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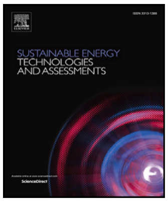

Original article

Sustainable energy management for indoor farming in hot desert climates

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ABSTRACT

Achieving food self-sufficiency in hot desert climates requires year-round farming, which is challenging due to extreme weather, water scarcity, and limited arable land. Indoor soil-less farming can mitigate these issues by reducing land and water use but increases operational complexity and electricity needs for cooling, impacting economic sustainability. This paper presents a resource management system using Artificial Intelligence of Things (AIoT) to simplify operations and optimize resources, alongside techno-economic analysis for economic viability. A case study on hydroponic tomato farming in hot deserts demonstrates that beyond a crop yield threshold (24.022 kg/m^2), significantly more energy is required for marginal yield increases (e.g., 18% more electricity for a 0.35% yield increase). Despite higher energy use, the techno-economic analysis shows a net present value increase even with unsubsidized electricity. Thus, optimizing energy alongside water and nutrients is crucial for economic sustainability in indoor farming.

Introduction

Achieving food self-sufficiency in any context requires farming activities to take place all year-round. This is a challenging endeavor in hot desert climates due to extreme weather conditions and the scarcity of water and arable land. For example, only 30,433.5 ha were allocated for productive and sustainable agriculture in Qatar in 2019, which correspond to 2.6% of the total country's area [1], and only a small portion of the available ground water is suitable for crop irrigation. As shown in Fig. 1, underground water reservoirs underwent significant depletion from 1971 to 2009. Most of the underground water in 2009 presented Total Dissolved Solid (TDS) levels above 1750 mg/L, which are deemed hazardous to any crop [2,3]. These TDS levels have most likely worsened in the last 15 years due to over-extraction for increased irrigation [4]. Long summers from May to September with mean maximum temperatures above 40 °C and average yearly rainfall totals of 68.1 mm/year including long dry spells from June through September [5] exacerbate the already precarious conditions.

Soil-less farming in hydroponics settings overcomes the severe limitations of arable land scarcity and provides one of the most water-efficient solutions for crop irrigation. Hydroponic systems also allow for higher plant density by stacking multiple crop layers vertically [6,7]. This practice optimizes the use of space, enabling the reduction of energy costs [8] and making it an attractive solution for high-density urban zones and expensive land areas [9]. However, indoor farming in high temperatures during most of the year require extensive use of cooling applications, such as evaporative cooling and air conditioning that are energy intensive. In addition, evaporative cooling needs significant amounts of water. Whether sourced from underground reservoirs, which in hot desert climates generally present higher salinity than mandated for evaporative cooling systems (i.e., up to 1200 mg/L [10]) as shown in Fig. 1, or the sea, such extensive use of water for cooling purposes entails substantial investments in energy for desalination and water pumping and transport processes. Energy efficiency is therefore a key challenge in achieving sustainability for indoor farming in Qatar as well as other hot desert climate regions.

The approach developed in this study provides a framework for evaluating trade-offs in the use of resources with reference crop output that help achieve economic sustainability, i.e., environmentally sound long-term economic development. The study focuses on the optimization of electricity and crop productivity in hydroponic tomato production, but the framework can be easily extended to the combined optimization of additional resources, such as water and nutrients. A network of IoT sensors enables the collection of environmental and resource data determining crop productivity in greenhouses, including electricity use. These data are used by a greenhouse digital twin to project crop productivity at the end of the crop cycle, at any point of the cycle. The results of the greenhouse digital twin are analyzed by a multi-objective optimization component based on a genetic algorithm

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