

Designing a Cost-Effective IoT System for Water-Efficient Hydroponic NFT Farming: A Frugal Innovation Approach

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Abstract. The increasing demand for sustainable and resource-efficient food production has accelerated the integration of Internet of Things (IoT) technologies into hydroponic cultivation systems. This study develops and evaluates a cost-effective IoT-enabled Nutrient Film Technique (NFT) prototype grounded in a frugal innovation framework. The system incorporates an ESP32-based printed circuit board integrated with DHT22 temperature–humidity sensors, TDS and pH sensors, and dual relay modules for automated pump regulation. Real-time environmental and nutrient data are transmitted to a mobile IoT dashboard to enable continuous monitoring and adaptive control. Experimental testing under simulated greenhouse conditions demonstrated stable automation performance, improved thermal stability (temperature fluctuation reduced from $\pm 6^{\circ}\text{C}$ to $\pm 2^{\circ}\text{C}$), and consistent nutrient concentrations within optimal thresholds (pH 5.8–6.5; TDS 900–1100 ppm). The closed-loop control mechanism enhanced irrigation precision and system responsiveness. These findings substantiate the prototype’s technical feasibility, operational reliability, and cost-effectiveness, highlighting its potential contribution to scalable, precision-oriented, and sustainable hydroponic production systems.

1 Introduction

Greenhouses are widely recognized as a vital component of modern agriculture because they provide controlled environments that enhance crop yields, optimize land use, and protect plants from climate variability. They offer significant potential to strengthen food security and resource efficiency through year-round cultivation. However, in many developing regions, greenhouse infrastructures remain underutilized or abandoned due to high operational costs, limited technical expertise, and the absence of affordable automation systems [1]. This underperformance not only undermines agricultural productivity but also diminishes the returns on infrastructure investments made by farmers and governments. The Nutrient Film Technique (NFT) have emerged as a viable solution for growing crops in controlled environments. However, the adoption of such

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systems, especially in small-scale farming, is often limited by the high cost of technology and the complexity of implementation [2].

This research focuses on designing a comprehensive Internet of Things (IoT) system for hydroponic greenhouses, with an emphasis on both the structural design and its integration into the greenhouse environment. The integration of Internet of Things (IoT) technologies with frugal innovation principles has been identified as a promising pathway. IoT-based irrigation systems leveraging affordable sensors, low-power communication protocols, and automation can reduce labor, optimize water use, and increase productivity while keeping costs manageable [3]. Previous studies have emphasized that conventional manual irrigation typically achieves only 40–60% efficiency, whereas automated drip irrigation can reach up to 90%, with IoT-based control further enhancing resource optimization [4], [5].

The concept of Frugal IoT is particularly relevant in resource-constrained settings. By prioritizing affordability, essential functionality, and local replicability, frugal IoT designs enable smallholder farmers to adopt automation without reliance on expensive proprietary systems [5]. Low-cost combinations of soil moisture sensors, pumps, smart timers, and drip irrigation networks can transform underutilized greenhouses into productive assets, aligning with broader goals of water conservation, climate resilience, and sustainable agriculture [6]. The system includes the design of a printed circuit board (PCB), sensor integration, and infrastructure setup within the greenhouse, ensuring seamless connectivity and automation [7]. The IoT structure is designed to monitor and control critical environmental parameters, such as temperature, humidity, pH, and nutrient levels while providing a cost-effective solution that is scalable for smallholder farmers [8].

The design of the system also considers how to connect all components within the greenhouse, including the IoT framework for real-time data collection and remote management. The system's efficiency is further analysed with a focus on water conservation, evaluating its potential to enhance water usage efficiency in the future [9]. This study seeks to offer an accessible and cost-effective alternative for small-scale farmers, facilitating the adoption of modern technologies that enhance resource management and overall sustainability in hydroponic agriculture.

The greenhouse referenced in this study was originally constructed for conventional agricultural activities but has remained unused. Following discussions with local stakeholders, the facility is planned to be repurposed for future hydroponic NFT cultivation. This research aims to support that transition by developing a cost-effective IoT-based prototype that can serve as the foundation for a fully operational hydroponic system. The proposed system incorporates low-cost sensors, a simplified control framework, and automated irrigation to enable accurate environmental monitoring and efficient resource management. By prioritizing affordability and functional simplicity, the design offers a scalable and adaptable solution for smallholder farmers, providing a pathway to adopt modern, technology-enabled farming practices without the high costs typically associated with advanced agricultural systems [10].

Against this backdrop, the present study focuses on supporting greenhouse revitalization through the development of a frugal IoT-based prototype for NFT hydroponic cultivation. The objectives of this research are twofold: (1) to design and

develop a cost-effective IoT system capable of monitoring and regulating key environmental and nutrient parameters in an NFT setup, and (2) to evaluate its technical feasibility in terms of automation performance, sensor stability, and operational reliability under simulated greenhouse conditions. By bridging affordability and functional integration, this study contributes to efforts aimed at democratizing smart agricultural technologies and reducing barriers to the adoption of technology-enabled hydroponic systems [1], [11].

2 Method

This study employed a design-oriented research approach [12] to develop and evaluate a frugal IoT-based Nutrient Film Technique (NFT) hydroponic prototype under controlled laboratory conditions. The first stage involved the conceptual development of a modular greenhouse design intended to accommodate NFT channels and IoT-based environmental monitoring, emphasizing structural simplicity, scalability, and compatibility with low-cost automation systems. The second stage focused on prototype construction, consisting of two 25×15 cm microgreen trays with continuous nutrient recirculation. The system integrated an ESP32 microcontroller, DHT22 temperature–humidity sensor, TDS and pH sensors, dual 12 V pumps, relay modules, and a custom two-layer PCB. Nutrient solution parameters were maintained within EC 300–600 $\mu\text{S}/\text{cm}$ and pH 5.8–6.3 [13], with calibration performed using standard buffer solutions. In the third stage, the prototype was tested using a closed-loop automation structure in which sensor data regulated pump activation and were transmitted via Wi-Fi to a mobile dashboard, confirming stable system responsiveness. System performance was evaluated based on sensor stability, communication latency, and automation responsiveness under simulated indoor conditions. **Fig. 1.** shows Research Framework of the Frugal IoT-Based NFT Hydroponic System.

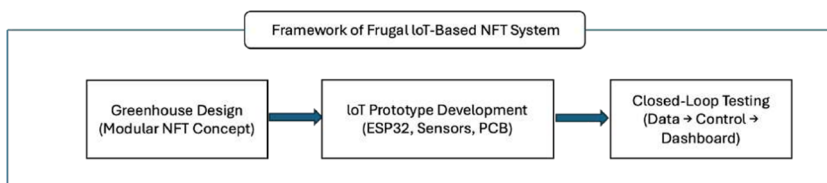


Fig. 1. Research framework of the frugal IoT-based NFT hydroponic system

3 Results and Discussion

3.1 Results

The results of this study encompass three key components: (1) the architectural design developed for the future full-scale greenhouse implementation, (2) the IoT-based prototype constructed for system validation, and (3) the performance evaluation of sensor accuracy, environmental monitoring, and preliminary automation behaviour under controlled laboratory conditions.

3.1.1 Greenhouse Architectural Design

The greenhouse concept presented in this study was developed through a systematic research process to determine the most suitable architectural configuration for supporting NFT hydroponic systems and IoT-based environmental control. The design has been formally submitted as an industrial design under the title “Modular Greenhouse Building Design for Precision Farming” (Application No. A00202506939). The design features a modular layout with a semi-cylindrical roof structure, transparent cladding for optimal light transmission, and an interior configuration that accommodates multiple NFT channels arranged in parallel rows. The structure is intended to support precision agriculture through stable environmental control, efficient nutrient distribution, and seamless integration with IoT- based monitoring technologies. This architectural design forms the blueprint for the next phase of research, in which the IoT prototype will be deployed at full scale. The modular greenhouse design for NFT-based precision agriculture presented in **Fig. 2**.

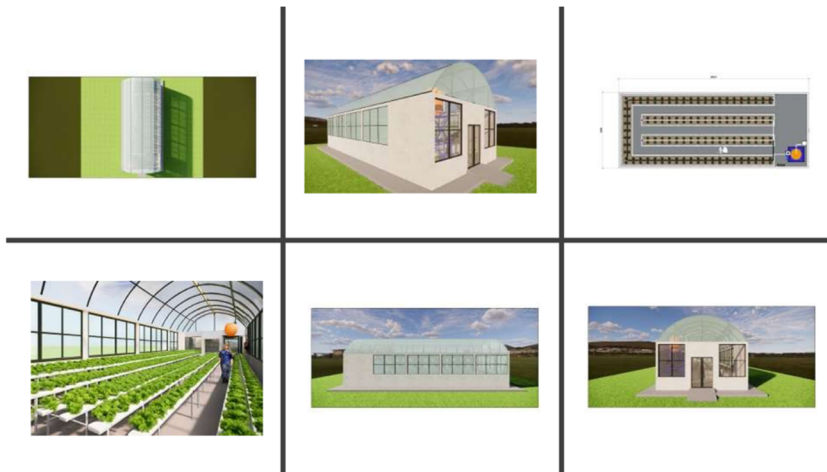


Fig. 2. Modular greenhouse design for NFT-Based precision agriculture

3.1.2 IoT Prototype Design and System Assembly

The IoT prototype developed in this study models the environmental control and nutrient monitoring functions envisioned for future deployment in the full-scale greenhouse. The system integrates an ESP32 microcontroller with pH, TDS, and temperature–humidity sensors, supported by two 12 V pumps controlled through relay modules. A custom-designed two-layer PCB consolidates all hardware components, including power regulation circuitry, optocouplers for electrical isolation, and an OLED module for local data visualization. The complete circuit schematic and PCB routing, as shown in the design output, demonstrate a compact and low-cost configuration that aligns with frugal innovation principles and facilitates easy replication. The prototype is complemented by mobile interfaces: the BLE- EC01 application enables real-time measurement and calibration of nutrient parameters, while the IoT dashboard provides remote control of pumps, lighting, and additional switches through a user-friendly

interface. In addition to the hardware framework, the embedded software responsible for sensor acquisition, pump automation, and dashboard communication has been formally registered as a copyrighted computer program (Registration No. EC002025171660), reinforcing the intellectual property foundation of the IoT automation system and complementing the separately registered industrial design for the modular precision greenhouse. **Fig. 3.** shows IoT monitoring interfaces and hardware architecture for the hydroponic control system.

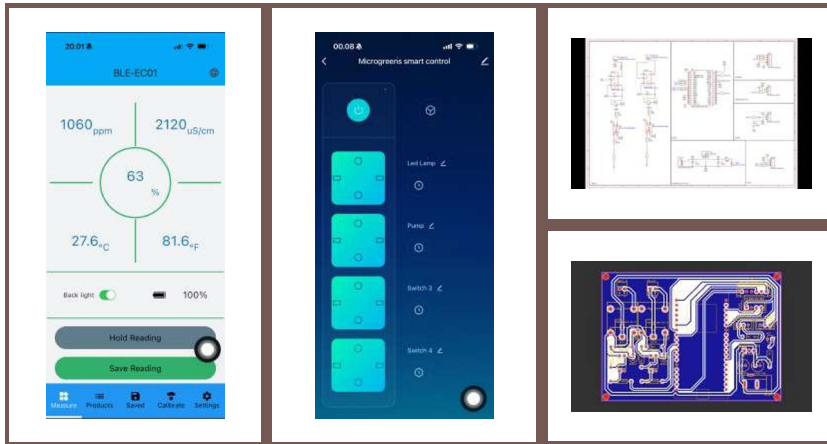


Fig. 3. IoT Monitoring interfaces and hardware architecture for the hydroponic control system

3.1.3 Prototype Testing and Sensor Performance

Testing was conducted under controlled indoor conditions using dual-spectrum LED grow lights to simulate the environmental characteristics of greenhouse operation (**Fig. 4.**). The prototype, consisting of two microgreen germination trays placed within a recirculating nutrient container mounted on a wooden support rack, demonstrated stable initial performance. Baseline sensor readings, including EC 84 $\mu\text{S}/\text{cm}$, TDS 42 ppm, temperature 28.5°C, and humidity 62%, confirmed proper sensor calibration, system responsiveness, and reliable communication between the nutrient reservoir, circulation pump, and sensing units. After calibration with standard buffer solutions, nutrient concentrations were gradually adjusted to the optimal range required for microgreen growth, as reflected in the early sprouting observed during testing. Throughout the experiment, real-time sensor data were continuously transmitted to the mobile dashboard with an average latency of 1.8 seconds, indicating consistent wireless communication and accurate environmental monitoring during the simulated greenhouse trial.

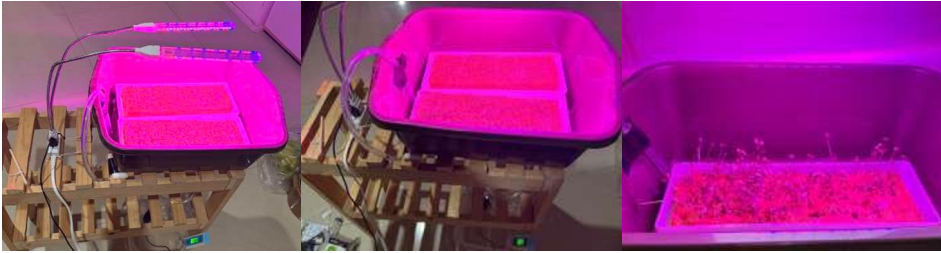


Fig. 4. Indoor prototype testing of the IoT-enabled microgreens NFT system under simulated greenhouse conditions

3.2 Discussion

The findings demonstrate that the developed IoT-based NFT prototype can deliver reliable environmental monitoring and automated control under simulated greenhouse conditions. The stable acquisition of EC, TDS, temperature, and humidity data confirms that the ESP32-based embedded architecture can sustain real-time sensing and communication, consistent with prior studies on IoT-enabled greenhouse control systems [14]. The observed improvement in thermal stability further supports evidence that sensor-driven automation enhances microclimate regulation and operational responsiveness in controlled agricultural environments [11].

The integration of continuous pH and TDS monitoring aligns with established hydroponic management principles, where precise nutrient regulation is critical for maintaining crop performance and system stability [2]. Previous research has shown that IoT-based irrigation and monitoring systems improve precision, reduce manual intervention, and enhance operational consistency [5], supporting the technical feasibility of the proposed configuration.

From a frugal innovation perspective, the use of low-cost components and simplified PCB integration directly addresses financial and technological barriers to smart agriculture adoption identified in developing regions [10]. Although volumetric water-use measurements were not conducted, the implementation of closed-loop recirculation and automated pump regulation is consistent with established smart irrigation frameworks associated with improved resource efficiency [15]. Collectively, these findings position the prototype within the broader trajectory of scalable and accessible digital agriculture systems.

4 Conclusion

This study presents the design and preliminary evaluation of a frugal IoT-enabled prototype intended to support NFT hydroponic cultivation and future deployment within a modular precision greenhouse. The prototype successfully integrated low-cost sensing components, an ESP32 microcontroller, a custom two-layer PCB, and automated pump regulation, demonstrating stable environmental monitoring and reliable system

responsiveness under controlled indoor conditions. The findings confirm that key hydroponic parameters; pH, TDS, temperature, and humidity can be effectively monitored and regulated using an affordable and compact hardware configuration.

By adopting a frugal innovation approach, the system was developed within a constrained budget while maintaining essential functional capabilities. This outcome underscores the feasibility of implementing cost-efficient IoT-based automation to reduce technological barriers in smart agriculture, particularly for smallholder and resource-constrained settings.

Although volumetric water-use measurements were not conducted during the prototype phase, the closed-loop control architecture establishes a structural foundation for precision irrigation and future efficiency evaluation. Accordingly, subsequent research will focus on full-scale greenhouse integration, empirical water-use validation, and multi-cycle crop performance assessment to further examine the system's operational scalability and sustainability.

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