Framework based on a coupled input-yield model for infrastructure-driven agriculture

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Abstract

As the population and demand for food increases, the need to produce food locally in a sustainable manner is imperative for a country's food security. Traditional agriculture in arid regions faces difficulties due to non-arable land and harsh climate, hindering crop growth. Controlled environment agriculture, particularly greenhouses, offers a practical solution by protecting crops from external elements and supplying necessary resources. However, controlled environment agriculture systems require significant energy and water resources to sustain optimal conditions for crop development. In greenhouse operations, the innovative approach of the potential repurposing of excessive cooling from underutilised mega infrastructure could lead to cost savings and more efficient production. Therefore, this research introduces a novel approach that utilises the infrastructure from the 2022 FIFA World Cup™ for agricultural purposes. It presents a unique methodology for the dual use of large-scale facilities, focusing on integrating agricultural systems near stadiums using existing cooling systems and space. The results indicate that at optimal conditions, such as day and night temperatures of 18 °C and 24 °C, tomatoes can be produced for $3.50 kg-1. Furthermore, the developed framework is flexible and can be applied globally for co-utilising infrastructure for agricultural production.

**Keywords**: Resource optimisation, Greenhouses, Energy, Crop yield, Infrastructure co-utilisation

# Introduction

The global population is growing rapidly, leading to a significant rise in the demand for essential resources like food, energy, and water. By 2050, it's estimated that the need for these resources will surge by approximately 60% for food, 55% for water, and 80% for energy (Larsson, 2018). Therefore, it is critical to enhance the production of these resources in an efficient and environmentally friendly manner.

In terms of food production, in regions like Qatar, with extreme weather and limited water, traditional agriculture is impractical, leading to heavy reliance on food imports, which can be wasteful and costly (Mahmood et al., 2020). Furthermore, standard agricultural practices and food transportation contribute significantly to global greenhouse gas emissions, exacerbating climate change and further impacting agricultural productivity. Conversely, greenhouses provide a controlled environment for plant growth, regulating temperature and humidity, making them a sustainable solution for food production in challenging climates and helping to mitigate food security issues.

Greenhouses in arid regions like Qatar require significant energy, affecting their cost-effectiveness and sometimes leading to shutdowns during summer (Mahmood et al., 2023a). However, Qatar's innovative approach to repurposing infrastructure from the 2022 FIFA World Cup™ offers an innovative solution. The advanced cooling systems from the seven state-of-the-art stadiums initially used to maintain temperatures during the tournament can be integrated with greenhouse systems. This repurposing can substantially reduce the production costs for greenhouses, enabling efficient, year-round food production. This strategy not only optimises stadium infrastructure post-event but also supports Qatar's goals for food security and sustainable development.

# Methodology

For optimal growth and development, plants cultivated in greenhouse settings need precise control over microclimate and irrigation (Engler and Krarti, 2021). Greenhouses provide the provision to and maintain these ideal conditions throughout different seasons, utilising various technologies and methods. Therefore, this study focuses on closed greenhouses as they are more energy-efficient in arid climates than open ones, reducing cooling needs and better maintaining conditions for crop cultivation.

## *Greenhouse requirement*

Greenhouses in challenging environments need continuous energy, water, and CO2 to support plant growth (Mahmood et al., 2023b). Energy is essential for regulating the internal climate, primarily for cooling. Furthermore, calculating the greenhouse's thermal load is crucial for efficiency and creating suitable growing conditions, especially in regions with extreme climates. The schematic of the closed greenhouse is demonstrated in Figure 1.



Figure 1: Closed greenhouse schematic.

## *Greenhouse input model*

The following equation calculates the cooling requirement of the greenhouse (Van Beveren et al., 2013):

|  |  |
| --- | --- |
|  | (1) |

Water is primarily used to irrigate crops and sustain the necessary humidity levels within the greenhouse. Greenhouses can optimise their water use by accurately assessing water requirements, ensuring that plants receive the right amount of hydration without wastage. The water requirement is determined by the following (Van Beveren et al., 2013):

|  |  |
| --- | --- |
|  | (2) |

CO2 plays a pivotal role in photosynthesis, and its addition to the greenhouse atmosphere can enhance both the quality and yield. Plants steadily utilise the available CO2, leading to a decrease in its concentration over time. Therefore, extra CO2 must be introduced from an external source to maintain the optimal levels necessary for plant growth. The amount of CO2 required is given as follows (Stanghellini et al., 2012):

|  |  |
| --- | --- |
|  | (3) |

## *Greenhouse yield model*

TOMGRO, which considers various greenhouse parameters, estimates crop yield in a greenhouse setting (Jones et al., 1999). The value of is calculated by the following:

|  |  |
| --- | --- |
|  | (4) |

The is given by:

|  |  |
| --- | --- |
|  | (5) |

The following equation gives the rate of dry fruit development of the plant:

|  |  |
| --- | --- |
|  | (6) |

The following equation calculates the total weight of the plant:

|  |  |
| --- | --- |
|  | (7) |

The total mature fruit weight is given as follows:

|  |  |
| --- | --- |
|  | (8) |

The details of the variables and parameters used in the greenhouse model can be found in Mahmood et al. (2023b).

## *Cost of production*

Greenhouse production costs consist of the initial capital and the operational cost. The total cost is given as follows:

|  |  |
| --- | --- |
|  | (9) |

The total cost of greenhouse operation includes factors like the discount rate () and the greenhouse's expected lifespan () in years. The discount rate is set at 0.1, while the lifespan is assumed to be 25 years. The cooling system's cost is reduced by utilising the existing cooling system infrastructure, contributing significantly towards reducing the overall capital cost.

|  |  |
| --- | --- |
|  | (10) |

The capital cost is given as follows:

|  |  |
| --- | --- |
|  | (11) |

The cost of different inputs is given in Table 1.

Table 1: Cost of different greenhouse inputs.

|  |  |  |
| --- | --- | --- |
| **Inputs**  | **Symbol** | **Price** |
| Structure construction  |  | $25 m-2  |
| Electricity  |  | $0.036 kWh-1  |
| Water  |  | $1.43 m-3  |
| CO2 |  | $2 kg-1  |
| Fertilizer  |  | $3.21 m-2  |
| Labour cost  |  | $15.23 m-2  |

## *Greenhouse optimisation*

The model for the greenhouse is optimised using decision variables to identify parameters that reduce production costs. The objective function is given by:

|  |  |
| --- | --- |
|  | (12) |

## *Co-utilisation of infrastructure*

Post-World Cup, some stadiums are planned to be downsized or repurposed, reducing their cooling needs and creating surplus capacity. This excess capacity presents an opportunity to support local food production by integrating stadium cooling systems with nearby greenhouse systems. This approach could significantly lower greenhouse capital costs, as cooling is a major financial factor.

# Results and discussion

The framework calculates the greenhouse's yield and energy, water, and CO2 needs in Qatar by utilising data on solar radiation and outside temperature from a standard typical meteorological year (TMY) file. Furthermore, the optimisation determines the decision variables that produce the lowest costs associated with yield production.

## *Optimum decision variables*

This model was simulated for a greenhouse with an area of 625 m2 (25m x 25m), focusing on tomato cultivation. It involves optimising various factors over the harvest period, including day and night temperatures, RH, CO2 levels, LAI, and the material used for the greenhouse covering. The optimal decision variables are a nighttime temperature of 18°C, while the daytime temperature is higher, at 24°C. The relative humidity level of 75%, with a CO2 concentration of 1000 ppm. In terms of output, the total yield achieved is 24.96 tons, producing a unit yield of 46.84 kgm-2. The total operational cost amounts to $ 46,442.34, resulting in a cost of $3.50 kg-1.

## *Infrastructure driven greenhouses*

This framework employs a generalised model with optimal decision parameters for greenhouses of various sizes adjacent to the constructed stadiums. Qatar's small, uniformly topographic area of 11,571 km² allows for using the same TMY data for all stadiums. Figure 2 illustrates the potential yield that could be achieved by constructing greenhouses adjacent to the stadiums using the available land and cooling. The greenhouse adjacent to Education City Stadium produces the lowest yield, at 239.19 tons, due to limited space, while the greenhouse near Lusail Stadium produces the highest yield, at 2568.59 tons, due to higher available land and cooling capacity. The proposed greenhouses can produce a total yield of 8240.91 tons by co-utilising the stadium's infrastructure. Figure 3 illustrates the variation in cooling capacity usage among the stadiums' greenhouses as it correlates with the available land and the capacity of each cooling system. Education City Stadium requires a minimal cooling capacity of just 1.64 %, in contrast to the ones near Al-Rayyan Stadium, which demand the highest cooling usage at 24.56 %. These results indicate that the proposed greenhouses only require a small part of the available cooling to operate throughout the year.



Figure 2: Potential yield produced by the proposed greenhouses.

# Conclusion

Open-field agriculture is unfeasible in arid regions like Qatar due to harsh climates, infertile land, and water scarcity. However, closed greenhouses offer a year-round solution but with high capital costs. Therefore, this study proposes using unutilised and sophisticated infrastructure from FIFA World Cup 2022™ for food production. The framework incorporates a model for greenhouse requirements and crop yield based on parameters such as temperature, humidity, CO2 levels, leaf area index, plant density, and covering material. Economic optimisation identifies optimal conditions for the most cost-effective yield, including specific temperature, humidity, and CO2 settings.

The proposed framework is both general and flexible, developed to be applicable across various geographical locations with differing infrastructures. Utilizing existing infrastructure can enhance food sustainability by utilizing available resources for food production. This approach not only optimizes the use of existing infrastructure and systems but also reduces the need for additional investments and environmental impacts associated with new constructions. By adapting and enhancing current infrastructures, food can be produced sustainably and cost-efficiently.



Figure 3: Total available and utilised cooling by the proposed greenhouses.

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