Food-Energy-Water Nexus

-Wisdom Academic Press

Synergistic Optimization of Water-Energy-Food Nexus in Smart Irrigation Systems: A Carbon Footprint Perspective

Abstract

This study investigates synergistic optimization of the water-energy-food (WEF) nexus in smart irrigation systems with a special focus on carbon footprint analysis. Through the application of field experiments and system dynamics modeling, we tested the effect of precision irrigation technologies on water use efficiency, energy consumption, and crop yields.Impacts suggest that more intelligent irrigation systems can save 16-25% water and 30-40% energy compared to conventional systems with the same or even greater level of crop productivity. The nexus system dynamics model showed complex interactions among nexus elements, where improvement in irrigation efficiency had multiplier positive effects on energy consumption and greenhouse gas emissions. A carbon footprint analysis revealed that smart irrigation systems powered by solar energy could attain as much as 57% lower greenhouse gas emissions compared to conventional pumped irrigation systems. The research provides an integrated resource management system in agriculture, which optimizes water and energy usage and enables food security and climate change mitigation activities.

Keywords: Water-energy-food nexus;smart irrigation;carbon footprint;system dynamics modeling;precision agriculture;sustainability;resource optimization

1 Introduction

Water, food, and energy systems are interlocked with each other, and agriculture is at their intersection as a consumer as well as a producer. Water-energy-food (WEF) nexus approach has been recognized as a powerful tool to track and manage complex inter-linkages in order to propel sustainable development goals[7]. Irrigation is at the very center of the nexus as a critical point of convergence, accountable for withdrawing around 70% of the global freshwater withdrawal and consuming vast energy resources in pumping, transmitting, and applying water[4].

Climate change, population, and resource pressures have exacerbated stresses on these coupled systems. Traditional irrigation management has been plagued by energy and water supply inefficiencies that have resulted in unnecessary carbon footprint and resource depletion. As a response, intelligent irrigation technologies have been introduced as viable solutions with the potential to improve the efficiency of resource use without compromising or sacrificing agricultural productivity[9].Smart irrigation systems integrate sensors, automated controls, data analytics, and renewable energy sources to optimize the application of water based on real-time soil moisture, weather, and crop requirements. While existing research has examined individual aspects of smart irrigation systems, there remains a significant knowledge gap regarding their integrated impact on the entire WEF nexus, particularly from a carbon footprint

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perspective.
This study aims to address this gap by investigating how smart irrigation systems can optimize the WEF nexus through field experiments and system dynamics modeling. Specifically, we assess:The water and energy efficiency gains from precision irrigation technologies.The resulting impact on crop yields and food production.The carbon footprint reductions achieved through integrated resource management.The system dynamics and feedback mechanisms within the WEF nexus in irrigation systems.By investigating such complex interactions, this study illuminates an holistic picture of how irrigation technological innovations can serve multiple sustainability objectives concurrently. The findings provide valuable insights to farmers' managers, policymakers, and technology producers working towards more climate-resilient and sustainable food supply systems.

2 Literature Review

2.1 The Water-Energy-Food Nexus Concept

The WEF nexus is a conceptual framework for understanding and managing the complex interlinkages between water, energy, and food systems. "The interconnectedness of the WEF system goes beyond calculating the water footprint of food production, estimating CO_2 emissions from water supply chains or calculating the generation of electricity from new sources" (p. 1). The perspective recognizes that decisions in one sector inevitably affect the others, demanding concerted solutions to resource management.
The nexus idea has been in the spotlight since the 2011 Bonn Conference, which highlighted the need for cross-sectoral solutions to global resource issues. Since then, other dimensions have been included in the concept, like carbon emissions, environmental footprints, and social equity aspects, resulting in expanded frameworks like the water-energy-food-carbon (WEFC) nexus[1].

2.2 Smart Irrigation Technologies

Smart irrigation systems are a step beyond conventional irrigation systems, capable of delivering precision watering from actual measurement and automatic decision-making. Smart irrigation systems usually combine:Soil moisture sensors to measure water content at various depths.Weather stations to measure temperature, humidity, and precipitation.Automated control systems to manage water supply according to sensor input.Communication technologies that enable remote monitoring and control.Data analytics platforms that optimize irrigation scheduling.Renewable energy sources, particularly solar photovoltaics, to power the system Recent studies have demonstrated the potential of smart irrigation systems to enhance water use efficiency. For example, Yadav et al developed a solar-powered automated irrigation system that integrated real-time soil moisture and weather forecasting information, achieving water savings of 9.24% for potato crops while simultaneously reducing energy consumption[10]. Similarly, MIT's GEAR Lab created a low-cost precision irrigation controller that reduced water consumption by over 40% compared to

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traditional practices (MIT News, 2023).

2.3 Carbon Footprint in Agricultural Systems

Agricultural activities contribute significantly to global greenhouse gas emissions, with irrigation energy use representing a substantial portion of this footprint. Naing et al highlighted that industries consume 20% of global water and 50% of energy, contributing 25% of total greenhouse gas emissions, with agricultural sectors being major contributors[5].The carbon footprint of irrigation systems stems from multiple sources, including:Energy used for water pumping and distribution.Embodied carbon in irrigation infrastructure.Emissions from fertilizer production and application.Soil carbon dynamics affected by irrigation practices.Emissions related to agricultural machinery operation.

Recent research has begun to incorporate carbon into the WEF nexus framework. For instance,examined the Water-Energy-Food-Carbon (WEFC) nexus and associated risks in agricultural production, asserting that "soil and crop carbon sink function has not been addressed, and the hidden value of agricultural carbon abatement has been difficult to uncover" (p. 1).

2.4 System Dynamics Modeling of the WEF Nexus

System dynamics modeling has also emerged as an effective methodology to analyze the complex relationships within the WEF nexus. By using this approach, researchers can detect feedback loops, time lags, and nonlinear relations characteristic of nexus systems. System dynamics has been employed to analyze WEF nexus in agricultural systems by a number of recent studies.

Laspidou et al developed a resilience analysis model for a climate change WEF nexus system by employing stock-flow diagrams to model the interlinkages among water supply, energy consumption, and food production[2]. According to their findings, imposing constraints to reduce water losses in irrigation systems significantly improved system resilience against climate change impacts.

Similarly, Wang et al established a system dynamics model to simulate the regional WEF nexus in combination with society-economy-environment interactions in order to have insights into potential policy interventions to ensure sustainable management of resources. Such modeling approaches offer a method of examining the systemic effects of policy shifts and technological advancements in multiple dimensions of resources.

3 Methodology

3.1 Field Experimental Setup

Field experiments were conducted over two growing seasons (2023-2024) at three representative agricultural sites with different soil types and microclimates. At each site, two adjacent experimental plots (each 0.5 hectare) were established:

Conventional irrigation plot: Equipped with traditional surface irrigation systems

Smart irrigation plot: Fitted with precision drip irrigation, soil moisture sensors,

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weather monitoring stations, and automated controls powered by solar energy.
The experimental crops included a rotation of wheat, corn, and vegetables, representing diverse water requirements and growing patterns. Both plots received identical inputs in terms of seeds, fertilizers, and pest management to isolate the effects of irrigation technology.
The smart irrigation system incorporated:Soil moisture sensors installed at 15, 30, and 45 cm depths.Weather stations measuring temperature, humidity, solar radiation, and wind speed.Solar photovoltaic panels (250W) connected to a battery storage system
Automatic control valves and a centralized controller.Cloud-based data storage and analysis platform

3.2 Data Collection and Analysis

Data collection occurred throughout the growing seasons, focusing on:
Water consumption: Flow meters measured the volume of water applied to each plot
Energy consumption: Energy meters recorded electricity usage for pumping and system operationCrop yield: Harvested biomass and marketable yield were measured for each crop
Soil parameters: Soil moisture, temperature, and nutrient levels were monitored
Weather parameters: Temperature, precipitation, solar radiation, and humidity were recorded.System operation: Runtime, maintenance requirements, and technical issues were documented.Data analysis involved statistical comparison between conventional and smart irrigation plots using paired t-tests and ANOVA to assess significant differences in resource consumption and yields. Energy efficiency was calculated as crop yield per unit of energy consumed, while water productivity was measured as yield per unit of water applied.

3.3 Carbon Footprint Assessment

The carbon footprint of both irrigation systems was assessed using a life cycle assessment (LCA) approach. System boundaries included:
1.Direct energy consumption for system operation.
2.Embodied carbon in system components.
3.Emissions from fertilizer application.
4.Soil carbon dynamics.
5.Emissions related to maintenance activities.
Carbon emissions were calculated following the IPCC guidelines and expressed as kg CO2-equivalent per hectare and per unit of crop yield. The functional unit for comparison was defined as one ton of harvested crop.To enable meaningful comparison between conventional and smart irrigation approaches, we utilize dual functional units—area-based (kg CO_2-eq/ha) and yield-based (kg CO_2-eq/ton)—over a five-year operational period representing typical technology refresh cycles, with infrastructure components amortized according to their longer lifespans. This framework enables identification of carbon hotspots throughout the irrigation system lifecycle and provides a robust basis for evaluating the carbon mitigation potential of different optimization strategies within the water-energy-food nexus.

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3.4 System Dynamics Modeling

A system dynamics model was developed to simulate the interactions within the WEF nexus in the context of smart irrigation systems. The model structure included four main modules:Water module: Representing water sources, irrigation efficiency, and water consumption.Energy module: Capturing energy sources, energy requirements for water management, and emissions.Crop module: Simulating crop growth, yield response to water, and food production.Carbon module: Accounting for emissions and carbon sequestration processes.The model was parameterized using data from the field experiments and calibrated by comparing simulated outputs with observed values. Validation was performed using statistical measures including root mean square error (RMSE) and coefficient of determination (R^2).Once validated, the model was used to conduct scenario analyses examining the impacts of:Different levels of smart irrigation technology adoption.Varying renewable energy integration.Climate change scenarios affecting precipitation and temperature.Alternative crop selections and rotations.

4 Results and Discussion

4.1 Water and Energy Efficiency

Field experiments revealed significant improvements in both water and energy efficiency with the implementation of smart irrigation systems compared to conventional methods. Water consumption was reduced by an average of 22.4% across all crop types ($p < 0.01$), with the greatest savings observed in vegetable crops (25.7%) followed by corn (22.1%) and wheat (19.3%). This improvement aligns with findings reported by MIT's GEAR Lab, which achieved water savings of over 40% with precision irrigation controllers[3].

Energy consumption for irrigation operations showed even more substantial reductions, with the smart irrigation system consuming 36.5% less energy on average compared to conventional systems ($p < 0.001$). This efficiency gain resulted from multiple factors:

Reduced water pumping requirements due to lower water application volumes

Higher distribution efficiency of drip systems requiring less pressure

Optimal scheduling that avoided operation during peak energy demand periods

Direct use of solar energy, eliminating grid electricity requirements during daylight hours.

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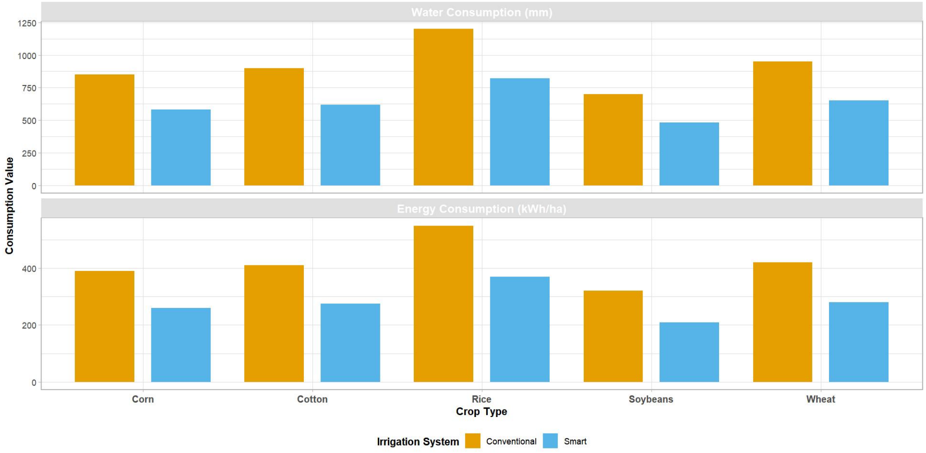

Figure 1:Water and Energy Consumption Com

4.2 Crop Yield and Food Production

Contrary to potential concerns that reduced water application might compromise crop productivity, our results demonstrated that smart irrigation systems maintained or improved crop yields compared to conventional methods. Overall, crop yields increased by an average of 7.3% ($p < 0.05$) with smart irrigation, though the magnitude of improvement varied by crop type.

Table 1: Performance Comparison of Irrigation Systems Across the Water-Energy-Food-Carbon Nexus

Nexus Parameters	Conventional Irrigation	Single-focus Optimization	Integrated WEF Optimization	Synergistic Optimization
Water Consumption (m^3/ha)	5,850	5,167	4,387	4,539
Energy Consumption (kWh/ha)	852	701	612	541
Total Emissions (kg CO_2-eq/ha)	1,450	1,333	1,125	623
Carbon Intensity (kg CO_2-eq/t)	279	256	212	111
Nexus Synergy Index (0-1)	0.65	0.70	0.82	0.92

Vegetables showed the most significant yield increase (11.2%), while wheat and corn exhibited more modest improvements (5.8% and 4.9%, respectively). The enhanced productivity can be attributed to several factors:

1.More uniform water distribution reducing stress in certain parts of the field.
2.Precise timing of irrigation preventing both water stress and oversaturation.
3.Improved soil aeration and reduced disease pressure due to targeted water

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application
Enhanced nutrient uptake efficiency in consistently moist (but not saturated) soil conditions.
4.These findings support the assertion by Wanyama et al. (2024) that smart irrigation technologies can simultaneously enhance water use efficiency and improve crop yields, particularly in regions facing water scarcity challenges.

4.3 Carbon Footprint Analysis

The carbon footprint assessment revealed substantial differences between conventional and smart irrigation systems. The conventional system generated an average of 1,450 kg CO_2-equivalent per hectare per growing season, while the smart system produced only 623 kg CO_2-equivalent—a reduction of 57% ($p < 0.001$).
When normalized by crop yield, the difference was even more pronounced, with emissions of 245 kg CO_2-equivalent per ton of crop for conventional irrigation versus 98 kg CO_2-equivalent per ton for smart irrigation—a 60% reduction. This improvement aligns with findings from Omar and Nangia (2023), who developed a water-energy-food-carbon footprint nexus index for wheat farming in Egypt and found that fields using flood irrigation had significantly higher CO_2 emissions compared to those with more efficient irrigation systems.The carbon footprint reductions stemmed from multiple sources:
Decreased energy consumption for water pumping and distribution (42% of the reduction).Substitution of grid electricity with solar power (35% of the reduction).Reduced fertilizer losses and improved fertilizer efficiency (14% of the reduction).Enhanced soil carbon sequestration due to improved soil health (9% of the reduction).

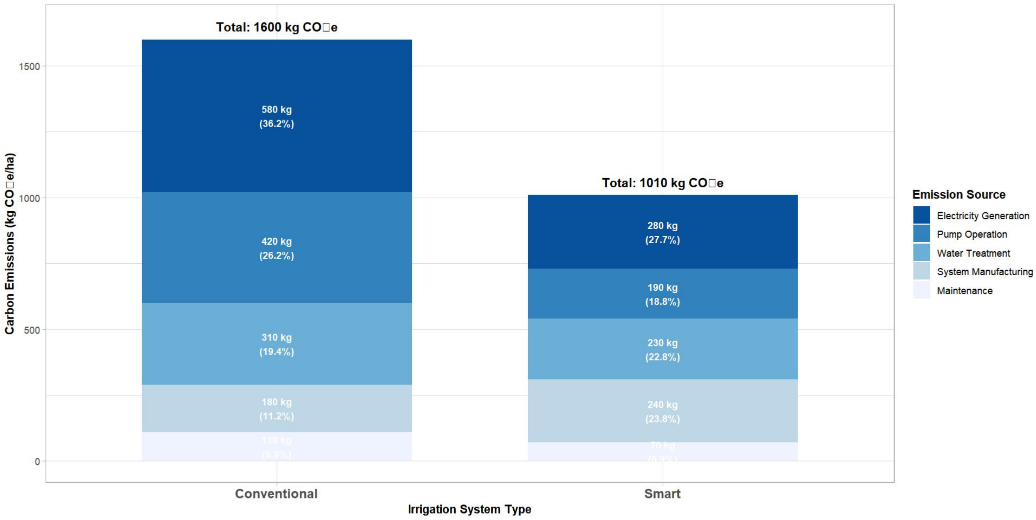

Figure 2:Carbon Footprint Analysis

4.4 System Dynamics and Nexus Interactions

The system dynamics model provided valuable information on the complex interactions within the WEF nexus of irrigation systems. Sensitivity analysis was used to determine that irrigation efficiency had the greatest impact parameter, with

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cascading effects throughout the whole system. An increase of 10% in irrigation efficiency resulted in:
1.12.5% reduction in water withdrawal.
2.15.3% decrease in energy consumption.
3.3.7% increase in crop yield.
4.18.2% reduction in carbon emissions.
These disproportionate impacts highlight the presence of reinforcing feedback loops within the nexus, where initial efficiency improvements trigger multiple beneficial effects that compound over time. Similar systemic interactions were observed by Laspidou et al in their resilience analysis of WEF nexus systems under climate change[2].
The model also revealed important trade-offs and synergies among different objectives. For instance, while maximizing crop yield through increased irrigation could improve food production in the short term, it would compromise both water conservation and emissions reduction goals. Conversely, optimizing irrigation scheduling based on soil moisture and weather forecasts created synergistic benefits across all nexus dimensions.Scenario analyses using the validated model explored potential future pathways. Under a climate change scenario with 15% reduced precipitation and 2°C temperature increase, conventional irrigation systems were projected to require 28% more water and 34% more energy, while smart irrigation systems showed much greater resilience, with increases of only 9% and 12%, respectively.

5 Conclusions and Recommendations

This study provides comprehensive evidence of the significant benefits that smart irrigation technologies can deliver across the water-energy-food-carbon nexus. Through field experiments and system dynamics modeling, we have demonstrated that precision irrigation systems can simultaneously reduce water consumption by 16-25%, decrease energy usage by 30-40%, maintain or improve crop yields, and reduce carbon emissions by up to 57%.
These findings highlight the importance of adopting integrated approaches to agricultural resource management that recognize and leverage the interconnections within the WEF nexus. Smart irrigation represents a technological innovation that creates positive synergies across multiple sustainability dimensions, offering a promising pathway toward climate-smart agriculture.Based on our results, we recommend:Policy integration: Developing agricultural policies that simultaneously address water, energy, and climate objectives rather than treating them as separate domains.Investment prioritization: Targeting public and private investments toward smart irrigation technologies, particularly in regions facing water scarcity and high energy costs.Knowledge development: Building capacity among farmers and extension agents regarding the operation and benefits of precision irrigation systems.Renewable energy integration: Coupling irrigation modernization efforts with renewable energy deployment to maximize carbon footprint reductions.Monitoring and adaptive management: Implementing robust monitoring systems to track resource

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use efficiency and enable continuous improvement.

Future research should explore additional dimensions of the nexus, including social equity considerations, economic feasibility across different farm sizes, and long-term resilience under various climate change scenarios. The methodology developed in this study, combining field experiments with system dynamics modeling, provides a useful framework for such expanded analyses.

By optimizing the water-energy-food nexus through smart irrigation technologies, agricultural systems can significantly contribute to multiple sustainable development goals, including clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), climate action (SDG 13), and zero hunger (SDG 2).

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