiversity decline, and the drastic reduction in Jordan River flows, from historical levels of approximately 1300 MCM yr^{-1} to less than 50 MCM yr^{-1} today [40]. Soil salinization remains widespread, affecting an estimated 60–70% of cultivated land, in line with reported patterns of land degradation driven by BTWW in irrigation, insufficient drainage, and increasing aridity [48]. Living Lab discussions further indicated that ecosystem degradation is perceived by stakeholders not only as an environmental concern, but also as a factor increasing pest pressure, production costs, and vulnerability to climate variability, thereby directly linking ecosystem decline to food and water system performance [27].

Taken together, the WEFE indices show that water scarcity (W = 0.71) represents a combined quantity–quality constraint dominated by irrigation deficits; energy adequacy (E = 1.00) primarily serves as an enabling condition that reduces operational vulnerability rather than a limiting factor; low food-system performance (F = 0.45) is largely driven by farmer coping behaviors under water and energy stress that translate into persistent yield gaps; and degraded ecosystem conditions (Eco = 0.50) weaken regulating services essential for sustaining both water quality and agricultural productivity.

The aggregated WEFE Nexus Index of 0.63 indicates that the Jordan Valley currently achieves only about two-thirds of its integrated WEFE potential. When major operational inefficiencies, particularly water distribution losses of approximately 50%, are considered, adjusted performance declines to around 0.50, underscoring the sensitivity of overall nexus sustainability to infrastructure efficiency and governance effectiveness. This finding aligns with strategic WEFE planning studies identifying improvements in water-use efficiency, treated wastewater reuse, and renewable energy integration as key leverage points for enhancing system performance [48,49].

The sensitivity analysis provides insights into the relative importance of different sectors in shaping the overall WEFE nexus performance in the Jordan Valley. The strong influence of energy-related parameters reflects the critical role of energy in supporting water and agricultural systems. Energy availability directly affects water pumping, desalination, irrigation systems, and agricultural operations, meaning that changes in energy supply or demand can propagate across multiple sectors within the nexus. Consequently, improvements in energy availability or efficiency can significantly enhance the overall WEFE performance. The high sensitivity observed for the ecosystem component, represented by biodiversity loss, highlights the importance of maintaining ecosystem health for sustaining the WEFE nexus. Ecosystem degradation can reduce soil quality, affect water quality, and ultimately impact agricultural productivity. The severe water scarcity conditions in the Jordan Valley are reflected in the WEFE index when small changes in water availability or demand can significantly influence the system balance. In contrast, food-related parameters show relatively lower sensitivity in the aggregated index. This implies that the variations in crop yields are partly mediated by other sectors, particularly water and energy availability. Improvements in irrigation efficiency, water management, and ecosystem conditions can therefore indirectly enhance food productivity within the nexus framework.

Overall, the results demonstrate that single-sector interventions, such as expanding irrigation infrastructure or increasing electricity supply in isolation, are insufficient to address the systemic constraints facing the Jordan Valley. Instead, the findings support a shift toward integrated WEFE-based planning, in which cross-sector coordination, participatory mechanisms such as Living Labs, and shared data platforms enable adaptive and system-wide optimization [27,39]. Prioritizing interventions such as water harvesting, solar-powered water services, upgraded wastewater reuse with improved blending strategies, regenerative soil management, and riparian ecosystem restoration is likely to generate the greatest cross-sector benefits. These integrated measures offer a robust pathway for strengthening climate resilience, improving resource-use efficiency, and supporting long-term sustainability in the Jordan Valley.

Comparable WEFE challenges are reported in other arid regions, including energy-intensive desalination and food-import dependence in Gulf countries (e.g., Saudi Arabia, UAE, Kuwait, Qatar), unsustainable fossil groundwater–energy–food linkages in Saudi Arabia, and technology-enabled but institutionally constrained WEFE interventions in dryland North Africa (e.g., southern Tunisia), all of which limit the operationalization of WEFE harmony under climate stress [50,51]. Building on these findings, the study identifies several priority areas for integrated sustainability interventions: (1) enhancing water-use efficiency and augmenting supply through conservation, groundwater recharge and wastewater reuse; (2) expanding safe wastewater recycling and desalination powered by renewable energy; (3) deploying renewable-powered water services including solar pumping and micro-hydropower; (4) promoting climate-smart and controlled-environment agriculture to close yield gaps; (5) investing in ecosystem restoration and nature-based solutions to improve soil health and biodiversity; and (6) strengthening integrated governance, data sharing and cross-sector coordination. The WEFE framework also underscores the importance of inter-linkages between pairs or triples of domains. For example, improvements in water and energy (WE) can jointly enable more reliable irrigation and reduce pumping costs; however, without parallel improvements in food productivity and ecosystem health (F and Eco), such gains may not translate into sustainable agricultural outputs. Conversely, enhancing food production in isolation may exacerbate ecosystem degradation and further strain water resources. These interactions highlight that integrated strategies, rather than single-domain optimization, are essential for sustainable outcomes, and the WEFE Index provides a structured means to explore these multi-dimensional trade-offs and synergies.

5. Conclusions

This study contributes a comprehensive and up-to-date WEFE assessment for the Jordan Valley, combining empirical indices with stakeholder insights to identify priority interventions. While the Jordan Valley shares characteristics with many arid regions, its specific institutional, hydrological and socio-economic context means that findings should be applied cautiously elsewhere. Nevertheless, the mixed-methods approach and nexus framework provide a transferable template for integrated resource assessment in similar settings. The findings of this study demonstrate that the sustainability of the Jordan Valley depends on the effective management of the tightly interconnected water, energy, food, and ecosystem systems. Chronic water scarcity, high-energy requirements, and extensive ecosystem degradation have created a fragile equilibrium in which interventions in one sector inevitably generate impacts across the others. The results show that integrating renewable energy into water and agricultural systems, expanding the safe reuse of treated wastewater, adopting water harvesting with climate-smart agricultural technologies, and restoring degraded ecosystems can generate synergistic benefits across the WEFE nexus. However, realizing these gains requires coordinated governance frameworks, cross-sector data sharing, and meaningful stakeholder participation to avoid fragmented policies that may exacerbate existing resource stresses. The Jordan Valley thus exemplifies the urgent need for a nexus-based management approach in arid and water-scarce regions, one that balances economic development objectives with environmental stewardship to enhance long-term water, food, and energy security. A key limitation of this assessment is the limited availability of consistent, high-resolution data and the absence of an integrated cross-sector data platform. Water, energy, agricultural, and environmental datasets remain fragmented across institutions, necessitating reliance on secondary sources and aggregated indicators, which constrained the precision of the optimization analysis. This limitation underscores the need for coordinated data collection efforts and shared digital platforms to enable more robust WEFE modelling and evidence-based planning in the future.

6. Future Directions

Building on the integrated WEFE assessment presented in this study and the stakeholder insights generated through the Living Lab process, future research should focus on advancing the WEFE framework toward a more comprehensive and operational decision-support tool for the Jordan Valley. This can be achieved through several complementary directions: (1) progressively incorporating all indicators recommended in Table 1—particularly those identified through stakeholder consultations—into future WEFE index development and WEFE knowledge or decision-support platforms, enabling a more comprehensive representation of water, energy, food, ecosystem, and governance interactions; (2) establishing integrated cross-sector data systems and long-term monitoring platforms linking water, energy, agriculture, and environmental datasets to improve data availability, consistency, and interoperability across institutions; and (3) applying the expanded indicator framework within scenario-based WEFE modelling to evaluate climate adaptation strategies, assess the impacts of integrated interventions, and strengthen the WEFE index as a practical policy and planning tool for adaptive and climate-resilient resource management in the Jordan Valley.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18073173/s1, Table S1: Demographic distribution of Living Lab stakeholders, including role/sector, number of participants, and sub-region representation in the Jordan Valley. Table S2: Sensitivity analysis of the water index and WEFE index under different values of α. Table S3: Uncertainty analysis of sectoral and overall WEFE indices, including 95% confidence intervals, annual trends, net change, direction of change, and p-values for the 2018–2023 assessment period. Table S4: Sensitivity analysis for WEFE nexus components, showing the effect of ±10% variation in key parameters on the WEFE index. Table S5: Consolidated Living Lab questions and analysis, including indicators, descriptions, sample questions, key findings from the five Living Labs, participant ratings, and notes from the qualitative assessment process.

Author Contributions: Conceptualization and methodology, L.H.; validation, A.A. (Abeer Albalawneh) and N.N.; investigation, L.H. and S.A.; resources, R.A.-R.; data curation, M.A.L.; writing—original draft preparation, M.a.N.; writing—review and editing, A.A. (Abeer Albalawneh); visualization, N.N.;

supervision, A.A. (Ahmad Alwan) and N.N.; project administration, A.A. (Ahmad Alwan) and N.N.; funding acquisition, N.N. All authors have read and agreed to the published version of the manuscript.

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