From Concept to Practice: Operationalizing the WEFE Nexus through a Low-Cost Solar-Powered Hydroponic System

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***Abstract*—Given the growing demand for food, limited natural resources, shrinking arable land, and rising energy costs, sustainable agricultural solutions are urgently needed. The Water-Energy-Food-Ecosystems (WEFE) Nexus provides an integrated framework for addressing these interconnected challenges by promoting synergies and minimizing trade-offs among sectors. This paper presents a community-led, solar-powered hydroponic system implemented in Wadi Al Wala, Jordan, as a practical and scalable example of the WEFE Nexus in action. The system was evaluated against soil-based agriculture across three cultivation cycles, focusing on water use, crop yield, land efficiency, and environmental performance. The ecological assessment used carbon dioxide emissions (kg CO_2 equivalent) as a key indicator to evaluate the system's sustainability. Findings showed that the hydroponic system reduced water consumption by 24.8–37.9% and boosted crop yields by 30.4–106.6% compared to traditional agriculture. Furthermore, solar-powered hydroponics significantly lowered carbon emissions by 66.7 kg and 13.2 kg CO_2 eq. and presented a benefit/cost ratio of 6.3 and 1.7 compared to diesel-powered and grid-powered hydroponic systems, respectively. The performance metrics and cost-benefit indicators observed over the three cultivation cycles validate the environmental and resource-efficiency benefits of integrating renewable energy into innovative agricultural practices. Four hydroponic upscaling scenarios were developed using the REWEFE decision-support tool, demonstrating that hydroponic greenhouses are practical WEFE Nexus models that conserve resources, enhance productivity, and support environmental sustainability. However, a rebound effect was observed in the form of increased energy demand, underscoring the need for further expansion of solar energy integration to ensure long-term resilience and sustainability.**

***Keywords*—WEFE Nexus, hydroponics, sustainability, resources management, traditional framing, Photovoltaic (PV) powered systems**

I. Introduction

The growing pressure on natural resources, driven by rapid population growth and rising per capita consumption, is further intensified by the impacts of climate change [1, 2]. By 2050, global demand for water, food, and energy is projected to rise significantly, making isolated, sector-specific solutions increasingly ineffective [3–5]. Addressing these interconnected challenges requires integrated frameworks that recognize and manage resource interdependencies [6]. The Water-Energy-Food-Ecosystem (WEFE) Nexus offers a comprehensive and systematic approach to address these complex interconnections. It provides a foundation for designing cross-sectoral strategies that promote sustainability, efficiency, and resilience [7]. The nexus framework facilitates the management of resource trade-offs, mitigation of conflicts, and maximization of synergies among sectors, thereby contributing to economic development, environmental protection, including Greenhouse Gas (GHG) emissions reduction, and social well-being [8, 9]. Despite extensive academic focus on the theoretical underpinnings of the Nexus concept, practical tools to support its implementation in governance and operations remain limited [10–12]. Successful implementation necessitates empirical evidence, robust analytical tools [13], identification of contextual challenges, and participatory stakeholder engagement. These challenges must be translated into measurable Nexus indicators, allowing for performance evaluation under various replication and upscaling scenarios. As such, there is a critical need for demonstrative Nexus interventions that serve as operational models, offering evidence-based solutions and pathways for effective cross-sectoral integration. This paper aims to bridge this gap by developing and evaluating context-specific, innovative technological solutions that operationalize the WEFE Nexus in real-world settings and by the local community. Unlike previous studies that primarily conceptualize the Nexus framework, this research demonstrates its practical application through the design, implementation, and assessment of a community-led, solar-powered hydroponic system in Wadi Al Wala, Jordan. By comparing its performance with traditional soil-based agriculture over three cultivation cycles, the study provides empirical evidence of resource efficiency, environmental benefits, and economic feasibility, thereby offering actionable pathways for scaling and replication.

At the core of the Nexus in Jordan lies the issue of food security, driven by the needs of a growing population and closely tied to sustainable agriculture and farmers' economic viability. Water scarcity remains a pressing issue in Jordan, exacerbated by declining precipitation, prolonged droughts, and increasing competition among sectors. Concurrently, high energy costs present a significant barrier to sustainable resource use. Climate change intensifies these interlinked challenges, threatening the resilience of both food and water systems. In this context, the research establishes a model built upon three key pillars. The first involves identifying sectoral challenges within the study area through a participatory stakeholder approach, which offers a comprehensive view of the interconnections and dynamics within the WEFE Nexus. The second pillar focuses on selecting context-specific technologies capable of addressing these interlinked challenges in an integrated manner. The third pillar entails evaluating the performance of the selected technology using predefined WEFE Nexus indicators. The solar-powered hydroponic system was selected as a promising technology to promote cross-sectoral synergies, minimize trade-offs, and deliver tangible socio-economic and environmental benefits for this specific region in Jordan. The demonstration site in Jordan is among the first closed-loop hydroponic systems developed for productive, non-experimental use in the country. Key innovations include smart agricultural technologies to improve water efficiency and yields, the use of locally sourced volcanic tuff as a substrate, and the social integration of hydroponics through a cooperative of unemployed agricultural engineers, about 50% of whom are women. System performance was evaluated across three cultivation cycles using predefined WEFE Nexus indicators, including water savings, crop productivity, land-use efficiency, CO_2 footprint, and benefit/cost ratio. Potential upscaling scenarios were then assessed with the REWEFE tool to examine replicability and broader impacts. Both the hydroponic technology and the REWEFE tool are well-suited for water-scarce, climate-vulnerable, and economically disadvantaged regions similar to Jordan.

II. Literature Review

The WEFE Nexus Framework supports the development of context-specific Nexus Bridging Plans (NBPs), tailored to various innovative technologies and their combinations such as solar-powered water reuse, agrivoltaics, and solar irrigation. It integrates diverse methodologies in a context-sensitive manner and fosters transdisciplinary collaboration, enabling the integration of Nexus modelling tools, practical implementation, and transformative knowledge beyond traditional disciplinary boundaries. Currently, decision-makers face a lack of comprehensive tools that effectively support the evaluation of various resource allocation strategies and the understanding of trade-offs across interconnected sectors. While several tools have been developed to address specific components of the WEFE Nexus, they often operate in isolation. Examples include Water Evaluation and Planning System (WEAP), an integrated tool for water resource planning [14], LEAP (Long-range Energy Alternatives Planning System), A tool designed for energy policy analysis and climate change mitigation assessment [15]. MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), A framework that characterizes metabolic flows across different societal and ecosystem levels [16]. Despite their strengths, these tools individually offer only partial insights, underscoring the need for more integrated and holistic approaches to support nexus-related decision-making. Climate, Land, Energy and Water Strategies (CLEWS) is an integrated system modeling tool aimed at analyzing interlinkages among climate, land use, energy, and water sectors [17]. Daher and Mohtar (2015) and Shehadeh *et al.* (2024) [13, 18] presented comprehensive WEFE Nexus modelling tools which offer a common platform for scientists and policy makers to put the Nexus into practice and identify sustainable national resource allocation strategies. Additionally, Shehadeh *et al.* [19] proposed an innovative framework aimed at enhancing resilient infrastructure management during periods of climate change. Therefore, the practical implementation of the Nexus approach requires the incorporation of modeling tools that analyze the interlinkages across the Nexus components to provide evidence to potential users and stakeholders of its contribution to the sustainability of agri-food systems, the preservation of ecosystems, and the creation of business opportunities.

The Nexus sectoral challenges in Jordan are quite complex. The agricultural sector in Jordan is the largest consumer of the country's freshwater resources, accounting for approximately 50% of total water use. This substantial demand places significant pressure on already limited water supplies and contributes to the country's growing water scarcity [20]. Therefore, food production in Jordan, which relies heavily on both water availability and affordable energy for water pumping, has become insecure. This dependence is exacerbated by Jordan's significant reliance on energy imports, amounting to over 93% since 2018 [21]. Moreover, climate change is worsening water scarcity, making it increasingly difficult to sustain resilient food and water systems. Altered rainfall patterns, rising temperatures, and extreme weather events are reducing water availability and straining agriculture and supply networks.

According to the UN's *Water and Climate Change* report (2020) [22], a significant share of greenhouse gas emissions in water management comes from the energy used in extracting, distributing, and treating water and wastewater. These energy-intensive processes contribute to climate change, creating a cycle that further stresses water resources. Enhancing energy efficiency and adopting low-carbon technologies in water systems is crucial to breaking this cycle and building climate resilience. Thus. the WEFE nexus approach could offer a comprehensive solution to Jordan's complex challenges by dismantling traditional sectoral boundaries and promoting integrated resource management [13]. However, despite the growing reference to the WEFE nexus in the literature for integrated resources management, a universally accepted framework for its definition and operationalization has yet to be established [23]. In this study, the paper introduces a comprehensive operational model for the Nexus framework, tailored to address specific sectoral requirements. This model incorporates the REWEFE (Rapid Evaluation of Water, Energy, Food, and Ecosystems) tool developed by Future Water, offering a detailed assessment of the WEFE nexus within a designated regional context (the nexus unit). This tool enables the implementers to assess different upscaling scenarios with associated future sectoral trends, better understand the interactions among water, energy, food, and ecosystem components, and evaluate the performance of the selected technology. Hydroponics have recently gained great attention as a sustainable agricultural alternative to conventional soil-based farming, particularly in water-scarce regions [24–26]. Hydroponic systems offer several well-documented advantages, including reduced fertilizer use, more efficient land utilization, improved water efficiency [26], and higher crop yields. These benefits highlight the potential of hydroponic interventions to simultaneously address multiple sectoral challenges, such as water scarcity, food security, and ecosystem health, which are further exacerbated by the impacts of climate change [27]. Solar energy, an abundant resource in Jordan, can fulfill the energy requirements of the hydroponic system [28] and minimize the CO_2 footprints of the hydroponic intervention. Thus, Solar-powered hydroponic systems offer greater sustainability and economic efficiency compared to hydroponic systems powered by fuel or the grid [29].

III. Materials and Methods

A. Hydroponic Implementation Area

Hydroponic greenhouses were established in Dhiban district/Madaba governorate in Wadi Al Wala area, part of the Wadi Mujib Basin located in central Jordan. The Wadi Mujib is one of the major basins in Jordan with two sub-catchment areas, Mujib and Wala. The basin spans approximately 6727km², with elevations ranging from 1,030m above sea level to 160m below. The climate in the Al Mujib basin varies from semi-arid in the upper basin mountains with an annual precipitation of 350 mm to the arid regions in its lower part at the Dead Sea shore with an annual rainfall average of 70mm for the last decade [29] (Fig. 1), with a significant decline observed over the past 30 years. Two key dams—Mujib Dam and Walah Dam—have been constructed in the basin.

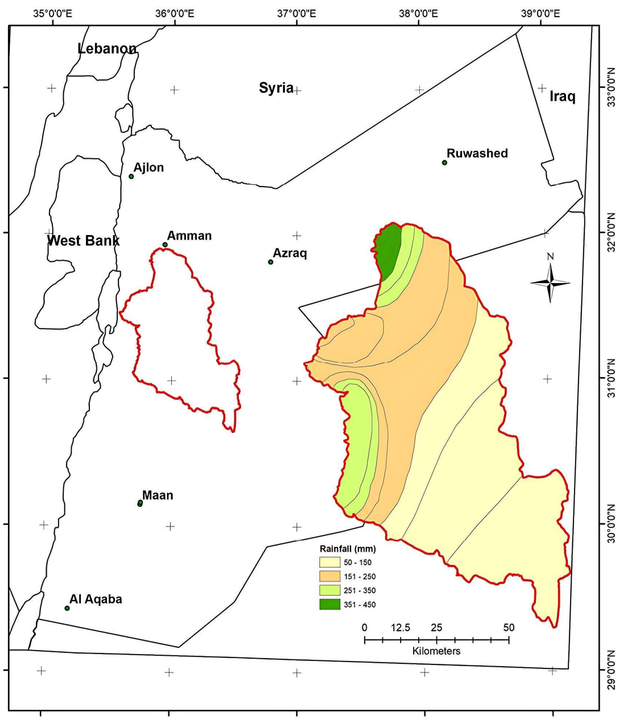


Fig. 1. Wadi Mujib Basin rainfall distribution.

The Mujib Dam has a storage capacity of 30 MCM [30], capturing both flood waters and base flow, while the Walah Dam's capacity was increased from 8 MCM to approximately 25 MCM following the elevation of its structure. These reservoirs are used for artificial groundwater recharge and to support irrigated agriculture downstream.

B. Methodology Framework

The flowchart (Fig. 2) outlines the methodology framework followed in this study. It begins with identifying sectoral challenges and interconnections through stakeholder consultations (Step 1), followed by selecting and designing a solar-powered hydroponic system tailored to local conditions (Step 2). Three cultivation cycles were conducted with continuous monitoring of key parameters (Step 3). Performance was then assessed using predefined WEFE indicators (Step 4), and upscaling scenarios were analyzed using the REWEFE tool (Step 5). Finally, a cost-benefit analysis was conducted to evaluate the economic feasibility compared to alternative energy sources (Step 6).

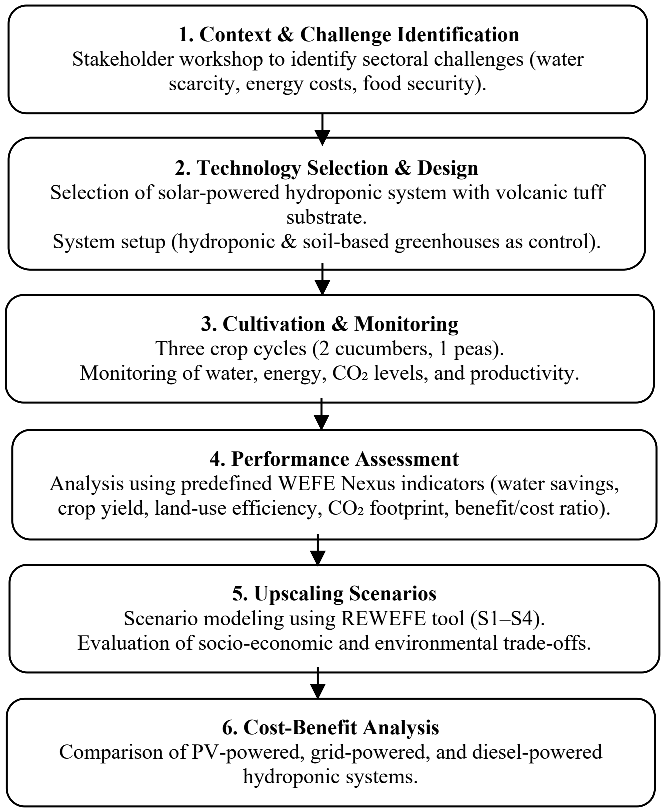


Fig. 2. Methodology framework.

C. Nexus Challenges in Wadi Al Wala

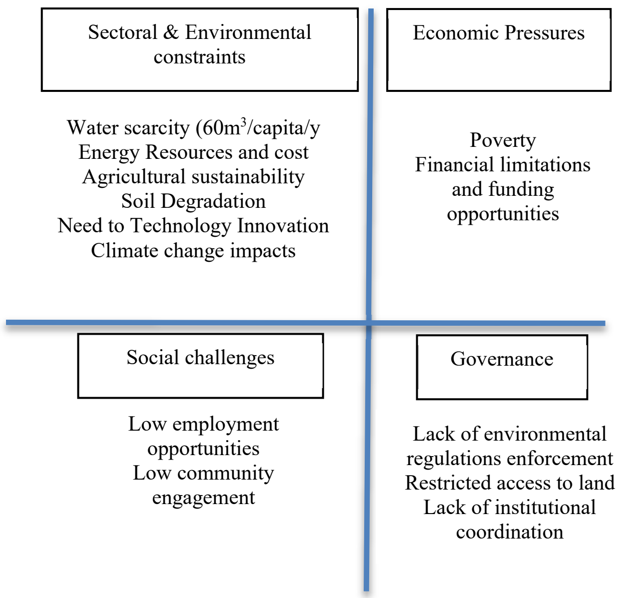


Fig. 3. Nexus challenges in Wadi Al Wala area.

Wadi Al Wala is subject to multiple socio-economic and environmental pressures. Fig. 3 outlines the key sectoral challenges, such as water scarcity, land degradation, agricultural decline, and shifting livelihoods, identified through four stakeholder consultation workshops and interviews with 21 local farming community members.

These issues are deeply interconnected, with cascading impacts that warrant further investigation. The complex interdependencies and feedback loops will be explored in more detail in the forthcoming *WEFE Framework 2.0 Handbook* (BONEX Project, unpublished report).

D. The Design of the Experimental Pilot

The experimental pilot is represented by the schematic diagram in Fig. 4. It comprises two agricultural systems. System 1 consists of two hydroponic plastic greenhouses (each measuring 46.5m×9m, with a total area of 418.5m²), powered by a solar Photovoltaic (PV) system. System 2 serves as the control and includes two traditional soil-based greenhouses with the same area (Fig. 5). Each greenhouse comprises 6 crop rows. The hydroponic system utilizes solar-powered drip irrigation with a soilless growing medium, volcanic tuff, which is locally sourced. The PV system used to run the drip irrigation is off-grid and produces an energy surplus of 1 kW/day. The solar panels used in this solar power generation system consist of 8 modules and have a capacity to produce 4 kW/day with dimensions of 230cm×115cm×5cm. The system has a PV rated power of 550 Watts and is equipped with an inverter of 10 kW. Water for irrigation is collected from the Al Wala valley stream, originating from upstream springs. It is filtered and recirculated in a closed-loop system within the hydroponic units. Fertilizers are delivered through a self-regulating fertigation system that automatically adjusts dosing based on the pH and Electrical Conductivity (EC) readings. The fertigation unit mixes the drainage water with the nutrient fresh solution to achieve the needed pH and EC.

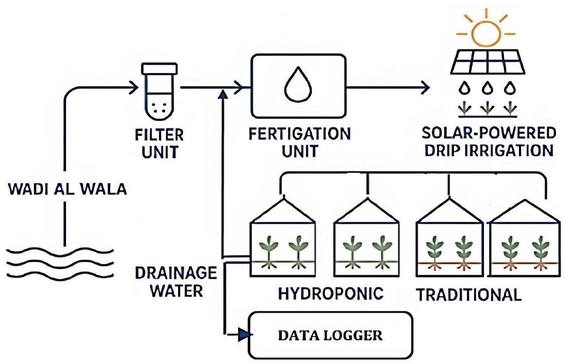
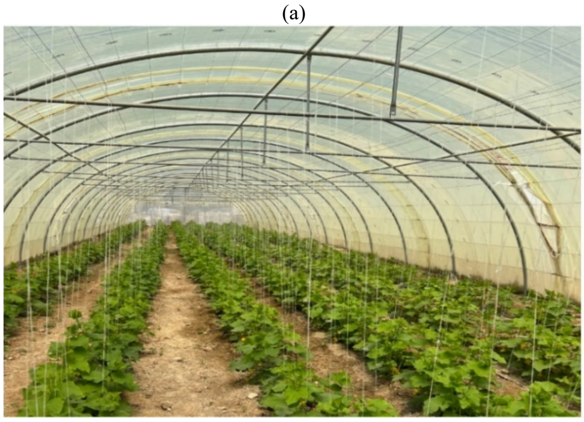


Fig. 4. Schematic diagram of the experimental pilot.

The pH and EC values were maintained at a range of (5.8–6.5)±0.1 and (1300 to 2900µS/cm)±3% respectively. The greenhouses are not supported by a control system for lighting, temperature, or Humidity as it is supposed to be a low-cost setup and running under environmental conditions comparable to soil-based ones. The four greenhouses were cultivated over three crop cycles, which included two cycles of cucumbers (one of them is during the hot summer) and one cycle of peas, in different months of the year. Additionally, the following parameters were monitored during the plantation cycle inside the hydroponic system: CO_2 emission (±50 ppm), temperature (±0.5 °C), Relative Humidity RH (±3%), and light (±200 LUX) using a monitoring system. Fig. 6 shows the environmental conditions (RH and Temperature) inside the hydroponic greenhouses during the cultivation phase of both crops.

(a)



(b)

Fig. 5. The experimental pilot in Wadi Al Wala (a) Hydroponics greenhouse (b) Traditional soil-based greenhouses.

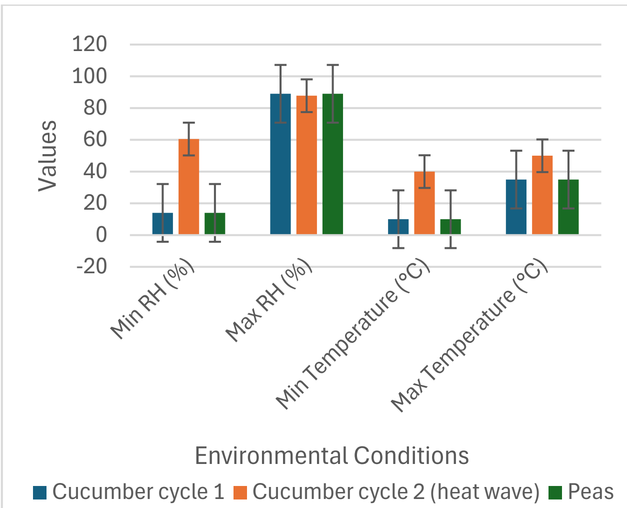


Fig. 6. Environmental conditions inside the hydroponic greenhouses during the cultivation phase of both crops (The data are the mean of standard error ± SE (n = 2)).

Fig. 7 shows the irrigation schedule across the different crops and for the hydroponic and soil-based systems.

Cucumbers and peas were chosen because of their local agricultural relevance and nutritional value. Both crops are widely consumed in Jordan and represent common greenhouse-grown vegetables, making them ideal for testing a system intended for local replication. Cucumbers are water-demanding crops, thus providing a robust benchmark for evaluating water-use efficiency in hydroponic systems compared to traditional soil-based farming. Peas, on the other hand, are leguminous plants that require different nutrient balances (notably nitrogen) and offer a complementary perspective on the adaptability of the hydroponic system to crops with varying nutrient requirements. Testing both crops ensured that the hydroponic system's performance could be assessed under diverse agronomic conditions and resource demands, providing stronger evidence of its versatility and scalability.

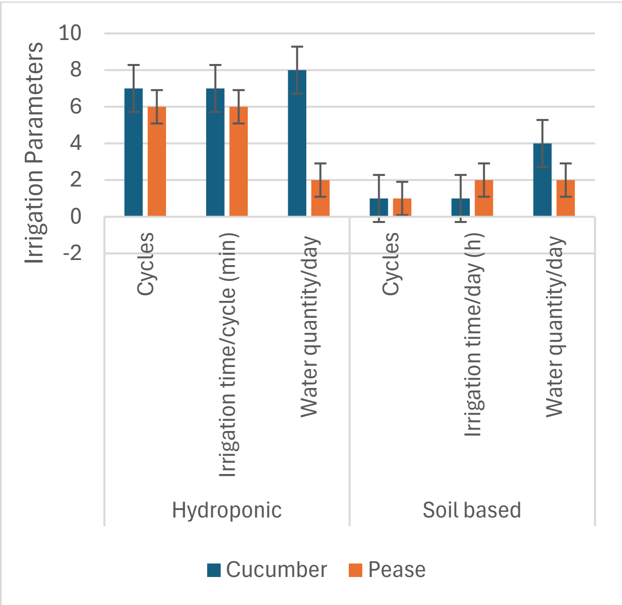


Fig. 7. Irrigation schedule across the different crops and for the hydroponic and soil-based system (The data are the mean of standard error ± SE ($n = 2$)).

E. Performance Indicators

The hydroponic system was implemented in two identical greenhouses operating under the same environmental and operational conditions, and the same approach was applied to the two soil-based greenhouses. Each crop cycle (two for cucumbers and one for peas) was conducted simultaneously across these paired systems to ensure consistency. Performance indicators were collected separately for each greenhouse and then averaged per crop type and cultivation cycle. Therefore, all reported values represent the mean performance across the replicated greenhouses rather than data from a single run.

1) Water consumption

Water consumption and water use efficiency are key indicators for evaluating the sustainability of agricultural practices. In this study, water consumption is measured in liters of water used per kilogram of crop produced (L/kg). The reported water quantity represents the total volume applied throughout the entire irrigation schedule for each crop cycle. The water consumption was compared to hydroponic soil-based greenhouses, and water saving was calculated.

2) Crop yield and land use efficiency

Land use efficiency was measured as the crop yield per unit cultivated area (kg/m²) with an accuracy measurement of ±2%, which is a standard metric for comparing agricultural productivity across different farming systems. This unit was chosen because it directly reflects the capacity of the hydroponic and soil-based systems to produce crops within the same available land footprint, which is particularly important in regions like Jordan, where arable land is limited.

3) Energy consumption per unit production

The energy consumption (in kWh per ton of crop) required to operate the drip irrigation system was assessed across three distinct energy sources: Diesel, grid electricity, and PV. This evaluation encompassed three cultivation cycles conducted in both traditional and hydroponic greenhouses.

For the solar-powered hydroponic system, energy output from the photovoltaic (PV) panels was monitored using the inverter's built-in energy meter with a measurement accuracy of ±1% to ±2%, which recorded daily energy generation and usage for the drip irrigation and fertigation systems. For the comparative scenarios (diesel- and grid-powered systems), energy consumption was derived theoretically by calculating the equivalent energy requirements for pumping and irrigation, using standard conversion factors: 1 liter of diesel produces 10kWh of energy, with an assumed generator efficiency of 35%. For the grid-powered scenario, energy demand was estimated using 0.13kWh per cubic meter of irrigation water, multiplied by the total water volume used in each crop cycle [31].

4) CO_2 uptake and carbon footprint analysis

This section is divided into two parts. The first part focuses on monitoring CO_2 concentration within hydroponic greenhouses in relation to light intensity, aiming to assess the influence of uncontrolled lighting on CO_2 uptake during crop growth. CO_2 levels (measured in ppm) were continuously recorded throughout the cultivation period using a CO_2 sensor data logger (TOMATIKI). The second part presents a comparative analysis of the carbon footprints associated with hydroponic systems powered by solar energy, diesel fuel, and grid electricity. For the fuel-powered system, secondary data were used assuming a diesel generator efficiency of 35% [32], with 1 liter of diesel producing 10 kWh of energy [33] and emitting 2.7 kg CO_2-equivalent per liter burned [33]. In the case of the grid-powered system, it was assumed that each kilowatt-hour of electricity consumed results in 0.435 kg CO_2-equivalent emissions [34].

The Pearson correlation coefficient (r) between light intensity (LUX) and CO_2 concentration (ppm) was calculated using the time-series data collected from the hydroponic monitoring system. For each cultivation cycle, paired observations of light and CO_2 levels were recorded at consistent time intervals. The correlation was computed using the standard formula:

$$r = \Sigma[(xi - \bar{x})(yi - \bar{y})] \, / \, \sqrt{[\Sigma(xi - \bar{x})^2 \times \Sigma(yi - \bar{y})^2]}$$

where xi and yi represent individual light and CO_2 measurements, and $\bar{x}$ and $\bar{y}$ are their respective means. This approach quantifies the strength and direction of the linear relationship between light availability and CO_2 uptake.

F. Assessment of Hydroponic Upscaling Scenarios Using REWEFE Tool

The REWEFE (Rapid Evaluation of the Water, Energy, Food, and Ecosystem) tool, developed by Future Water, is a user-friendly, Excel-based application designed to provide a comprehensive overview of the WEFE nexus within a defined region (the nexus unit). It offers a standardized methodology applicable across various global contexts, enabling implementers to assess different upscaling scenarios and better understand the interactions among water, energy, food, and ecosystem components. This tool has been used to evaluate the performance of four hydroponic upscaling scenarios. The four scenarios consist of a small hydroponic system (S1), an expanded hydroponic system (2), a small hydroponic system powered by solar energy (S3), an expanded hydroponic system powered by solar energy (S4), and traditional farming is used as the baseline scenario. The input data required by the tool consists of land use, water and energy demands, production figures, and ecosystem monetary values. REWEFE input data were obtained through a combination of primary and secondary sources. Primary data included direct measurements and operational records from the PV-powered hydroponic system (e.g., energy use, water consumption, and crop yield). Secondary data, such as pumping, rainfed and irrigated areas, and fertilizer use (S1), were sourced from peer-reviewed literature, official statistics, and remote sensing platforms like EarthMap, Google Earth Engine, AQUASTAT, and WaPOR. A comprehensive explanation of the methodology and data will be provided in the forthcoming WEFE Framework 2.0 Handbook (BONEX Project, unpublished report). The results reflect the changes in each sector for each scenario.

G. Cost Analysis

The cost analysis of the PV-powered hydroponic system implemented in the study area was carried out in two phases. The first phase assessed the installation costs and included a comparative analysis with other hydroponic systems implemented in different locations and by different stakeholders. The second phase involved a cost-benefit analysis to evaluate the economic feasibility of the PV-powered system in comparison to systems powered by diesel fuel and by the grid. This phase aimed at determining the benefit-to-cost ratio of each energy source. This analysis included cost elements, namely Investment and operation of the PV system and the loss of agricultural land. However, the benefits entailed savings in energy purchasing costs, and a decrease in CO_2 costs through the use of PV panels. PV is assumed to have a functional lifespan of 25 years, regular operation within design parameters without significant degradation beyond the typical performance warranty decline (usually around 0.5 % to 1 % efficiency loss per year). However, the Annual maintenance cost is assumed to be approximately 1–2 % of the initial system capital cost.

A sensitivity analysis was also performed to assess how the energy source and CO_2 valuation affect the benefit-cost (B/C) ratio of the PV system. Two scenarios were considered: a grid-powered system (€0.087/kWh, 0.4 kg CO_2/kWh) and a diesel-powered system (€0.88/L, 2.68 kg CO_2/L). A CO_2 price of €83.2/ton was applied. B/C ratios were calculated under varying energy prices (± 20%) with and without CO_2 valuation to evaluate the system's economic performance under different market and policy conditions.

H. Model Barriers

The applicability of the proposed Nexus operationalization model may be constrained by several barriers identified through stakeholder feedback. Technical barriers include the limited availability of skilled labor and the complexity of long-term, cross-sectoral planning required for integrated systems. Financial barriers center on the high upfront investment needed for infrastructure such as PV systems and controlled agriculture. Institutional barriers involve bureaucratic delays and the absence of a centralized coordination body to oversee implementation across sectors. Social barriers reflect cultural resistance to adopting unfamiliar technologies, which can slow uptake and engagement at the community level. Addressing these challenges is critical to ensure the model's effective and sustainable deployment. The mitigation of these barriers can be supported through the implementation of recommendations outlined in the National Green Growth Plan for Jordan [35] and the National Water Strategy 2023–2024 [20], both of which emphasize the importance of institutionalizing the Water-Energy-Food-Ecosystems (WEFE) Nexus. On the financial front, while the high upfront costs of photovoltaic (PV) systems pose a significant barrier—particularly for smallholder farmers Jordan Energy Strategy for 2020–2030 [21] provides a framework for targeted subsidies and incentives aimed at promoting renewable energy adoption in the agricultural sector, thereby helping to reduce these financial constraints.

IV. Results and Discussion

A. Performance Evaluation of Hydroponic Versus Soil-Based Farming Systems

1) Water use efficiency, crop yield, land use efficiency, and energy efficiency

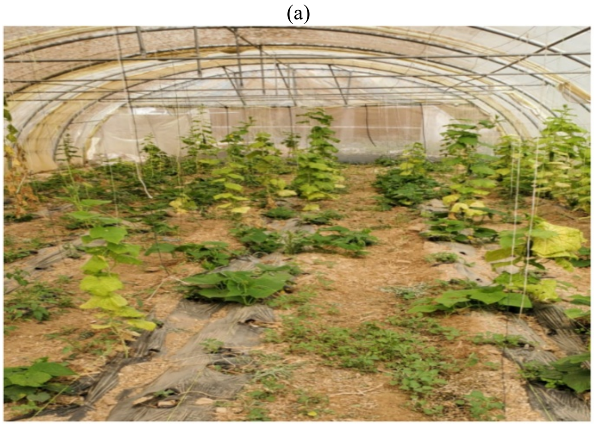
Table 1 presents data on water savings, crop yield increases, and land use efficiency for both hydroponic and soil-based farming systems across three planting cycles. The comparison considered variations in crop type and planting season. Results from the analysis indicate that the hydroponic system consistently outperformed traditional soil-based farming in terms of crop yield and land use efficiency, particularly for cucumbers and peas. Importantly, the hydroponic system exhibited greater resilience to heat waves. In cucumber cycles 1 and 2, traditional farming experienced significant crop losses, while hydroponic systems maintained stable production. For instance, in cucumber cycle 1 under normal conditions, hydroponic greenhouses achieved land use efficiency that was twice as high as that of soil-based greenhouses. Crop yields in hydroponics increased by 106.6 % for cucumber cycle 1 and by 30.4 % for peas, compared to their soil-based counterparts. Naresh *et al.* [36] reported a 25–30 % increase in cucumber yield with the implementation of a hydroponic system. In contrast, our results showed a 30–107 % increase in yield, depending on the crop and cycle. This comparatively higher yield enhancement in our study may be attributed to local system optimizations, such as the use of volcanic tuff as a growing substrate and tailored fertigation protocols. Water consumption and water use efficiency key indicators of agricultural sustainability, especially in water-scarce countries like Jordan also favors hydroponics. Water savings in hydroponic systems were 24.8 %, 37.9 %, and 29 % for cucumber cycle 1, cucumber cycle 2, and peas, respectively. The recirculation and reuse of drainage solution eliminate discharge and increases water saving. Grewal *et al.* [37], reported a 33% reduction in water use through the reuse of drainage water, which agrees with the current presented results. Additionally, Rodolfo *et al.* [38] reported a lower water use efficiency (22.68%) when closed-loop system is implemented for tomato, and Yang *et al*. [39] achieved an average saving in water of 26.7% using different substrates to grow cucumber. Water savings in the hydroponic system were mainly due to its closed-loop fertigation, which precisely adjusted water and nutrient delivery based on pH and EC, reducing over-irrigation and runoff. Climatic factors also played a role; during the heatwave in cucumber cycle 2 (40–50 °C), soil-based greenhouses required much more water due to high evaporation, while the hydroponic system maintained stable consumption through controlled irrigation and recirculation.

Table 1. Water use efficiency, crop yield, and land use efficiency for hydroponics versus soil-based systems

Cycle	Water Saving (%)	Crop Yield Improvement (%)	Land use efficiency-Hydroponic (kg/m^2)	Land use efficiency-Traditional (kg/m^2)
Cucumber 1	**24.8**	**106.6**	**3.1**	**1.5**
Cucumber 2 (during heat wave)	**37.9**	**500**	**0.7**	**0.1**
Peas	**29.0**	**30.4**	**1.5**	**1.15**

Across all cycles, hydroponic systems used less than half the irrigation water required by traditional farming. This efficiency gap widened significantly under heat stress: during heat waves, irrigation water needs increased sevenfold in hydroponics, compared to a 25-fold increase in traditional soil-based farming, highlighting the superior resilience of hydroponic systems under extreme conditions (Fig. 8). This suggests that hydroponic systems are suitable interventions to operationalize the WEFE nexus framework and fulfill the demand of the water and food sectors in an integrated way and in climate change time.

(a)



(b)

Fig. 8. Cucumber production inside hydroponic greenhouses (a) and soil-based greenhouses (b) during the heat wave (cucumber cycle 2).

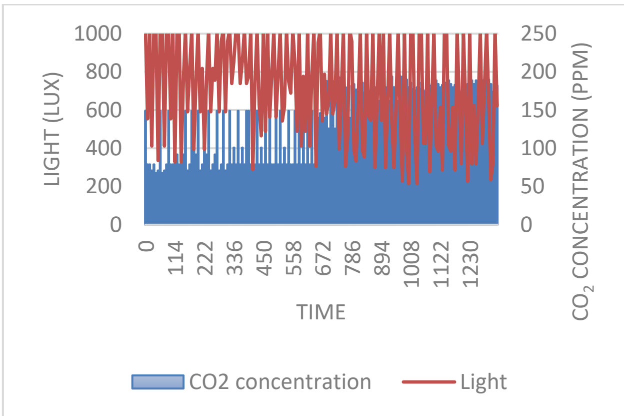
Table 2 presents the energy consumption per unit of production for both hydroponic and traditional agricultural systems across three plantation cycles and various energy sources. The data clearly indicate that energy consumption is significantly lower when Photovoltaic (PV) energy is used. Additionally, hydroponic systems consistently demonstrate a substantially lower energy consumption per unit of production (kWh/ton) compared to traditional agriculture.

Table 2. Energy consumption per unit of production for hydroponic and traditional systems across three plantation cycles and energy sources

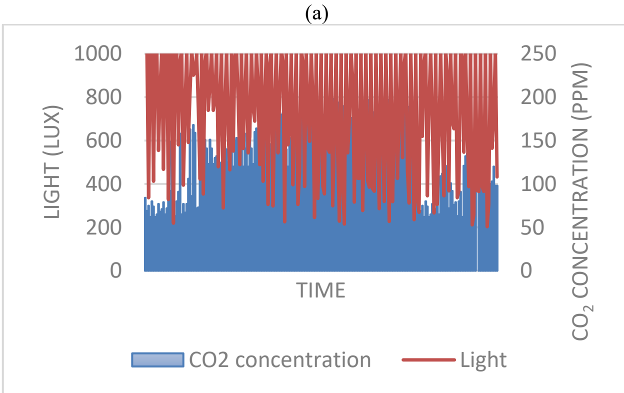
Cycle & Crop	**Energy Source**	**Hydroponic (kWh/t crop)**	**Traditional (kWh/t crop)**
Cycle-1: Cucumber	Diesel	15.8	40.0
	Grid	11.2	27.7
	PV	7.7	19.2
Cycle-2: Cucumber	Diesel	65.0	540.0
	Grid	45.0	380.0
	PV	31.7	260.0
Cycle-3: Peas	Diesel	31.5	53.6
	Grid	22.3	37.1
	PV	15.4	25.8

2) Footprint of CO_2

a) CO_2 uptake in hydroponic greenhouses



(a)



(b)

Fig. 9. Correlation between CO_2 concentrations and intensity of light in hydroponic greenhouses. (a) Cucumber cycle 2, and (b) Peas cycle.

Fig. 9 illustrates the relationship between CO_2 concentration inside the greenhouse and light intensity throughout the growth cycles of cucumbers and peas. The relationship between light intensity and CO_2 concentration was analyzed using continuous monitoring data. A moderate negative correlation was observed, with Pearson correlation coefficients of *r*=-0.63 for cucumber cycle 2 and *r*=-0.58 for peas, confirming that lower light intensity corresponds to reduced CO_2 uptake due to lower photosynthetic activity. These results reinforce the need for potential light-control measures to optimize plant growth in hydroponic systems, particularly during low-light conditions.

b) Comparative analysis of CO_2 emissions in solar-, fuel-, and grid-powered hydroponic systems

This section investigates the CO_2 emissions that can be avoided by implementing a PV-powered hydroponic system instead of fuel or grid-powered hydroponics. It was found that the implementation of PV-powered hydroponic systems can reduce the CO_2 emissions by 66.7 kgCO_2eq, and by 13.2 kgCO_2eq compared to fuel- and grid-powered hydroponics, respectively (Fig. 10). This shows how the hydroponic systems can meet the demand of the ecosystem within the WEFE nexus framework.

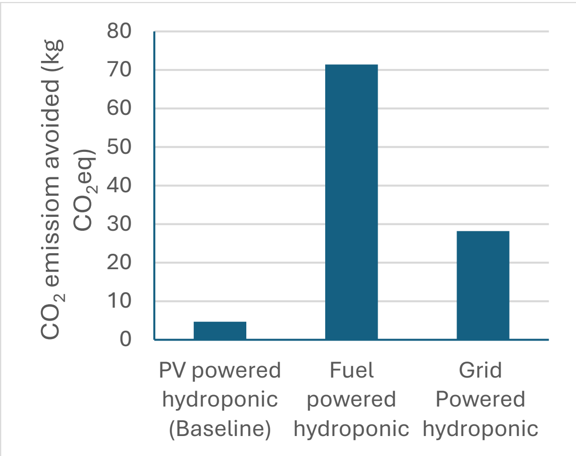


Fig. 10. CO_2 Emissions avoided in fuel-and grid-powered hydroponic systems compared to PV-powered systems.

3) Cost analysis

The comparison between the current system and similar hydroponic systems implemented in Jordan, as reported by workshop stakeholders, indicated that the installation cost of the current system is approximately 30% lower.

This reduction is mainly due to the use of a low-cost hydroponic technology that excludes humidity and CO_2 control components. With respect to the cost-benefit analysis, Table 3 (a) and (b) present the results comparing grid- and fuel-powered hydroponic systems to the PV-powered system.

The results of the cost-benefit analysis indicated Benefit-to-Cost (B/C) ratios of 1.71 and 6.3 for the grid-powered and fuel-powered hydroponic systems, respectively. These values demonstrate that, in both cases, the PV-powered hydroponic system offers significantly higher economic returns relative to its costs. The sensitivity analysis results (Fig. 11) show that the B/C ratio is highly sensitive to the source and cost of displaced energy. In the grid-powered scenario, the inclusion of CO_2 valuation significantly improved the B/C ratio, raising it from 1.2 to 1.7 at baseline conditions. However, the diesel-powered scenario yielded much higher B/C ratios, even without CO_2 valuation, due to the higher cost and emissions intensity of diesel fuel.

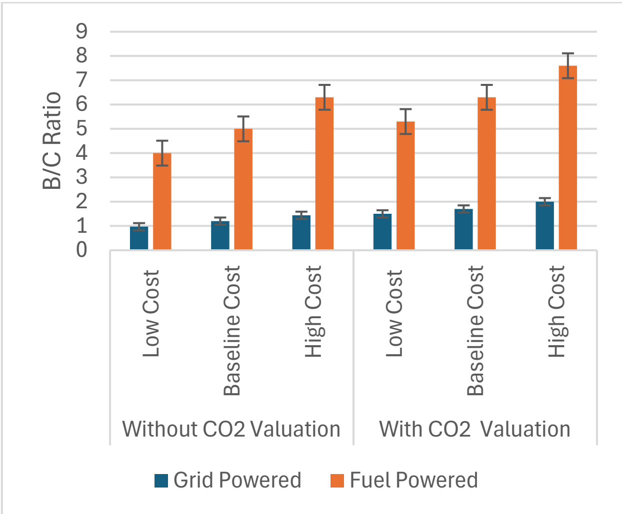


Fig. 11. Benefit/Cost Ratio with and without CO_2 valuation: grid- and diesel-powered vs. PV-powered hydroponic systems (The data are the mean of standard error ± SE (*n*=2)).

Table 3. Cost benefit analysis comparing (a) grid- and (b) fuel-powered hydroponic systems to the PV-powered system

(a)

Cost element	Indicator base	Nº Units	Units	Nº Units	Units	Total EUR
Investment and operation of PV system	Solar PV production capacity	93.60	kWh	50.0	EUR/MWh	4.68
Loss of agricultural land (if any)	Area and economic value	0.00	ha	0.0	EUR/ha	0
Total Costs						**4.68**
Benefits-direct						
Provisioning	**Indicator base**	**Nº Units**	**Units**	**Nº Units**	**Units**	**Total EUR**
Savings in energy purchasing costs	Decrease in energy purchases	64.92	kWh	87.0	EUR/MWh	5.65
Regulating	**Indicator base**	**Nº Units**	**Units**	**Nº Units**	**Units**	**Total EUR**
Decrease in CO_2 costs through use of PV panels	CO_2 emissions avoided	28.24	KgCO_2eq	83.2	EUR/t (CO_2eq)	2.35
Total Benefits						**8.00**
BENEFIT/COST RATIO						**1.71**

(b)

Cost element	Indicator base	Nº Units	Units	Nº Units	Units	Total EUR
Investment and operation of PV system	Solar PV production capacity	93.60	kWh	50.0	EUR/MWh	4.68
Loss of agricultural land (if any)	Area and economic value	0.00	ha	0.0	EUR/ha	0
Total Costs						**4.68**
Benefits-direct						
Provisioning	**Indicator base**	**Nº Units**	**Units**	**Nº Units**	**Units**	**Total EUR**
Savings in energy purchasing costs	Decrease in energy purchases	26.7	kWh	87.0	EUR/MWh	23.5
Regulating	**Indicator base**	**Nº Units**	**Units**	**Nº Units**	**Units**	**Total EUR**
Decrease in CO_2 costs through use of PV panels	CO_2 emissions avoided	71.4	KgCO_2eq	83.2	EUR/t (CO_2eq)	5.9
Total Benefits						**29.5**
BENEFIT/COST RATIO						**6.3**

B. Assessment of Hydroponic Upscaling Scenarios Using REWEFE Tool

Four upscaling scenarios were compared to explore the changes that might occur in the different WEFE nexus sectors when hydroponic systems are introduced at different upscaling levels. The four scenarios consist of a small hydroponic system (S1), an expanded hydroponic system (2), a small hydroponic system powered by solar energy (S3), an expanded hydroponic system powered by solar energy (S4), and traditional farming is used as the baseline scenario. Fig. 12 shows that a small-scale hydroponic system (S1) significantly reduces energy consumption, requiring less irrigation and exhibiting greater energy efficiency compared to traditional greenhouse agriculture.

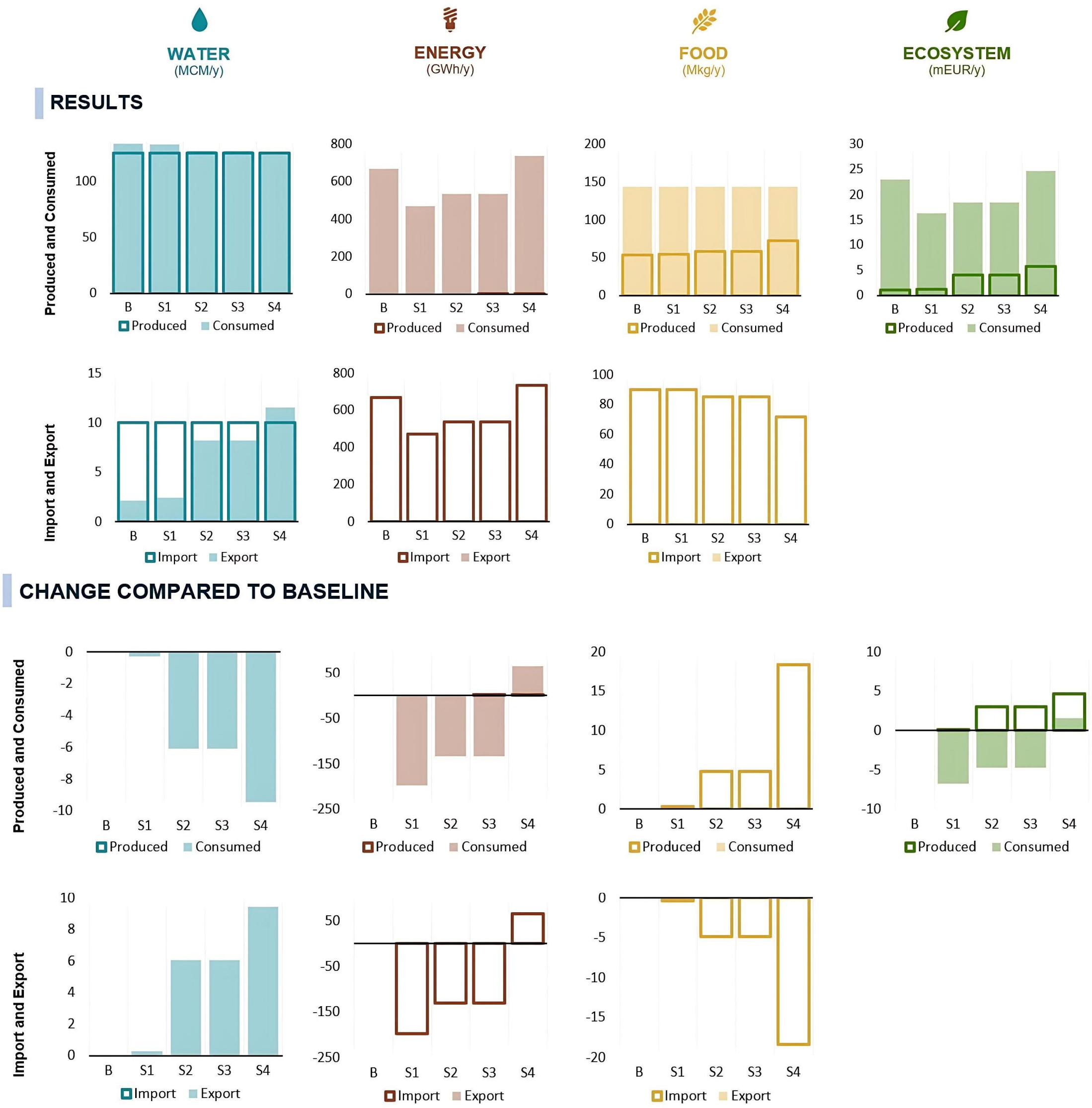


Fig. 12. Results of the four REWEF scenarios. Scenarios: Baseline (B) Traditional greenhouse with no recirculation/reuse of water.(S1) Development of a small hydroponic system; (S2) – Expansion of hydroponic system; (S3) – Hydroponic system powered by solar energy; and (S4) – Upscaled scenario reflecting a higher adoption rate leading to a larger scale hydroponic system and increased solar power coverage.

However, in the upscaled scenario (S2), the expansion of hydroponic operations leads to increased energy demand, which poses a potential limitation in energy-scarce contexts such as Jordan. The transition to solar-powered hydroponics (S3) offers substantial ecosystem benefits. These include reduced water usage, resulting in increased outflows from the nexus unit, and lower CO_2 emissions due to the adoption of renewable energy sources. Water consumption is reduced by 5–7% as a result of decreased reliance on conventional irrigation, and there is no indication of blue water stress, as water demand and supply remain balanced. Across all scenarios, the deployment of hydroponic systems contributes to increased food production, with improvements ranging from 1% to 34%. Additionally, water recirculation within the system minimizes the need for fertilizers, and the soilless cultivation method alleviates pressure on soil resources, thereby promoting healthier ecosystems. Overall, the implementation and scaling of hydroponic systems within the nexus unit enhance water efficiency and food productivity.

However, the increased energy demand observed in the large-scale scenario (S4) underscores the importance of expanding renewable energy capacity to sustain the long-term viability of such systems. However, while increased agricultural production (1–34%) enhanced food security across the different scenarios, it also led to higher water and energy demands, potentially compromising ecosystem integrity, particularly in water-scarce countries. In such contexts, a rebound effect was observed in the form of increased energy consumption, underscoring the need for further integration of solar energy solutions to ensure long-term system resilience and sustainability.

V. Conclusion

This study underscores the effectiveness of solar-powered hydroponic systems as a practical Model and sustainable solution for addressing the interlinked challenges of water scarcity, food insecurity, and energy dependence in Jordan. By outperforming conventional agriculture in water efficiency, crop productivity, and environmental impact, the hydroponic system presented in Wadi Al Wala offer both a proof-of-concept and a scalable policy model for operationalizing the WEFE Nexus through integrated, locally tailored interventions. The results of the Nexus-based performance indicators highlight the potential for replicability and scalability of such systems in similar resource-limited settings to meet the sectoral demands simultaneously. The findings showed that hydroponic systems saved 25–38% more water compared to traditional soil-based agriculture. Additionally, hydroponics demonstrated superior crop productivity, increasing yields by 30–107% over three cultivation cycles. Environmentally, solar-powered hydroponic systems notably reduced CO_2 emissions by 66.7 kg CO_2 eq and by 13.2 kg CO_2 eq compared to fuel-powered and grid powered hydroponics, respectively. However, the observed increase in energy demand under upscaling scenarios emphasizes the need to simultaneously invest in renewable energy infrastructure to ensure the long-term sustainability of hydroponic agriculture within the WEFE Nexus framework. The REWEFE tools showed that water consumption is reduced by 5–7% as a result of decreased reliance on conventional irrigation. Across all scenarios, the deployment of hydroponic systems contributes to increased food production, with improvements ranging from 1% to 34%. Finally, the current study demonstrates that hydroponic greenhouses outperform soil-based farming, even under uncontrolled environmental conditions. Future research should explore AI-based automation to optimize energy and water use and nutrient management.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Arwa Abdelhay wrote the paper and contributed to data collection, analysis, and compilation. Serena Sandri reviewed the paper and contributed to data collection, analysis, and compilation. Munjed Alsharif contributed to data collection and analyzed the system performance data. Nooh Alshyab and Luay Jum'h analyzed the sectoral issues collected from the stakeholders' consultation workshop and supported secondary data collection needed for the REWEFE tool. Ismail Abushaikha supported the secondary data collection needed for the REWEFE tool. All authors had approved the final version.

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