Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2024, 12, 80-96
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Assessing the Water-Energy-Food-Ecosystems Nexus in Smart Irrigation: A Potato Farming Case Study in Lebanon

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How to cite this paper: Karnib, A., Laamrani, H., & El Kharraz, J. (2024). Assessing the Water-Energy-Food-Ecosystems Nexus in Smart Irrigation: A Potato Farming Case Study in Lebanon. *Journal of Geoscience and Environment Protection, 12,* 80-96.
https://doi.org/10.4236/gep.2024.128005

Received: July 12, 2024
Accepted: August 10, 2024
Published: August 13, 2024

Abstract

This study examines the Water-Energy-Food-Ecosystems (WEFE) nexus in Lebanese agriculture, with a focus on the shift from conventional surface irrigation techniques to advanced smart irrigation systems in the Bekaa region, specifically targeting potato cultivation. The study quantitatively analyzes the interaction among water, energy, and agricultural outputs at the farm scale using the WEFE Nexus framework for scenario analysis. It evaluates variations in water productivity, environmental effects, and economic outcomes, offering a detailed view of existing practices and their sustainable improvement potential. The WEFE Nexus assessment demonstrates that smart irrigation integration significantly decreased resource usage: water consumption was reduced by 58%, diesel fuel use for irrigation dropped by 57%, and the demand for labor and fertilizers decreased by 47% and 49%, respectively. This change led to enhanced crop yields and increased resource efficiency, demonstrating the potential of smart irrigation as a transformative strategy for sustainable agriculture in Lebanon and other arid areas. Economic analysis showed that farmers could recover the costs of installing the smart irrigation system within 3 months. The findings highlight the need for further research on integrating smart irrigation with renewable energy, showing potential for sustainable agricultural development.

Keywords

Water-Energy-Food-Ecosystems Nexus, Sustainable Agriculture, Smart Irrigation, Q-Nexus Model

1. Introduction

The agricultural sector in Lebanon, especially in the Bekaa Valley, is vital to the nation's socioeconomic well-being. It provides significant employment opportunities and is a cornerstone for the country's food security. The Bekaa Valley is a key agricultural region, accounting for around 42% of the country's total agricultural land and nearly 50% of its irrigated land (Ministry of Agriculture, 2003; World Bank, 2018). It is the foremost area for fruit and potato production; the Bekaa Valley produces 37% of the Lebanon's fruits and 57% of its potato (Ministry of Agriculture, 2003).

The country is at a pivotal moment, where balancing the increasing demands for food and economic development with the necessity of preserving its limited natural resources is essential. Additionally, unsustainable practices, particularly the excessive use of water and energy, present significant threats to resource availability, environmental health, and the sustainability of agricultural productivity (Larkin et al., 2020; Karnib, 2017).

Recent studies and practical implementations have explored the incorporation of advanced agricultural methods within the Water-Energy-Food-Ecosystems (WEFE) Nexus framework. Particularly, investigations into irrigation systems have shown significant potential for the sustainable management of water, energy, and food resources (Sewilam et al., 2023; Rasul & Sharma, 2016; Shah et al., 2007; Chaibi et al., 2023). The importance of the WEFE Nexus is particularly evident in areas where agricultural activities are heavily reliant on water and energy resources (Howells et al., 2013; FAO, 2014).

The Water-Energy-Food-Ecosystems (WEFE) Nexus initiatives are essential for Lebanon, aiming to optimize water resource use while ensuring energy security and food sufficiency for its growing population. This integrated approach provides a comprehensive analysis of the interconnections between water, energy, food, and environmental systems, identifying potential synergies and trade-offs within these sectors (Karnib, 2018; Albrecht et al., 2018; Karnib & Alame, 2020; UNESCWA, 2015). By implementing the WEFE Nexus methodology, Lebanon can enhance its resilience against climate change and other environmental challenges.

This study offers a comprehensive analysis of the Water-Energy-Food-Ecosystems (WEFE) Nexus within Lebanon's agricultural sector, with a focus on the Bekaa Valley, specifically targeting potato cultivation. Our study focuses on comparing traditional irrigation methods with modern, sustainable approaches, particularly emphasizing the benefits of smart irrigation systems. This comparative evaluation draws on recent findings highlighting the advantages of smart irrigation systems in boosting water and energy efficiency in agriculture affected by water scarcity.

Using the Q-Nexus model for scenario-based analysis, this study aims to examine the quantitative interactions related to water, energy, and agricultural production, building on the methodological framework established by Karnib &

Alame (2020) in their WEFE nexus analysis. The objective is to gain a comprehensive understanding of current agricultural practices and identify pathways to enhance resource efficiency and reduce environmental impacts. Ultimately, this research intends to contribute to the sustainable agricultural transformation in Lebanon, aligning with the nation's Sustainable Development Goals (SDGs) and enhancing resilience against climate change and global environmental challenges.

2. Methods

Several methods have been established for integrated WEFE Nexus modeling, such as input-output models, system dynamics, and multilevel models. Significant advancements include Giampietro et al.'s (2013) multilevel perspective using the MuSIASEM framework, Feng et al.'s (2016) system dynamics approach, and Karnib's (2017) input-output modeling. Although the MuSIASEM and system dynamics approaches are quite comprehensive, they have limitations due to their high data demands and complexity (Kaddoura & El Khatib, 2017).

Karnib (2017) introduced the Q-Nexus model, which utilizes the Leontief production function to illustrate the interactions within the Water-Energy-Food (WEF) sectors. The model is particularly beneficial due to its simplicity and linear nature, making the interdependencies within the WEF Nexus more comprehensible compared to more complex models.

The Q-Nexus model measures the output of each sector in physical units: cubic meters (m^3) for water, kilograms (kg) for food, and megajoules (MJ) for energy. It further divides each sector into subsectors, such as groundwater and surface water for water, electricity and renewable energy for energy, and different types of agricultural products for food. The efficiency of each technology in the system is indicated by a technology coefficient (t_i), which quantifies the resource input required to generate a specific output (Karnib & Alame, 2020).

To apply the Q-Nexus model to the agricultural context of Bekaa valley, specific local parameters are incorporated, including water sources, energy consumption patterns, workforce utilization, and fertilizer application. This localized adaptation ensures the model accurately reflects the region's farming practices.

Various scenarios may be simulated using the Q-Nexus model to analyze the impacts of different agricultural practices. These scenarios included variations in water and energy sources, crop production levels, and irrigation techniques. This comprehensive analysis helps identify the complex interdependencies and trade-offs associated with each policy strategy.

Figure 1 illustrates the conceptual framework used in this study. The framework applies the Q-Nexus model to evaluate the quantitative interconnections between food production, water resources, and energy use. Potential scenarios consider various crop types and quantities, irrigation systems (conventional, smart), and water sources (groundwater, surface water, wastewater, agricultural recycled water). Energy inputs included diesel fuel, fossil-fuel-derived electricity, and renewable energy. The Q-Nexus model facilitated a comprehensive scenario analysis, leading to an impact assessment that examined water and energy conservation, emissions and toxicity release, and associated costs. This integrative approach supports decision-making in the WEFE Nexus, optimizing sustainability and resource management.

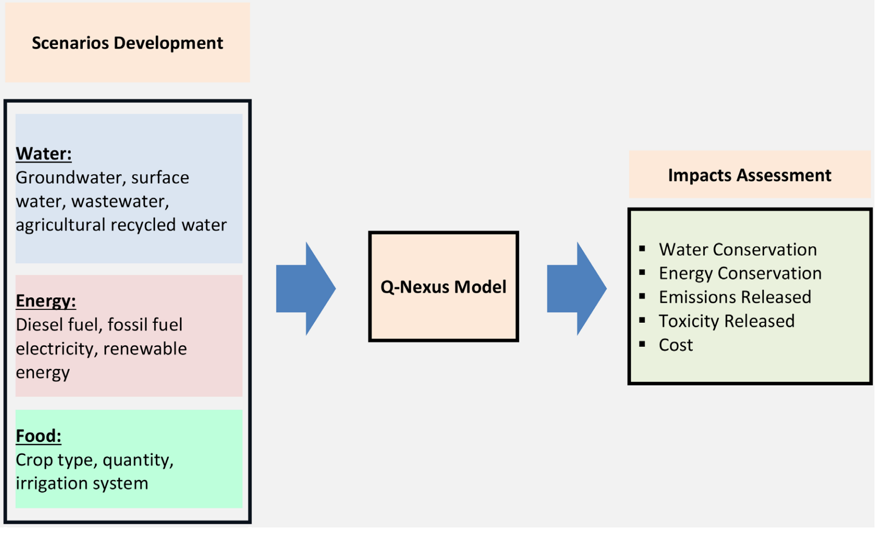

Figure 1. Proposed WEFE nexus analysis framework.

As illustrated in Figure 1, the initial stage entails the creation of various scenarios that depict different conditions and management strategies in food production, water sourcing, and energy utilization. These scenarios were then fed into the Q-Nexus model, incorporating specific local data to simulate the interactions and dependencies within the Nexus. The model generates scenario outputs, providing detailed insights into the outcomes of each simulated condition. The final stage involves an impact assessment, evaluating the scenarios' effects on water and energy conservation, emission levels, environmental toxicity, and cost-effectiveness. This progressive method is intended to guide sustainable decision-making by highlighting the trade-offs and synergies associated with different resource management practices.

2.1. Data Acquisition and Scenario Formulation

To apply the Q-Nexus model at the farm level, data is collected through a combination of on-site evaluations, farmer interviews, and review of regional and national agricultural records. This comprehensive data collection includes variables such as water and energy consumption, crop yields, and fertilizer application rates. Scenarios are then developed to compare current practices with potential improvements, specifically focusing on the transition from traditional irrigation methods to smart irrigation systems. These scenarios provide the basis for assessing the efficiency and sustainability of various agricultural practices.

The data collection process involves several key procedures to ensure comprehensive and accurate information. First, on-site evaluations are conducted through direct observation and measurement of water and energy use, as well as soil and crop conditions. This approach provides precise and current data about farming practices and resource utilization. Second, farmer interviews are conducted using structured formats to understand their practices, challenges, and perceptions of irrigation methods and resource management. These interviews gather detailed information on labor input, costs, and the perceived benefits of various irrigation techniques. Finally, the review of agricultural records from regional and national sources is undertaken to complement field data and offer a broader context for the findings. This review includes analyzing data on crop yields, fertilizer application rates, and historical water and energy use.

Building on the collected data, the study develops multiple scenarios to explore the impact of transitioning from traditional to smart irrigation systems. These scenarios include: the Baseline Scenario, which reflects current farming practices using traditional surface irrigation methods; the Smart Irrigation Scenario, which represents the implementation of smart irrigation systems, incorporating automated water management and optimized fertilizer use. Each scenario is analyzed to compare the efficiency, cost-effectiveness, and environmental impact of different irrigation practices (Karnib, 2017; Karnib & Alame, 2020; Al Edwani et al., 2023).

This comprehensive assessment aims to provide a detailed understanding of the trade-offs and synergies associated with different irrigation practices, supporting informed decision-making for sustainable agricultural development in the Bekaa region.

2.2. Environmental Consequences of Farming Practices

Agricultural practices significantly impact the environment, contributing to several ecological problems. Among the important concerns are carbon dioxide (CO_2) emissions generated by the energy consumption and fertilizers used in farming. Moreover, fertilizers used in agriculture can degrade water quality through runoff, leading to higher concentrations of harmful substances in aquatic ecosystems.

2.2.1. CO_2 Emissions

This study examines CO_2 emissions by evaluating the carbon footprint associated with diesel fuel used for irrigation and the application of fertilizers. Each of these inputs contributes to the overall emissions impact, quantified by specific emission factors (Tabatabaie & Murthy, 2021; IPCC, 2006). Approximate average emission factors of 0.067 kg CO_2 equivalent per megajoule for diesel fuel and 0.6 kg CO_2 equivalent per kilogram for fertilizers are applied. It is important to note that emission factors for diesel can vary based on the diesel type and usage conditions (IPCC, 2006). Similarly, emission factors for fertilizers depend on the fertilizer type and its application method. According to IPCC (2006) guidelines, the variability in emissions is influenced by nitrogen content, application techniques, and local soil and climatic conditions. By using these average emission factors, we aim to provide a practical estimation of the emission reduction potential from reduced diesel and fertilizer use. This method offers an initial perspective that supports broader environmental and policy objectives by simplifying the complex process of calculating precise emissions, which would require detailed data on specific conditions and practices. However, it is important to acknowledge that these approximations may not fully capture the nuanced variations in emissions from different sources and under varying conditions. Accurate emissions accounting and the development of effective reduction strategies require detailed, context-specific analyses.

2.2.2. Toxicity Release

The toxicity resulting from agricultural practices is primarily caused by nutrient leaching. This study estimates this process using a simple equation that calculates the potential leaching amount. The calculation is based on the total fertilizer applied and an assumed leaching percentage, indicating the portion of nutrients that may leach out due to irrigation. While this model is basic and does not account for the complex interactions between soil, water, and nutrients, it offers an initial estimate of the leaching potential.

The toxicity released is calculated as follows:

$$L = F \times P \quad (1)$$

where:

L = Potential leaching amount (kg);

F = Total amount of fertilizer applied (kg);

P = Presumed leaching percentage (a decimal value representing the presumed fraction of the applied fertilizer that could leach out due to irrigation).

This equation assumes a direct proportionality between the amount of fertilizer applied and the potential for leaching, with the leaching percentage (P) acting as a simple way to estimate how much of the applied nutrients might be at risk of leaching. The value of P should be selected based on general knowledge about the irrigation system, soil type, and local conditions, but without more specific data, a conservative estimate might be necessary. For example, flood irrigation is presumed to have a higher leaching percentage of 15% due to excessive water application, which increases nutrient runoff and leaching. Conversely, precise irrigation, which applies water and nutrients to the plant at the right time and place and in small measured doses, is assumed to have a lower leaching percentage of 3%, thereby minimizing nutrient loss.

2.3. Study Area and Data Collection

Bekaa Valley is a pivotal agricultural region in Lebanon, characterized by its fertile soil and favorable climate for diverse crop cultivation (**Figure 2**). The climate in Bekaa Valley is typically Mediterranean, with hot, dry summers and cool, wet winters. Rainfall, though more abundant than in other arid regions, is still limited, making efficient irrigation practices essential.

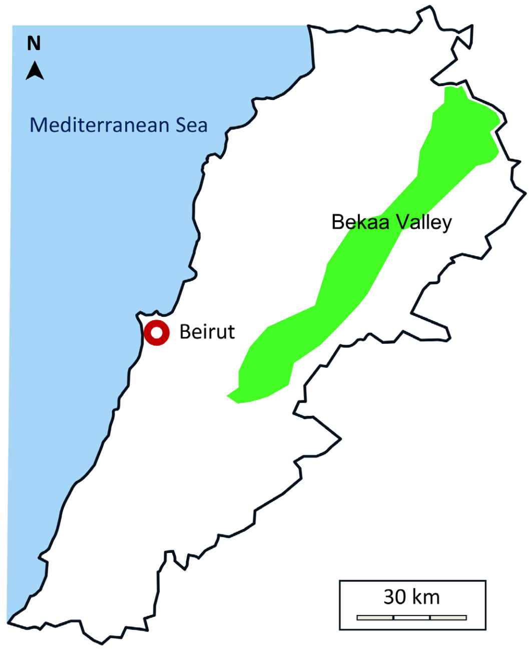

Figure 2. Map of Lebanon showing the location of Bekaa Valley.

Potato cultivation is a cornerstone of agricultural activity in Bekaa (Dal et al., 2021), representing 72% of domestic potato production (Choueiri et al., 2017). The fertile soils of the valley, combined with the ample sunlight and the availability of water sources, create optimal conditions for growing a variety of potatoes. This agricultural activity plays a significant role in the local economy, providing employment for a large portion of the population and contributing to Lebanon's food security. The harvesting and processing of potato are central to the agricultural calendar in Bekaa, with local markets and factories processing and distributing the produce. The tradition and expertise developed in potato agriculture underscore the Bekaa's contribution to both the national economy and the sustenance of its communities.

Table 1 presents the total harvested area of potato, yield, and overall production both at the national and regional scale (FAOSTAT, 2024; Choueiri et al., 2017).

Table 1. Information related to potato cultivation.

Particular	National	Regional (Bekaa valley)
Area harvested (hectares)	11,000	7700
Yield (tons/hectare)	27	27
Production (tons)	297,000	207,900

Surface irrigation for potato production requires between 4500 to 8000 m^3/hectare. This range is due to the high evaporation and runoff losses associated with surface irrigation methods. Efficient water management practices can reduce these losses. The variability in the range is also influenced by local climate conditions, soil type, and specific crop water needs (Djaman et al., 2021; Badr et al., 2022; De Pascale et al., 2011; Choueiri et al., 2017; Karam et al., 2014).

Diesel use for pumps in surface irrigation for potato production ranges from 100 to 150 liters/hectare, with a diesel use rate of 0.02 to 0.03 liters/m^3. These values reflect the higher energy required to lift and distribute larger volumes of water. Factors influencing these values include the efficiency of the pumping equipment, the height of the water lift (pumping head), and the total volume of water being moved (Jaafar & Kharroubi, 2021).

Labor requirements for surface irrigation range from 150 to 300 hours/hectare. This high labor input is due to the manual management required for controlling water flow across the fields, maintaining furrows, and adjusting water distribution. The wide range accounts for variations in field size, the complexity of the irrigation setup, and the efficiency of labor practices (Djaman et al., 2021; Karam et al., 2014).

Fertilizer use in surface irrigation systems ranges from 200 to 250 kg/hectare. Surface irrigation is generally less efficient in nutrient delivery, leading to higher fertilizer requirements to achieve desired crop yields. This inefficiency can result in nutrient losses through runoff and deep percolation, necessitating higher application rates (De Pascale et al., 2011; Ahmed et al., 2023).

Productivity in surface irrigation systems is generally lower, with yields ranging from 20 to 30 tons/hectare. The lower productivity is due to the less efficient water and nutrient use, leading to potential stress on the crops during critical growth periods. However, with improved management practices, some fields may achieve yields at the higher end of this range (Djaman et al., 2021; Ahmed et al., 2023).

Water Productivity (WP) in surface irrigation systems ranges from 3.13 to 6.67 kg/m^3. This measure reflects the amount of crop yield produced per unit of water used. The lower WP in surface irrigation is due to higher water losses through evaporation, runoff, and inefficient water distribution. The range of values indicates that even within surface irrigation, there can be significant variability based on specific management practices and local conditions (Djaman et al., 2021).

On the other hand, implementing smart irrigation technologies in potato production in Lebanon offers substantial benefits across all resource use compared to traditional surface irrigation methods. Smart irrigation systems can reduce water usage by up to 35 - 65 (Ahmed et al., 2023; Nourani et al., 2019). This reduction in water use directly decreases diesel consumption for pumps. Smart irrigation also minimizes labor by automating water management (Sharma et al., 2015; O'Shaughnessy et al., 2016). Enhanced fertilizer efficiency through fertigation lowers fertilizer requirements from 200 - 250 kg/hectare to 150 - 200 kg/hectare, as nutrients are delivered more effectively and losses are minimized (Sharma et al., 2015). Consequently, crop productivity improves significantly, with potential yields increasing from 20 - 30 tons/hectare to higher levels due to better water and nutrient management (Nourani et al., 2019). Water Productivity (WP) is markedly enhanced with smart irrigation, as precise irrigation and nutrient delivery optimize plant growth conditions (O'Shaughnessy et al., 2016; Potato Business, 2023; UNESCWA, 2021). This not only ensures sustainable water use but also maximizes agricultural output, making smart irrigation a highly beneficial approach for potato production in Lebanon.

2.3.1. Agricultural Data Acquisition

The key features of the smart irrigation system used include self-automated control, ensuring optimal irrigation schedules; precision watering, delivering the exact amount of water needed by crops; data-driven optimization, utilizing real-time data to fine-tune irrigation practices; and remote control and management, allowing farmers to monitor and adjust their systems from anywhere (SmartLand, 2024).

2.3.2. Preparing Data for Integrated Nexus Evaluation

As outlined in Section 2, the key factors for evaluating the nexus through the Q-Nexus model are the intensities across sectors. This includes the measurement of water, energy, labor, and fertilizers intensities (**Table 2**), which are derived from the data shown in **Table 3**.

Table 2. Setting up intensities for nexus analysis.

Particulars	Traditional Irrigation	Smart Irrigation
Water Intensity (m^3/kg of potato produced)	0.1846	0.0771
Energy Intensity (MJ/kg of potato produced)	0.2192	0.0814
Labor Intensity (hours/kg of potato produced)	0.0096	0.0054
Fertilizer Intensity (kg/kg of potato produced)	0.0096	0.0049

Table 3. Data collected from field.

Particulars	Traditional Irrigation	Smart Irrigation
Water use (m^3/hectare)	4800	2160
Diesel use for irrigation at the farm level (liters/hectare)	150	60
Labor (hours/hectare)	250	150
Fertilizers (kg/hectare)	250	138
Productivity (tons/hectare)	26	28

3. Results and Discussion

3.1. Baseline Scenario: Conventional (Surface) Irrigation Method

The analysis of the WEFE nexus for the baseline scenario was performed to evaluate the impacts of producing 1.5 million tons of potato, which represents the overall potato production in Bekaa Valley during the year 2022 (FAOSTAT, 2024).

3.1.1. Resource Utilization Metrics

The baseline scenario, representing traditional irrigation practices, showed significant water and energy consumption, primarily due to the use of diesel-powered surface irrigation. For the 207,900 tons of potato production in Bekaa Valley, approximately 38.5 million cubic meters (MCM) of water and 170.2 terajoules (TJ) of diesel fuel are used for irrigation. **Figure 3** and **Figure 4** show the obtained results of resources used for the baseline scenario.

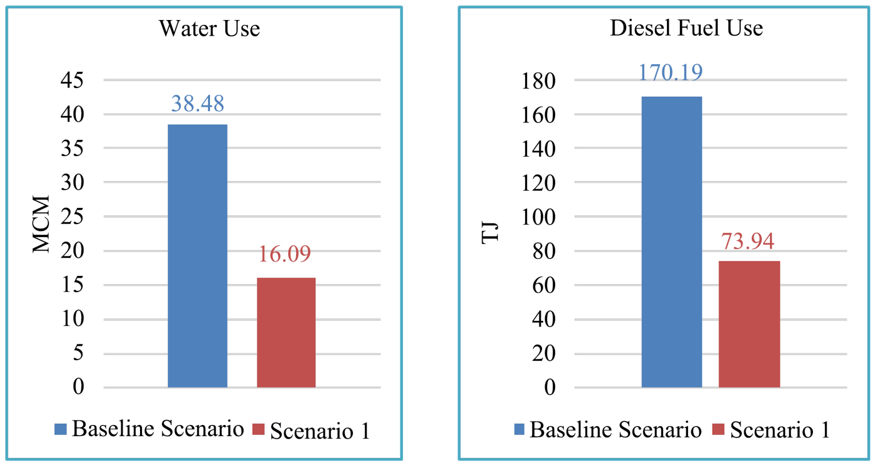

Figure 3. Total water and diesel fuel use.

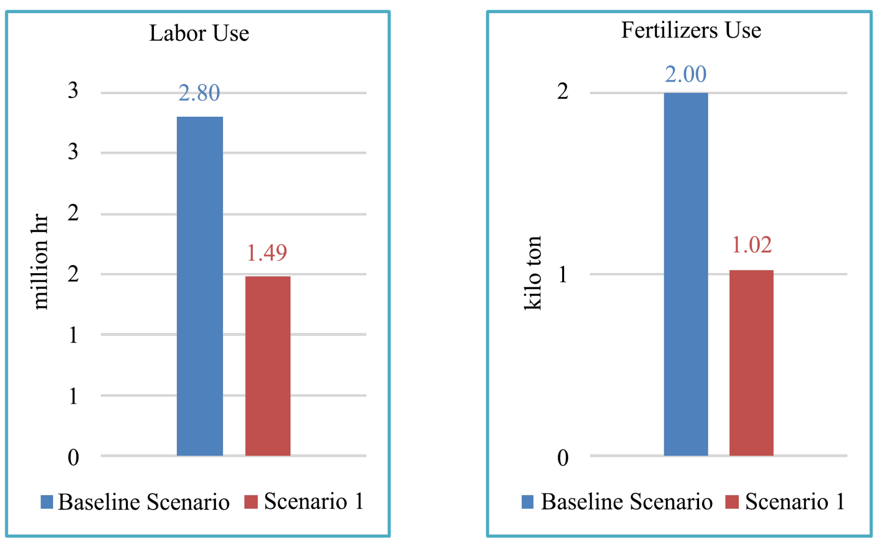

Figure 4. Total labor and fertilizers use.

3.1.2. Environmental and Economic Outcomes

The environmental assessment revealed high levels of greenhouse gas (GHG) emissions, approximately 12.6 kilotons of CO_2 equivalent, primarily from diesel combustion and fertilizer use. Economically, the cost of diesel fuel and fertilizers for agricultural operations amounted to USD 1.2 million and USD 2.6 million, respectively. Table 4 presents the estimated environmental impacts and cost of diesel fuel and fertilizers for the baseline scenario.

Table 4. Estimated environmental impacts and cost for the baseline scenario.

Particulars	Unit	Value
GHG emissions	Kilo ton CO_2 eq	12.6
Toxicity released	ton	299.9
Expense of diesel fuel	Million USD	1.2
Expense of Labor	Million USD	1.7
Expense of fertilizers	Million USD	2.6

3.2. Scenario1: Adoption of Smart Irrigation System

3.2.1. Resource Utilization Metrics

In Scenario 1, the integration of smart irrigation system is analyzed to assess their impact on resource utilization for potato production in Bekaa Valley. Figure 3 and Figure 4 show the obtained results of resources used in Scenario 1.

In this scenario, water consumption decreases substantially to 16.09 MCM, showcasing the efficiency of smart irrigation systems in minimizing water losses and enhancing the precision of water application. Diesel fuel usage decreases to 73.94 TJ, indicating a reduction in reliance on fossil fuels. Labor working hours are optimized, demonstrating the potential for increased efficiency in agricultural operations. Fertilizer use is also optimized to 1.02 kilotons, suggesting that the more precise water and nutrient delivery system could enhance nutrient use efficiency and reduce the overall quantity of fertilizers needed.

3.2.2. Environmental and Economic Outcomes

The potential for smart irrigation to reduce environmental footprint and improve farm profitability is evaluated in this scenario. Table 5 presents the estimated environmental impacts and cost of diesel fuel and fertilizers for Scenario 1.

Table 5. Estimated environmental impacts and cost for Scenario 1.

Particulars	Unit	Value
GHG emissions	Kilo ton CO_2 eq	5.6
Toxicity released	ton	51.0
Expense of diesel fuel	Million USD	0.5
Expense of Labor	Million USD	0.9
Expense of fertilizers	Million USD	1.3

The shift to smart irrigation significantly reduces greenhouse gas emissions to 5.6 kilotons of CO_2 equivalent, a substantial decrease reflecting the lower dependency on diesel fuel. Toxicity release is also reduced to 51 tons, indicating a decrease in environmental pollutants. Economically, the scenario presents notable cost savings, with diesel fuel expenses dropping to 0.5 million USD and fertilizer expenses to 1.3 million USD. This reduction in costs is attributed to the decreased need for diesel fuel and the more efficient use of fertilizers, underscoring the economic viability of transitioning to more sustainable agricultural practices.

3.3. Comparative Evaluation: Conventional (Surface) Irrigation vs. Smart Irrigation

3.3.1. Efficiency of Resource Use

The implementation of smart irrigation systems has demonstrated a significant decrease in resource use. Water consumption decreased to 16.09 MCM, representing a 58% reduction compared to the baseline. Energy consumption from diesel fuel decreased by 57%. Similarly, the demand for labor and fertilizers dropped by 47% and 49%, respectively. Simultaneously, there is a notable improvement in productivity, with potato yield per hectare increasing by 8% (Figure 5).

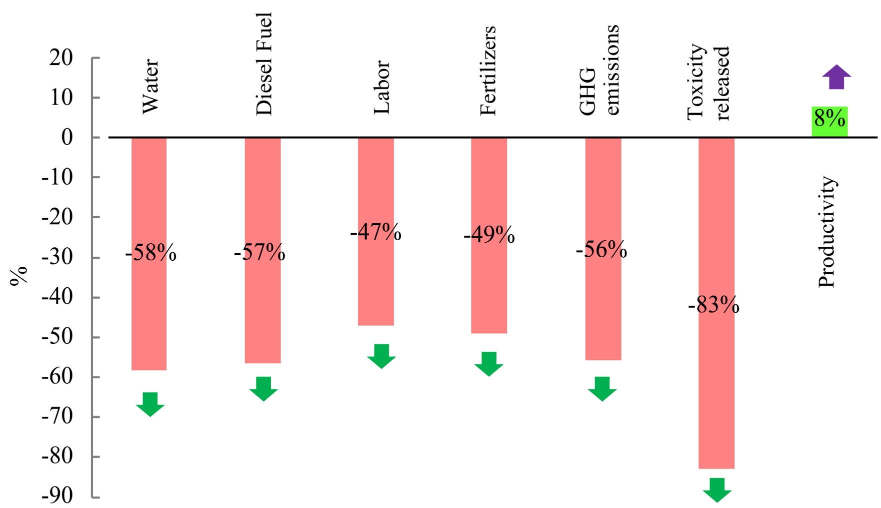

Figure 5. Percentage of change in outputs of Scenario 1 in comparison with the baseline scenario.

By comparing the total water consumption under Scenario 1 (smart irrigation) to that of the baseline scenario (conventional surface irrigation), the calculated water savings amount to 22.39 million cubic meters annually, representing a significant 58% reduction when compared to conventional irrigation practices.

The adoption of smart irrigation has also impacted labor requirements, and fertilizer usage. With more precise water and fertilizer application, labor costs have been reduced (Figure 4), as there is less need for manual labor in water and fertilizer management. Moreover, the efficiency of smart irrigation allows for targeted fertilizer application, which has led to a decrease in fertilizer use and cost.

3.3.2. Improved Crop Yield

Productivity improvements were notable, with potato yield increasing from 26 to 28 tons per hectare, and overall potato quality improving. These enhancements underscore the efficiency gains from adopting precision irrigation.

3.3.3. Ecological Advantages

The shift to sustainable practices led to a significant decrease in GHG emissions, decreasing from 13 to 6 kilotons CO_2 equivalent, highlighting the environmental advantage of reducing fossil fuel use and adopting cleaner energy sources. Furthermore, toxicity potential from fertilizer runoff decreased from 300 to 51 ton, reflecting better nutrient management, and reduced environmental contamination.

3.3.4. Economic Advantages

Economic analysis indicated substantial savings in operational costs. The expense of diesel fuel in agriculture dropped to USD 0.54 million, and fertilizer costs reduced to USD 1.33 million under the smart irrigation scenario, illustrating the cost-effectiveness of the sustainable practices (Figure 6).

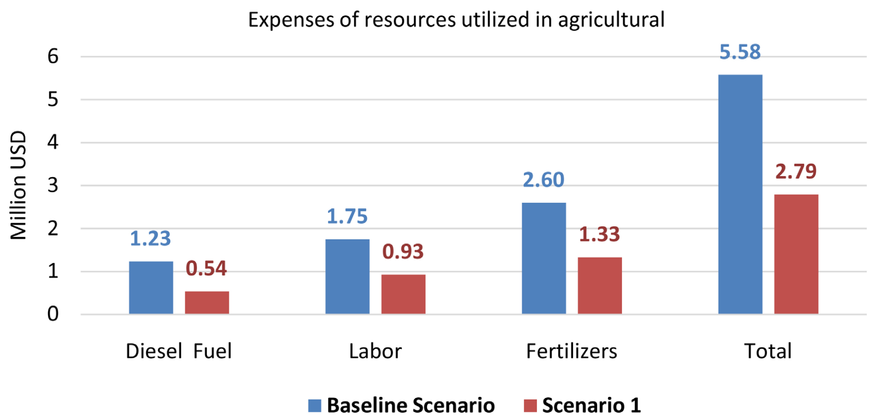

Figure 6. Total expenses of resources utilized in agricultural production.

Due to these significant savings, farmers can fully recover the costs of installing smart irrigation systems in just 3 months. This quick payback period not only highlights the immediate economic benefits but also demonstrates the long-term financial soundness of adopting smart irrigation technologies. The swift return on investment makes smart irrigation a compelling and viable choice for farmers, promising both immediate profitability and sustained economic stability.

To effectively apply the findings from our study to other arid and semi-arid regions globally, they must be adjusted to fit local conditions, including particular crop types, soil properties, and socio-economic factors. Policy support and investment in infrastructure, as well as pilot projects to refine and validate the technology in different regions, are essential for broader implementation. These steps can ensure the scalability and effectiveness of solar-powered smart irrigation systems in enhancing resource efficiency and sustainability in agriculture worldwide.

4. Conclusion

The study's examination of the water-energy-food-ecosystems (WEFE) nexus, with a focus on shifting to smart irrigation in Lebanese agriculture, provides substantial evidence of the viability and impact of sustainable practices. It has been shown that integrating smart irrigation significantly boosts resource efficiency, with water usage reduced by 58% and diesel fuel consumption for irrigation cut by 57%. The demand for labor and fertilizers dropped by 47% and 49%, respectively. These findings underscore the potential of sustainable methods in addressing the pressing challenges of water scarcity and energy sustainability.

Moreover, the economic and environmental advantages of these sustainable practices are clear. Reduced operational costs for water and fertilization, along with significant decreases in greenhouse gas emissions, demonstrate that it is possible to achieve economic efficiency while also promoting environmental health. The reduction in resource costs allowed farmers to recover the costs of installing the smart irrigation system within just 3 months. This rapid payback period highlights both the immediate economic benefits and the long-term financial viability of adopting smart irrigation technologies, making it a highly attractive option for farmers. This supports the overarching objectives of sustainable development by showcasing a balance between economic growth and environmental conservation.

The study emphasizes the importance of sustainable agriculture for resilience against environmental challenges, particularly in semi-arid regions like Lebanon. Smart irrigation is shown to be an effective solution for sustainable agriculture, offering a model for similar regions globally and helping achieve sustainable development goals.

Finally, a more detailed environmental impact assessment, particularly regarding CO_2 emissions and toxicity release, would enhance the robustness of our study's conclusions. Future research will aim to incorporate more granular data and employ advanced analytical methods to capture the full spectrum of environmental impacts. This could include lifecycle assessments, detailed emission inventories, and comprehensive toxicity modeling to provide a deeper understanding of the environmental benefits and trade-offs associated with smart irrigation systems. We will consider these aspects for further development of our research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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