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Optimizing Crop Schedules and Environmental Impact in Climate-Controlled Greenhouses: A Hydroponic vs. Soil-Based Case Study

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ABSTRACT

Optimizing greenhouse operations in arid regions is essential for sustainable agriculture due to limited water resources and high energy demands for climate control. This paper proposes a multi-objective optimization framework aimed at minimizing both the operational costs and environmental emissions of a climate-controlled greenhouse. The framework determines optimal allocation of growing area among three crops (tomato, cucumber, and bell pepper) throughout the year. These crops were selected for their varying growth conditions, which induce variability in energy and water inputs, providing a comprehensive assessment of the optimization model. The model integrates factors such as temperature, humidity, light intensity, and irrigation requirements specific to each crop. It is solved using a genetic algorithm combined with Pareto front analysis to address the multi-objective nature effectively. This approach facilitates the identification of optimal trade-offs between cost, emissions, and yield, offering a set of efficient solutions for decision-makers. Applied to a greenhouse in Qatar, the model evaluates two scenarios: a hydroponic system and a conventional soil-based system. Results indicate that the multi-objective optimization effectively reduces operational costs and environmental emissions while fulfilling crop demand.The hydroponic scenario demonstrates higher water-use efficiency, resulting in lower overall emissions despite higher initial setup expenses. The soil-based system shows higher emissions due to increased fertilizer use and water consumption. The optimized allocation balances multiple crops simultaneously throughout the year based on seasonal conditions, enhancing overall sustainability. This study underscores the potential of advanced optimization techniques in enhancing the efficiency and sustainability of greenhouse agriculture in challenging environments.

Keywords: Multi-Objective Optimization, Hydroponics, Climate-controlled Agriculture, Greenhouses

INTRODUCTION

Background

The growing global demand for food, coupled with the challenges posed by climate change and resource scarcity, has intensified the need for innovative agricultural practices. In arid regions, the situation is particularly critical, as extreme temperatures, limited water availability, and high energy requirements create significant obstacles for sustainable food production. Greenhouse agriculture has emerged as a viable solution to address these challenges by enabling controlled environments for crop cultivation. However, optimizing greenhouse operations to balance resource use, operational costs, and environmental impact remains a complex task.

Greenhouses offer a controlled environment that can mitigate the adverse effects of harsh climatic conditions, making them indispensable in arid regions. By regulating factors such as temperature, humidity, and light intensity, greenhouses facilitate year-round cultivation and higher yields. Nevertheless, maintaining these conditions requires substantial water and energy inputs, particularly for cooling and irrigation systems, which can increase costs and environmental emissions. To ensure the sustainability of greenhouse agriculture, it is imperative to adopt strategies that optimize resource allocation while minimizing operational expenses and environmental impacts [1].

Research on greenhouse optimization in arid climates covers a broad spectrum of topics, including water management, energy efficiency, and crop scheduling. Early work by [2] demonstrated the advantages of greenhouse cultivation for extending growing seasons and improving crop yields in regions with scarce water resources. In parallel, studies have shown that precise climate control systems significantly reduce water wastage and energy consumption, particularly when combined with automation technologies [3]. Furthermore, recent investigations by [4] have highlighted the potential of integrating renewable energy sources, such as solar power, to reduce the carbon footprint of greenhouse operations.

Hydroponic systems have emerged as one promising avenue for achieving high water-use efficiency [5]. Compared to conventional soil-based approaches, hydroponics can lower water consumption while maintaining or even enhancing crop yield. Additionally, the nutrient solution in hydroponic setups can be carefully regulated and recycled, minimizing both resource use and environmental discharge. Despite these advantages, challenges remain in balancing initial setup costs and the technical expertise needed to maintain such systems, as indicated by [6].

Multi-objective optimization has also been widely explored to identify trade-offs between economic viability and environmental sustainability. By employing advanced computational methods such as genetic algorithms, researchers have been able to analyze various configurations of crop types, resource allocations, and climate control strategies, revealing Pareto-optimal solutions that can guide policymakers and greenhouse operators [7]. However, many existing models focus on one or two objectives (e.g., water or energy), highlighting the need for a holistic framework that simultaneously considers cost, emissions, and other operational constraints.

These studies highlight the importance of a multi-faceted approach to greenhouse optimization in arid environments. By building prior work in water management, energy efficiency, and multi-objective optimization, the present study seeks to advance the state of the art through an integrated framework that addresses the complex interplay of cost, emissions, and resource limitations in a comprehensive manner.

Objectives and Outline

This study aims to create an integrated optimization framework that enhances the sustainability of climate-controlled greenhouse operations, particularly in arid regions. The research focuses on three interconnected objectives. Firstly, it aims to minimize operational costs, specifically targeting water and energy expenses, which are significant contributors to overall costs. Secondly, it seeks to reduce environmental emissions linked to energy consumption and cooling needs. Finally, the study emphasizes the importance of maintaining adequate crop diversity to satisfy market demands and strengthen agricultural resilience against climatic and economic challenges.

Following this introduction, the data and methods describe the methodology, detailing the mathematical formulation, decision variables, objectives, and constraints. Afterward, the case study section focuses on the implementation of the genetic algorithm, emphasizing how multi-objective optimization is employed to handle competing goals. Then, the results are presented and analyzed, offering insights into the trade-offs between cost and emissions under the two cultivation scenarios. Finally, the conclusion concludes by summarizing the key findings, discussing the implications for greenhouse operations in arid regions, and suggesting avenues for further research.

DATA AND METHODS

Case study

This study develops an optimization framework to enhance the sustainability of climate-controlled greenhouse operations in arid regions, notably in Qatar. Greenhouses located in these areas face unique challenges, such as extreme temperatures, water scarcity, and high electricity demands for cooling and irrigation purposes. Addressing these challenges requires a holistic approach that accounts for the tradeoffs between economic costs, environmental impacts, and resource constraints. The proposed framework introduces a multi-objective optimization model that determines efficient allocation of growing area to multiple crops simultaneously, aiming to reduce greenhouse emissions and costs while satisfying market demands. A case study was conducted to evaluate the framework's applicability to a medium-scale greenhouse in Qatar. The greenhouse was designed to cultivate three crops: tomato, cucumber, and bell pepper, selected for their economic value, varying resource requirements, and high consumption in the local market. The study considered two cultivation systems: a hydroponic system, which offers higher water-use efficiency and precise nutrient management, and a conventional soil-based system, which is more commonly adopted but generally less efficient in water usage. The optimization model was tailored to reflect the specific environmental conditions of Qatar, taking into consideration the average monthly temperatures, water availability, and electricity prices. The methodology integrates multi-objective optimization and scenario analysis to achieve operational efficiency while minimizing environmental emissions. The subsequent section describes the mathematical formulation utilized in this model.

Table 1: Key data used in the optimisation model.

Parameter	Value	Unit
Average Monthly Temp.	25 – 40	°C
Water Availability	1000 - 1500	Liters/day
Energy Cost	0.12 - 0.15	USD/kWh
Water Cost	0.05 - 0.07	USD/Liter
Greenhouse Area	500	m²
Heat Transfer Coeff	5 - 6	W/(m²·K)
Cooling Capacity	30000	BTU/h

Mathematical Formulation

This model optimizes the operational cost, environmental emissions, and crop yield of a climate-controlled greenhouse. The greenhouse is designed to grow three crops: tomato, cucumber, and bell pepper, over a 12-month period with the ability to allocate different percentages of growing area to each crop monthly. The mathematical formulation of the multi-objective optimization problem is presented below:

Objective functions:

Minimize the operational cost (*C*):

$$C = \sum_{j=1}^{12}\sum_{i}(W_i \cdot x_{ij} \cdot c_w + E_i \cdot x_{ij} \cdot c_e) \quad (1)$$

Where:

$i \in \{Tomato, Cucumber, Bell\ Pepper\}$

$j \in \{1,2,\ldots,12\}$

W_i: Water requirement of crop *i* (liters/month).

c_w: Cost per unit of water.

E_i: Energy requirement of crop *i* (kWh/month).

E_i: Cost per unit of energy.

Minimize Environmental Emissions (*E*):

$$E = \sum_{j=1}^{12}\sum_{i}(E_i \cdot x_{\{ij\}} \cdot e_e + Q_{\{ij\}} \cdot e_c) \quad (2)$$

where:

$i \in \{Tomato, Cucumber, Bell\ Pepper\}$

e_e: Emission factor per unit of energy.

Q_{ij}: Cooling load for crop *i* in month *j*, calculated as:

$$Q_{ij} = U \cdot A \cdot \Delta T_{ij} \quad (3)$$

U : Heat transfer coefficient (W/m²·K).

A: Greenhouse surface area (m²).

ΔT_{ij}: Temperature difference between the greenhouse interior and the external environment for crop *i* during month *j*.

e_c: Emission factor for cooling load (kg CO_2 per unit energy).

Decision variable:

$x_{ij} \in \{0,1\}$ is the binary decision variable such that $x_{ij}=1$ if crop *i* is cultivated during month *j*, and $x_{ij}=0$ otherwise.

Subject to the following constraints:

Crop Diversity Constraint: To meet market demands and ensure crop diversity, each crop must be cultivated at least once annually:

$$\sum_{j=1}^{12} x_{ij} \geq 1 \quad (4)$$

Water usage constraint**:** The total water usage across all crops must not exceed the annual water availability, which is equal to 2000 L/day:

$$\sum_{j=1}^{12}\sum_{i}(W_i \cdot x_{ij}) \leq water\ limit \quad (5)$$

Energy usage constraint: The total energy consumption must not exceed the available energy budget, which is equal to 25000 kWh/day:

$$\sum_{j=1}^{12}\sum_{i}(E_i \cdot x_{ij}) \leq energy\ limit \quad (6)$$

Cooling capacity constraint: The total cooling load must remain within the greenhouse's cooling capacity, which is equal to 300,000 BTU/h:

$$\sum_{j=1}^{12}\sum_{i}(Q_i \cdot x_{ij}) \leq Cooling\ capacity \quad (7)$$

Monthly cultivation constraint**:** Only one crop can be cultivated in the greenhouse during each month:

$$\sum_{i} x_{ij} = 1 \quad (8)$$

Non-negativity and binary constraints: The decision variables are binary:

$$x_{ij} \in \{0,1\}, = \ \forall i,j$$

A genetic algorithm (GA) is employed to solve the multi-objective optimization problem. The GA is chosen due to its robustness in handling complex, non-linear problems with multiple objectives and constraints.

Scenario Analysis

The optimization framework is applied to two scenarios. The first scenario assumes the greenhouse is equipped with a hydroponic system, which allows for precise control of water and nutrients.Hydroponic systems reduce water usage by up to 30-40% compared to soil-based systems and optimize fertilizer application to match plant growth requirements, minimizing waste. Energy demand in this scenario is primarily for pumping water and maintaining nutrient solutions, with substantial requirements for climate control in Qatar's hot environment.

The second scenario represents a traditional soil-based cultivation approach. Soil systems typically have higher water requirements due to evaporation and less efficient delivery methods. Nutrient delivery is less precise, potentially leading to higher fertilizer use and leaching. The model accounts for these differences by adjusting the water efficiency parameters and nutrient costs appropriately. Each scenario is evaluated for its ability to meet crop demands while minimizing costs and emissions. The model allows for simultaneous cultivation of multiple crops with flexible area allocation, reflecting real-world greenhouse operations. This approach enables more efficient resource utilization as different crops can be allocated optimal space based on their specific requirements and market value during each month.

Results and discussion

This section presents the outcomes of the multi-objective genetic algorithm applied to optimize greenhouse operations in the two scenarios described previously: hydroponic and soil-based systems. The results focus on (i) cost, emissions, and yield trade-offs, (ii) monthly resource usage, and (iii) crop distribution over the 12-month planning horizon.The genetic algorithm was executed for 50 generations with a population size of 100 individuals. The optimization yielded a set of Pareto-optimal solutions representing different trade-offs between operational cost, environmental emissions, and crop yield. Figure 1 illustrates the 3D Pareto front, showing the relationship between operational cost (USD), environmental emissions (kg CO_2-eq), and total yield (kg) for both systems. The results reveal distinct regions in the solution space for each cultivation system. The hydroponic system generally occupies a region with higher costs but lower emissions, while the soil-based system shows lower costs but higher emissions. This pattern aligns with the inherent characteristics of each system: hydroponic systems require higher initial investment and maintenance but offer better resource efficiency. Table 2 summarizes key indicators for the best Pareto-optimal solution identified in each scenario based on the optimization results.Figure 1. Pareto-optimal solution.

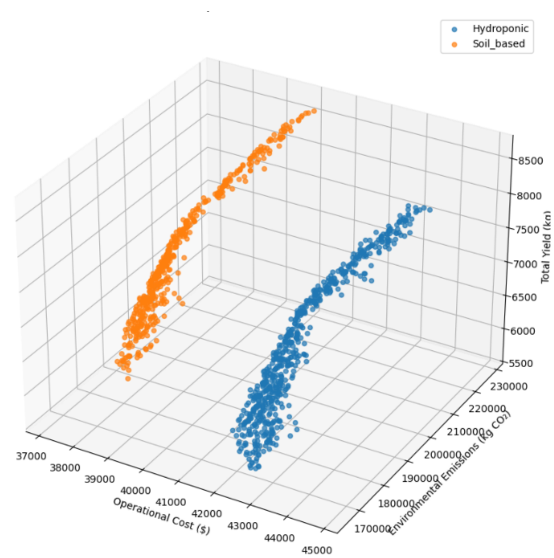

Table 2. Comparison of key performance metrics between Cultivation Systems

Metric	Hydroponic System	Soil-Based System	Difference (%)
Total Operational Cost ($)	39,682.43	35,174.01	-11.36
Environmental Emissions (kg CO_2)	170,842.96	186,321.28	9.06
Water Usage (liters)	218,636.69	328,635.76	50.31
Energy Usage (kWh)	290,353.62	288,190.91	-0.74
Total Yield (kg)	5,910.15	5,686.28	-3.79

The optimization results reveal several important insights regarding greenhouse operations in Qatar's arid climate. In terms of operational costs, the soil-based system shows an 11.36% cost advantage over the hydroponic system. This finding might initially seem counterintuitive given hydroponics' reputation for efficiency. However, it reflects the higher installation, equipment, and maintenance costs associated with hydroponic systems, which offset some of their operational advantages. Despite its cost advantage, the soil-based system produces 9.06% higher environmental emissions than the hydroponic system. This difference primarily stems from the additional fertilizer emissions in soil-based cultivation and the higher water consumption, which has associated emissions from pumping and treatment. The hydroponic system's better nutrient management and recycling capabilities help reduce its overall environmental footprint. The most striking difference between the two systems is in water usage. The soil-based system requires 50.31% more water than the hydroponic system, a significant consideration in Qatar's water-scarce environment where desalination is both expensive and energy-intensive. This substantial difference in water efficiency represents a compelling advantage for hydroponics in arid regions. Interestingly, energy usage remains relatively similar between the two systems (only 0.74% difference). This result suggests that while hydroponic systems have additional energy requirements for pumping and circulation systems, these are largely offset by the soil-based system's potentially higher cooling needs due to heat retention in the soil medium. In terms of crop yields, the soil-based system produces 3.79% less total yield than the hydroponic system. The crop-specific breakdown reveals interesting patterns: soil-based systems perform better for tomatoes (+25.14%) and bell peppers (+3.19%), while hydroponic systems excel at cucumber production (-25.93% in soil compared to hydroponic). These differences reflect the varying suitability of each crop to different growing environments and the optimization algorithm's response to these factors.

The optimized monthly crop allocation reveals a strategic approach to dealing with Qatar's climate variations. During the hottest months (May-September), the model allocates more space to heat-tolerant crops. In both systems, cucumber receives higher allocation during the hottest summer months (July-August in hydroponic; August-October in soil-based) when its water efficiency and heat tolerance provide advantages. Bell pepper, which generally requires less extreme temperatures, receives higher allocation during the milder months. Tomato allocations are strategically distributed throughout the year, with higher percentages in transitional seasons. These allocation patterns demonstrate how the optimization balances multiple factors: crop-specific requirements, seasonal temperature variations, resource constraints, and market demands. The ability to allocate growing area flexibly among multiple crops simultaneously enables more efficient greenhouse utilization compared to single-crop approaches.

In the context of Qatar's specific challenges, these results underscore the importance of considering multiple criteria when selecting greenhouse systems. While hydroponics offers clear advantages in water efficiency, critical in a water-scarce environment, soil-based systems may still be attractive for farms with limited capital or technical expertise. The model provides decision-makers with valuable information on the trade-offs involved, allowing them to select solutions that best align with their specific priorities, constraints, and environmental conditions.

CONCLUSION

This study presents a multi-objective optimization framework tailored to the challenging climatic and resource conditions of Qatar. By simultaneously minimizing operational costs and environmental emissions while maximizing crop yield, the framework reveals important trade-offs between water-efficient hydroponic systems and more traditional soil-based approaches. The results underscore that hydroponic cultivation can substantially reduce water usage, of particular importance in a country reliant on energy-intensive desalination, while also moderating emissions through more precise nutrient management. Nevertheless, the soil-based scenario retains economic viability through lower operational costs, though it incurs higher resource consumption and resultant environmental impacts over time. A key insight from this study is the value of flexible crop allocation throughout the year. The optimization shows that simultaneously growing multiple crops with varying area allocations based on seasonal conditions can significantly improve overall greenhouse performance compared to single-crop approaches. Strategic alignment of crop allocations with monthly temperature variations can reduce both water consumption and cooling loads, thus lowering operational costs and emissions. The differences between hydroponic and soil-based systems are substantial in some metrics (particularly water usage, with a 50.31% difference) but minimal in others (such as energy usage, with only a 0.74% difference). These nuanced findings highlight the importance of comprehensive analysis that considers multiple factors rather than focusing on single metrics when evaluating greenhouse systems. These insights are particularly valuable for policymakers, agricultural planners, and greenhouse operators seeking to optimize production efficiency under harsh climatic constraints. Future work could expand upon this research by integrating real-time climate data, exploring additional crop varieties, or leveraging renewable energy sources to further mitigate environmental impacts and foster resilient, cost-effective greenhouse systems in Qatar and beyond.

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