AN IOT BASED AUTOMATION SYSTEM FOR GREENHOUSE CULTIVATION

by

SIDDHARAM

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DEPARTMENT OF SOIL AND WATER CONSERVATION ENGINEERING

KELAPPAJI COLLEGE OF AGRICULTURAL ENGINEERING AND FOOD TECHNOLOGY, TAVANUR - 679 573

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SUMMARY AND CONCLUSION

Chapter V

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The research aimed to develop and evaluate a low-cost IoT automation system for precise management of irrigation, fertigation, and microclimate in cucumber cultivation, addressing global challenges in water scarcity. The experiment employed a Completely Randomized Design CRD over two seasons, comparing four IoT-automated treatments ($I_{1t}o$ I_4) against one non-automated control I_5. The efficacy was validated through CRD analysis (ANOVA), but critically, a sophisticated time-lagged correlation analysis in MATLAB was performed to quantify the temporal impact of microclimate on yield, ensuring the results were robust and reproducible. The reliability of the low-cost hardware was confirmed by validation tests, with all integrated sensors demonstrating high fidelity, including a DHT22 Humidity (R^2 of 0.985 and NPK Sensor Precision of 1ppm. This validated system provided the foundation for establishing the superiority of automated, sensor-driven resource management.

The analysis of crop yield parameters provided compelling evidence of the IoT system's efficacy, yield superiority and treatment efficacy. In both seasons, the IoT-automated treatments achieved significantly higher results across all key metrics, specifically in terms of total yield, where Season 1 results for the best-performing IoT treatments (I2, I3, and I4) clustered between 95 and 96 t/ha. In contrast, the non-automated control (I5) dropped significantly to 80.5 t/ha, representing the lowest yield recorded and demonstrating the fundamental yield-limiting effect of non-responsive management. Regarding the yield per plant, the automated treatments (I1 to I4) consistently maintained levels between 3800 g and 3932 g, while the lowest value was recorded for the non-automated I5 treatment at 3261.35 g, which isolated it as the statistically poorest group. Furthermore, moderate performance levels observed in the I1, I2, and I4 treatments were found to be statistically on par ($p > 0.05$) with each other, confirming that a range of IoT-controlled

The comparison of microclimate management and its subsequent impact on yield validated the precision control mechanisms of the IoT system, particularly in terms of temperature regulation where the automated system achieved a mean temperature of 30.10°C. This intervention successfully prevented the high heat buildup observed in the non-automated greenhouse, which reached a mean of 30.90°C. While the maximum temperature in the IoT-automated plot was maintained at 33°C—notably lower than the 35.6°C recorded in the non-automated house—the system reflected greater control stability with a coefficient of variation (CV) of 4.57% compared to 4.31% in the non-automated environment, with a recorded minimum temperature of 28°C. Similarly, the IoT system maintained a mean relative humidity (RH) of 79.90% with superior stability, evidenced by a CV of 6.14% against the highly variable 10.00% CV of the non-automated house. Furthermore, the maximum light intensity in the open field reached 28,140 lux, whereas the IoT-automated plot was limited to 24,335 lux; this confirmed the effectiveness of the greenhouse cladding material in acting as passive shading to create desirable diffuse light. Ultimately, these results confirmed the functional shading capability of the structure, which passively shielded the crops and constituted the measured environmental differences even in the absence of active curtains.

Time-Lagged correlation analysis showed that the highest magnitude of correlation for yield was observed in the 4-day interval for the mid-day period 480 to 1020 minutes. This critical finding indicates that the cumulative photosynthetic and thermal balance in the immediate past four days (mid-day activity) has the greatest predictive influence on future fruit sizing and growth. The correlations with temperature were strongly negative heat stress, while correlations with light were positive, confirming that IoT control over these two variables is paramount.

The superior management of the IoT system translated into the highly efficient use of critical resources, as evidenced by the WUE and FUE metrics. The maximum WUE was achieved by the automated I4 treatment, which reached 382.5 kg/ha-mm in Season 1, representing a stark contrast to the lowest value of 155.1 kg/ha-mm recorded by the non-automated I5 treatment. Similarly, the automated system demonstrated a clear and significant advantage in Season 2, specifically achieving an FUE of 109.87 in Season 1 compared to 94.06 for the non-automated system, thereby proving the tangible value of NPK sensor-driven delivery.

The economic analysis confirms that the IoT-automated greenhouse system is a superior financial investment, yielding a Benefit-Cost Ratio (BCR) of 2.22 and a Net Present Worth (NPW) of ₹5,13,205, which significantly outperforms the non-automated system's BCR of 1.86. Despite the higher initial capital requirement for automation, the system's ability to optimize resource use and enhance crop productivity results in a 45% higher net profitability over a 12-year period. Consequently, the study concludes that the integration of IoT for microclimate and irrigation management is a financially rational and highly viable strategy for modernizing protected cultivation.

The implementation of the IoT-based automation system for microclimate and resource management in cucumber cultivation represents a successful paradigm shift toward precision agriculture in the polyhouse environment. The research conclusively proves that the low-cost IoT framework can provide the necessary stability and precision for simultaneous management of temperature, humidity, water, and nutrient delivery with high scientific rigor. The measurable results including superior crop yield, higher WUE, enhanced FUE, and a high BCR provide robust justification for its adoption. The IoT automation system is not merely an alternative to manual farming; it is a scientifically validated, technologically reliable, and economically superior solution that effectively addresses the challenges of resource scarcity and the need for maximized productivity in controlled environment agriculture.

SCOPE FOR FUTURE WORK PROACTIVE CONTROL MODELLING:

Climate Generalization and Seasonality Testing: Although the system performed successfully across two seasons, future work must evaluate its performance through a complete annual cycle, including the high-rainfall (monsoon) and high-temperature (peak summer) periods. This is essential to test the system's robust response to extreme climate variables and refine the control algorithms, ensuring that the precision and yield gains are maintained irrespective of the outside weather conditions

Predictive and Proactive Control: Utilizing the strong 4day midday correlation data to develop predictive models that allow the IoT system to initiate corrective actions (e.g., pre-cooling) based on forecasted microclimate trends, moving beyond current reactive control.

Scalability to High-Value Commercial Crops: To demonstrate the broader commercial applicability and profitability of the low-cost design, future research should adapt the validated control logic to other high-value cash crops commonly grown in polyhouses, such as capsicum, tomato, or cut flowers. This would prove the scalability of the system beyond cucumber and quantify the resource savings for different crop physiology profiles

Optimizing Deficit Irrigation: Further research should focus on optimizing the I_2 and I_3 deficit irrigation levels to establish the precise set-point that maximizes WUE without sacrificing the statistically high yield demonstrated by the I_1 treatment.

Disease Prediction Integration: Integrating RH and Temperature data into a real-time risk model to allow the IoT system to dynamically adjust ventilation for disease prevention, protecting the realized yield gains.