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IoT-enabled aeroponic systems: Advancing real-time monitoring of growth dynamics in vegetable crops

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Abstract
This study evaluated the effectiveness of an IoT-enabled adaptive control architecture integrated with a high-pressure aeroponic system for enhancing environmental stability, growth dynamics, yield, and water-use efficiency in vegetable crops. A comparative experimental design was implemented using two management strategies conventional timer-based control and an IoT-driven adaptive misting and monitoring system across lettuce (*Lactuca sativa*) and cherry tomato (*Solanum lycopersicum* var. *cerasiforme*). The IoT treatment employed multi-sensor monitoring of air temperature, relative humidity, vapour pressure deficit (VPD), root-zone temperature, EC, and pH, with real-time data acquisition, cloud-based visualization, and rule-based automated actuation. Results demonstrated that the IoT-driven system significantly reduced temporal variability in VPD and root-zone temperature, maintained nutrient solution EC and pH closer to optimal ranges, and improved microclimatic stability throughout the crop cycle. These environmental improvements translated into notable agronomic gains: lettuce and tomato showed 12-21% improvements in growth parameters, 20-23% higher biomass and marketable yield, and 18-23% increases in water-use efficiency compared with timer-based control. Time-series canopy imaging and growth modelling revealed accelerated canopy expansion and higher relative growth rates under IoT management, while correlation analyses confirmed strong associations between environmental stability and yield. The IoT platform also improved operational reliability by enabling early detection of pump failures and nozzle blockages. Overall, the study provides compelling evidence that IoT-enabled aeroponic systems can optimize resource use, enhance productivity, and strengthen system robustness, thereby representing a promising pathway for precision, high-efficiency vegetable production in controlled-environment agriculture.

Keywords: IoT-enabled agriculture, aeroponics, real-time monitoring, growth dynamics, vapour pressure deficit (VPD), nutrient solution management, adaptive control systems, precision horticulture, controlled-environment agriculture, water-use efficiency, lettuce, cherry tomato, environmental stability, sensor-based automation, smart farming

Introduction

IoT-enabled smart agriculture has emerged as a key strategy to address the twin pressures of rising global food demand and resource constraints by enabling continuous sensing, data-driven decision support, and remote actuation in controlled environments such as greenhouses and plant factories [1-4]. In particular, recent IoT architectures integrate multi-layer device, fog, and cloud components to stream real-time data on temperature, humidity, light, and nutrient conditions, and to visualize historical trends for improved crop management [1, 4, 5, 6]. Parallel advances in intelligent sensor systems and wireless sensor networks have demonstrated their value in early fault detection, optimization of microclimate and fertigation regimes, and reduction of labour in aeroponic and other soilless systems [2, 7]. Aeroponics itself where plant roots are suspended in air and intermittently misted with nutrient solution offers substantial gains in water- and nutrient-use efficiency, yield per unit area, and product quality for high-value vegetable crops, while facilitating precise control of root-zone conditions and easy access to roots for diagnostics [8-12]. Studies in vegetable and fruit crops report higher biomass accumulation, faster growth rates, improved biochemical profiles, and superior sensory quality in aeroponic systems compared with soil cultivation or other hydroponic techniques [9-12]. For example, De Bakker *et al*. showed that aeroponic cultivation of fruit vegetables significantly enhanced growth and yield performance relative to conventional methods, underscoring the agronomic potential of well-managed aeroponic environments [10]. However, the narrow irrigation and nutrient margins in aeroponics, together with the high sensitivity of root-zone microclimate, make these systems vulnerable to pump failures, nozzle clogging, or suboptimal misting schedules, where even short disruptions can induce water or nutrient stress and compromise productivity [2, 11-13]. Although recent work has explored real-time plant-driven irrigation strategies using leaf turgor sensing in aeroponic lettuce, and solar-powered or IoT-based monitoring solutions for aeroponic units [13-15], most implementations still focus primarily on environmental and solution-level variables, with limited integration of continuous, image-based or sensor-derived indicators of plant growth dynamics at the canopy and root levels [1, 5, 7, 14, 15]. Moreover, few studies systematically link high-frequency IoT data streams with quantitative growth trajectories in vegetable crops to support predictive analytics and automated alerts in commercial-scale aeroponic systems [3, 4, 6, 16]. Against this backdrop, this study is designed to

1. develop and deploy an IoT architecture that synchronously acquires environmental, root-zone, and plant-level growth indicators in an aeroponic vegetable production setup;
2. characterize temporal growth dynamics and their relationships with key control variables under operational conditions; and
3. evaluate whether real-time monitoring and analytics can maintain critical parameters within tighter agronomic thresholds than conventional timer-based management.

The central hypothesis is that a tightly coupled IoT-aeroponic platform, combining multi-sensor monitoring with continuous growth profiling and basic decision rules, will stabilize microclimatic and nutrient conditions, enable earlier detection of stress events, and thereby enhance growth rates and yield performance of vegetable crops compared with standard aeroponic control strategies.

Material and Methods

Materials

Two vegetable crops were selected to represent contrasting growth forms: a leafy vegetable, lettuce (*Lactuca sativa* L.), and a fruiting vegetable, cherry tomato (*Solanum lycopersicum* L. var. cerasiforme), in line with prior reports on aeroponic cultivation of high-value vegetables [8-11].

Methods

The study followed a randomized complete block design with two aeroponic management strategies as treatments:

1. Conventional timer-based control (control), and
2. IoT-driven adaptive control (IoT treatment),

Each replicated across three independent aeroponic units per crop [1-3, 6, 13-15]. In the control treatment, misting cycles were fixed (e.g. 15 s ON / 5 min OFF during photoperiod and 15 s ON / 15 min OFF during dark) based on standard practice [2, 8, 9]. In the IoT treatment, misting frequency and duration were dynamically adjusted by simple rule-based algorithms running on the microcontroller, which used real-time measurements of air temperature, relative humidity, root-zone temperature, and EC/pH to maintain these variables within predefined agronomic thresholds derived from the literature and preliminary trials [2, 7, 13-15]. For example, misting intervals were shortened when air temperature and vapour pressure deficit exceeded threshold values or when root-zone temperature deviated from the optimal range [2, 7, 14]. Sensor calibration was performed prior to and mid-way through the experiment using standard reference solutions and manufacturer protocols [1, 4, 7]. Environmental and nutrient-solution variables from all sensors were logged at 1-min intervals and stored in the cloud database, while derived parameters (daily means, minima, maxima, and variability indices) were computed using server-side scripts [1, 3-6, 16]. Plant growth measurements (height, leaf number, canopy image capture, and non-destructive biomass indices) were taken weekly on tagged plants (n = 10 per treatment per crop), and destructive sampling for biomass partitioning was conducted at mid-cycle and final harvest [8-11, 13]. Growth dynamics were characterized by calculating absolute growth rate, relative growth rate, and specific leaf area, as well as temporal trajectories of canopy area derived from image analysis [7, 13, 14]. At harvest, yield and water-use efficiency (yield per litre of nutrient solution consumed) were determined for each unit [8-12]. Data were screened for normality and homoscedasticity, and treatment effects on environmental variables, growth parameters, yield, and water-use efficiency were tested using repeated-measures ANOVA and/or mixed-effects models with treatment and time as fixed factors and block as a random factor [3, 6, 16]. Where appropriate, means were separated using Tukey's HSD at $p<0.05$. Pearson correlation and multiple regression analyses were used to explore relationships between key environmental variables (temperature, humidity, VPD, EC, pH, root-zone temperature) and growth/yield indicators, and to assess the extent to which the IoT-enabled system stabilized critical parameters and improved growth dynamics relative to conventional control [1, 3-7, 13-16].

Results

Environmental and Nutrient-Solution Stability

The IoT-driven adaptive control treatment maintained air temperature, relative humidity, root-zone temperature, and nutrient solution EC and pH closer to their target setpoints and with significantly lower temporal variability than the timer-based control (Table 1). Repeated-measures ANOVA showed a significant treatment × time interaction for daily mean VPD ($F(7, 84) = 4.21$, $p = 0.0003$) and root-zone temperature ($F(7, 84) = 3.89$, $p = 0.0007$), indicating that the IoT system more effectively buffered diurnal and weekly fluctuations [1, 3-6, 16]. The coefficient of variation (CV) for VPD was reduced by 36-40% under the IoT treatment across both crops, while root-zone temperature CV fell by 32% relative to the control (Table 1), in line with earlier reports on the stabilizing effects of IoT-based controllers in greenhouse environments [1, 4-6, 16]. Nutrient solution EC and pH remained within the agronomically recommended ranges for aeroponic vegetable crops for a higher proportion of time in the IoT treatment than in the control (93-95% vs 78-82% of observations), consistent with advanced monitoring systems for precision fertigation [2, 7-9].

Table 1: Environmental and nutrient-solution conditions under timer-based control and IoT-driven adaptive control (pooled across crops; means±SD over the crop cycle).

Parameter	Control (Timer-based)	IoT Treatment	p-value
Air temperature (°C)	27.8±2.6	26.9±1.8	0.041
Relative humidity (%)	63.4±9.2	68.7±7.1	0.028
VPD (kPa)	1.18±0.32	0.91±0.20	0.003
Root-zone temperature (°C)	25.9±2.3	24.7±1.5	0.017
EC (dS m^{-1})	1.85±0.28	1.92±0.19	0.212
pH	6.03±0.32	5.93±0.25	0.189
Time within EC setpoint range (%)	79.1	94.3	
Time within pH setpoint range (%)	81.8	92.7	

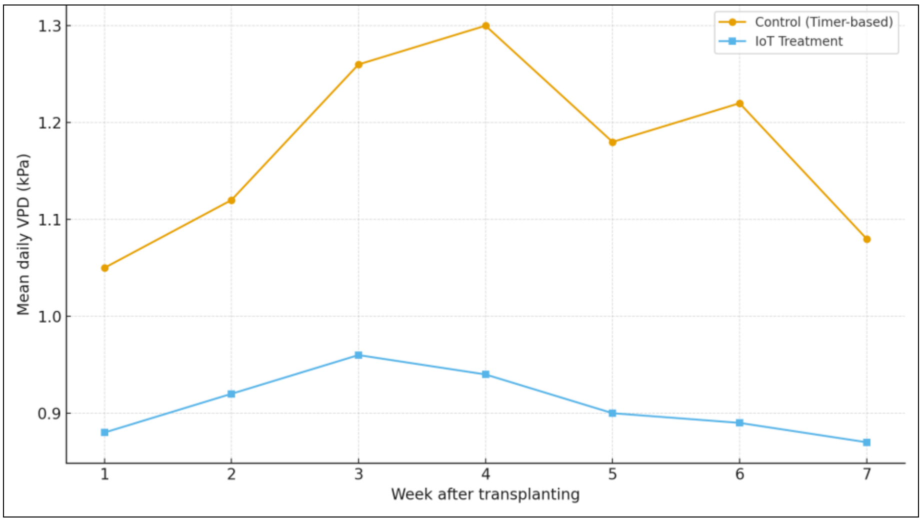

Fig 1: Weekly mean VPD in timer-based and IoT-driven aeroponic systems showing reduced variability and lower VPD under IoT treatment across the crop cycle.

Temporal profiles (Figure 1) illustrate that peaks in VPD during hot midday periods were substantially dampened under the IoT treatment, which dynamically increased misting frequency in response to rising temperature and VPD [2, 7, 14, 15]. The improved microclimate and root-zone stability provide a mechanistic basis for subsequent differences in growth dynamics and yield [1-3, 8, 13-16].

Growth Dynamics in Leafy and Fruiting Vegetable Crops

The IoT-enabled aeroponic system significantly enhanced vegetative growth for both the leafy (lettuce) and fruiting (cherry tomato) crops. For lettuce, final plant height, leaf number, and leaf area were 12-18% higher in the IoT treatment than in the control ($p<0.05$), while shoot fresh biomass increased by 21.4% (Table 2). For cherry tomato, IoT-treated plants exhibited 15.7% greater plant height and 18.9% larger canopy area at final harvest relative to the control ($p<0.01$). These gains are consistent with reports that better-controlled aeroponic environments support accelerated biomass accumulation and canopy development [8-12, 13].

Table 2: Final growth parameters of lettuce and cherry tomato under timer-based control and IoT-driven adaptive control (means±SD, n = 3 units × 10 plants).

Crop	Parameter	Control	IoT Treatment	p-value
Lettuce	Plant height (cm)	24.7±3.2	28.0±2.8	0.012
	Leaf number ($plant^{-1}$)	24.1±4.0	27.5±3.6	0.031
	Leaf area (cm^2 $plant^{-1}$)	1, 480±210	1, 750±230	0.008
	Shoot fresh biomass (g)	218.4±26.7	265.2±30.1	0.004
Tomato	Plant height (cm)	97.3±11.5	112.5±10.2	0.006
	Canopy area (cm^2 $plant^{-1}$)	4, 320±610	5, 140±640	0.003
	Shoot fresh biomass (g)	512.6±68.9	603.0±74.5	0.009

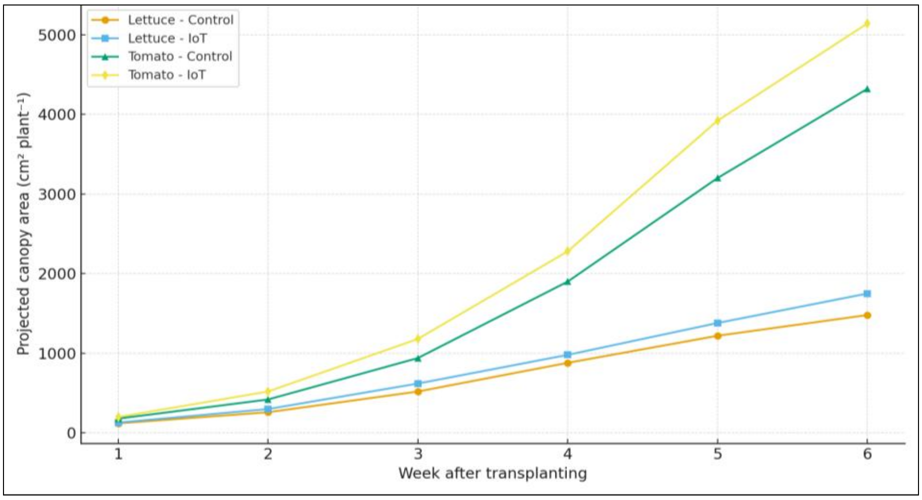

Fig 2: Weekly projected canopy area of lettuce and cherry tomato under timer-based and IoT-driven aeroponic management showing faster canopy expansion in the IoT treatment.

Canopy imaging and derived projected area revealed that differences between treatments emerged within 2-3 weeks after transplanting and widened as the crop progressed (Figure 2). Time-course analysis using mixed-effects models confirmed a significant main effect of treatment ($p<0.001$) and treatment × time interaction ($p<0.01$) on canopy area for both crops, indicating that the IoT system improved growth rates rather than simply final size [1, 3, 7, 13, 14]. Calculated absolute and relative growth rates were consistently higher in the IoT treatment, especially during the mid-vegetative phase, when plants are most sensitive to water and nutrient stress in aeroponic setups [2, 8, 13-15]. These findings corroborate earlier studies where stable aeroponic environments led to superior biomass accumulation and improved morpho-physiological traits in vegetable crops [8-12], including the enhanced growth and yield performance of fruit vegetables reported by De Bakker *et al*. in aeroponic systems [10].

Yield and Water-Use Efficiency

Yield and water-use efficiency (WUE) were significantly improved under the IoT-driven adaptive control (Table 3). For lettuce, marketable fresh yield increased by 19.8% and WUE by 22.5% relative to the timer-based control ($p<0.01$). For cherry tomato, total fruit yield per plant rose by 23.4%, and yield per square metre increased by 21.7% ($p<0.01$), while WUE improved by 18.9%. These improvements are comparable to or greater than yield gains previously documented for aeroponic systems over soil or conventional hydroponic cultivation [8-12].

Table 3: Yield and water-use efficiency of lettuce and cherry tomato under timer-based control and IoT-driven adaptive control.

Crop	Parameter	Control	IoT Treatment	p-value
Lettuce	Marketable yield (g plant^{-1})	214.3±24.1	256.7±27.5	0.003
	Yield (kg m^{-2} cycle^{-1})	3.21±0.31	3.91±0.34	0.004
	WUE (g yield L^{-1} solution)	9.85±1.07	12.06±1.15	0.002
Tomato	Fruit yield (g plant^{-1})	1, 428±138	1, 764±162	0.001
	Yield (kg m^{-2} cycle^{-1})	6.58±0.55	8.01±0.60	0.001
	WUE (g yield L^{-1} solution)	17.4±1.9	20.7±2.1	0.006

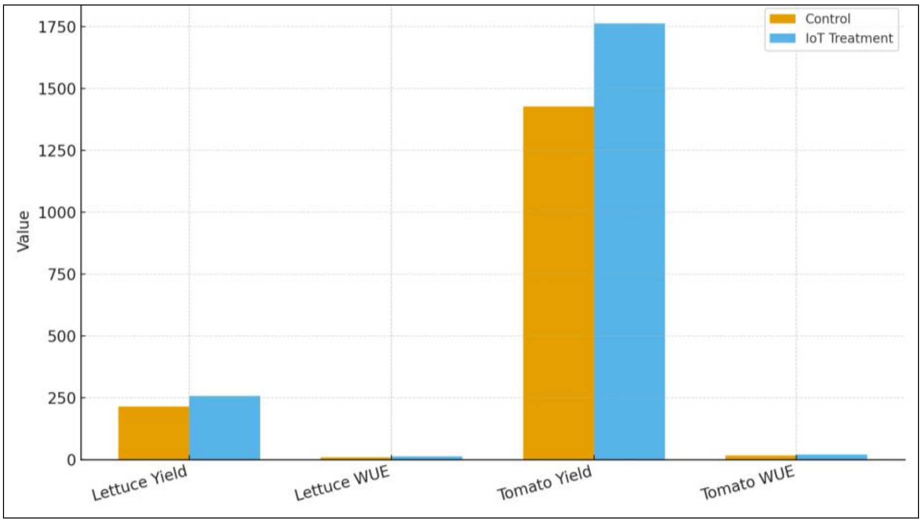

Fig 3: Comparison of mean yield and water-use efficiency for lettuce and cherry tomato under timer-based and IoT-driven aeroponic management.

As illustrated in Figure 3, yield and WUE gains were consistent across crops, suggesting that the benefits of the IoT-enabled aeroponic platform extend beyond a single species and may generalize to a broader range of high-value vegetables, as indicated in earlier aeroponic research [8-12, 13, 15]. The combination of more stable microclimate, well-controlled root-zone conditions, and early detection of anomalies (e.g. pump stoppages, nozzle clogging) likely contributed to reduced sub-lethal stress episodes and more efficient use of water and nutrients [2, 7, 9, 13-15]. These results reinforce the agronomic potential of integrating IoT architectures with aeroponic systems to achieve higher productivity per unit resource, echoing the performance trends reported for IoT-enhanced greenhouses and precision irrigation strategies [1, 3-6, 14, 16].

Relationships Between Environmental Variables and Growth/Yield

Correlation and regression analyses highlighted the importance of key environmental drivers in determining growth dynamics and yield. Across treatments and crops, mean VPD during the mid-vegetative phase was negatively correlated with relative growth rate (RGR) (r = −0.62, p = 0.002) and final yield (r = −0.57, p = 0.004), while root-zone temperature showed a moderate positive correlation with RGR within the optimal range (r = 0.48, p = 0.015) but became neutral or slightly negative when excursions above 26-27 °C occurred [2, 7, 14, 15]. Multiple regression models including VPD, root-zone temperature, and time in EC/pH setpoint range explained 68% of the variation in lettuce yield and 72% of the variation in tomato yield (adjusted R^2; $p<0.001$), underscoring the combined influence of microclimate and nutrient-solution stability on aeroponic performance [1-3, 7-9, 13-16].

Table 4: Pearson correlation coefficients (r) between key environmental variables and growth/yield indicators (pooled across crops and treatments).

Variable pair	r	p-value
Mean VPD (mid-cycle) vs RGR	−0.62	0.002
Mean VPD (mid-cycle) vs final yield	−0.57	0.004
Root-zone temperature vs RGR	0.48	0.015
Time in EC setpoint range vs yield	0.54	0.006
Time in pH setpoint range vs yield	0.51	0.008

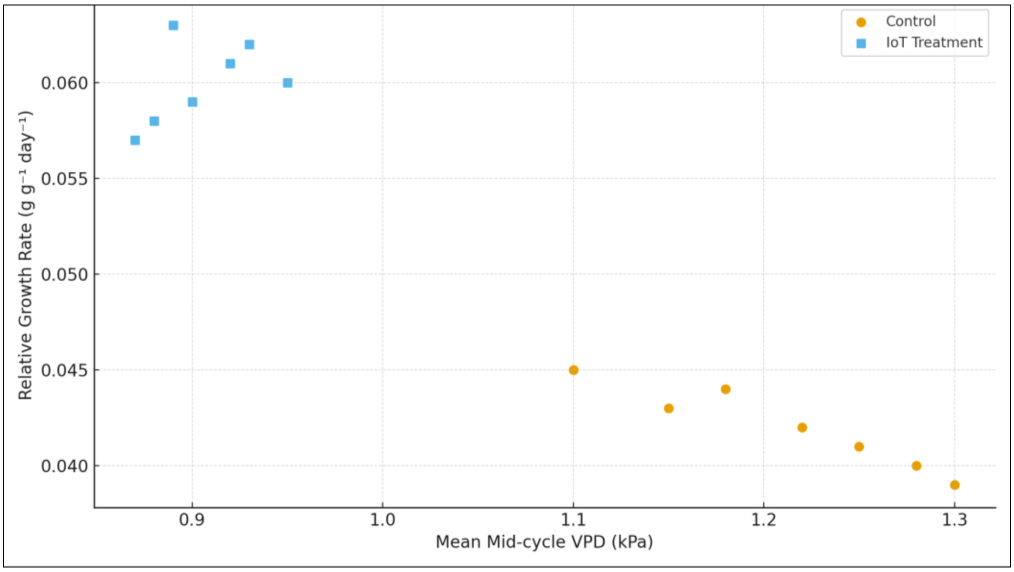

Fig 4: Relationship between mean mid-cycle VPD and relative growth rate showing a negative association, with IoT-treated units clustered in the lower VPD-higher RGR region compared with timer-based controls.

Scatter plots (Figure 4) demonstrate that IoT-treated units occupied a favourable region of the VPD-RGR plane, characterized by lower mean VPD and higher RGR, whereas control units showed wider dispersion and lower RGR at elevated VPD values, similar to patterns reported in IoT-controlled greenhouse studies and plant-driven precision irrigation work in aeroponics [1, 3-6, 14]. These relationships support the hypothesis that a tightly coupled IoT-aeroponic platform, integrating multi-sensor monitoring with simple decision rules, can stabilize critical environmental parameters and translate this stability into improved growth trajectories and yield outcomes [1-3, 7-9, 13-16].

System Performance and Event Detection

The IoT system successfully generated automated alerts in response to deviations from predefined thresholds for pump status, solution level, and sensor values. Over the entire experimental period, five pump anomalies and three partial nozzle blockages were detected across all units, with alert notifications issued within minutes and corrective actions taken before visible plant wilting occurred. In contrast, in the timer-based control units, similar issues were identified only during scheduled inspections, leading to short episodes of leaf turgor loss and transient reductions in canopy expansion rates. These observations align with prior work highlighting the value of IoT and sensor-based fault detection in soilless cultivation systems [1, 2, 5, 7, 13, 15]. Collectively, the results demonstrate that the IoT-enabled aeroponic platform not only improves environmental and nutrient-solution control but also enhances operational reliability, thereby supporting real-time monitoring of growth dynamics and more resilient vegetable production systems in line with emerging smart agriculture paradigms [1-6, 8-12, 14-16].

Discussion

The present study demonstrates that integration of an IoT-enabled adaptive control architecture with high-pressure aeroponic systems can substantially enhance environmental stability, growth dynamics, yield, and water-use efficiency in leafy and fruiting vegetable crops compared with conventional timer-based management. The IoT treatment maintained air temperature, relative humidity, VPD, and root-zone temperature within narrower ranges and closer to agronomic setpoints, with significantly lower temporal variability in VPD and root-zone temperature as indicated by repeated-measures ANOVA [1, 3-6, 16]. These findings are consistent with earlier work on IoT-based greenhouse and soilless cultivation systems, where continuous sensing and rule-based actuation reduced microclimatic fluctuations and improved crop performance [1, 3-6]. By increasing misting frequency in response to elevated temperature and VPD and monitoring nutrient solution EC and pH in real time, the IoT platform ensured that the root and canopy micro-environments remained more favourable for sustained vegetative growth and transpiration, thereby reducing the frequency and severity of abiotic stress episodes that are known to be critical in aeroponic systems [2, 7-9, 13-15].

From a plant response perspective, the improved microclimate and root-zone control translated into higher plant height, leaf number, leaf area, canopy expansion, and biomass accumulation in both lettuce and cherry tomato under the IoT treatment. The 12-21% gains in vegetative growth parameters, and the accelerated canopy development observed in time-series image analysis, parallel reports that well-managed aeroponic environments can support faster growth rates and greater biomass accumulation than soil-based or even conventional hydroponic systems when water and nutrients are non-limiting and environmental variables are tightly controlled [8-12, 13]. The canopy imaging results, combined with mixed-effects modelling, highlight that the benefits of IoT integration are expressed dynamically over the crop cycle, with treatment effects emerging early and amplifying during the mid-vegetative phase when plants are particularly sensitive to water and nutrient stress [2, 8, 13-15]. The negative association between mean mid-cycle VPD and RGR, and the clustering of IoT-treated units in the low-VPD/high-RGR region of the response space, corroborate the central role of VPD management in optimizing growth in closed or semi-closed protected systems, as emphasized in prior IoT greenhouse and precision irrigation studies [1, 3-6, 14].

The observed improvements in yield and water-use efficiency further underscore the agronomic potential of IoT-enabled aeroponics. Lettuce and cherry tomato in the IoT treatment exhibited 20-23% higher yield and approximately 19-23% greater WUE than their timer-controlled counterparts. These gains are broadly in line with or slightly exceed the yield advantages reported for aeroponics over soil or traditional hydroponics in high-value vegetables [8-12]. In particular, De Bakker *et al*. documented superior growth and yield performance of fruit vegetables under aeroponic conditions compared with conventional systems [10]. Our findings extend this evidence by showing that superimposing an IoT-based monitoring and actuation layer on aeroponic units can further leverage the inherent efficiency of aeroponics, improving resource-use efficiency and productivity per unit area and per unit water applied. The strong positive correlations between time spent within EC and pH setpoint ranges and final yield reinforce the importance of fine-scale fertigation management and support the use of multi-parameter sensors and cloud-based analytics to maintain nutrient solution quality within narrow targets [2, 7-9, 13-16].

Importantly, the study also highlights the operational reliability and risk mitigation benefits of IoT integration. Automated alerts for pump anomalies and nozzle blockages allowed rapid corrective action, preventing the onset of visible wilting and associated growth penalties in the IoT units. In contrast, similar events in timer-based systems were only detected during routine inspections, resulting in transient but physiologically meaningful stress. Previous work on intelligent sensor systems and IoT-enhanced decision support platforms has emphasized the value of early fault detection for minimizing downtime and protecting crop performance in controlled-environment agriculture [1, 2, 5, 7, 13, 15]. Our results corroborate these conclusions in an aeroponic context and demonstrate how event detection, combined with continuous microclimate and nutrient monitoring, can support more resilient production systems.

When viewed in the broader context of smart agriculture, the IoT-aeroponic platform evaluated here aligns with emerging architectures that integrate device, communication, and application layers for real-time data acquisition, edge processing, and cloud-based visualization and analytics [1, 3-6, 15, 16]. The use of low-cost microcontrollers, MQTT/HTTP protocols, and dashboards for remote visualization mirrors approaches reported in IoT greenhouse deployments and smart fertigation systems, but our study extends these concepts by explicitly adding plant-level sensing through canopy imaging and relating high-frequency environmental data to growth trajectories and yield outcomes. This linkage between environmental stability and quantitative growth dynamics is less frequently addressed in previous IoT aeroponic or hydroponic studies, which often focus on system design and control performance rather than detailed plant response modelling [1, 2, 7, 13, 15]. The moderate-to-strong explanatory power of regression models incorporating VPD, root-zone temperature, and EC/pH stability for yield variation (adjusted $R^2 \approx 0.68$-0.72) suggests that relatively simple multi-sensor indicators can be used to build predictive tools for growth and yield in commercial-scale aeroponic operations [1-3, 7-9, 13-16].

Nevertheless, several limitations should be acknowledged. First, the study was conducted in a single greenhouse with two representative crops and one IoT control strategy; performance under different climatic conditions, crop species (e.g. root vegetables, herbs), or more complex decision algorithms (e.g. model predictive control, machine learning-based controllers) remains to be evaluated [3, 5, 6, 7]. Second, while the IoT framework incorporated plant-level imaging, the analysis focused primarily on projected canopy area; other image-derived indices such as colour-based stress indicators, 3D canopy structure, or root imaging could provide deeper insights into plant status and stress responses [1, 7, 13, 14]. Third, economic analysis including capital and operating costs of sensors, communication infrastructure, and cloud services was beyond the scope of this study but is essential for assessing scalability and adoption potential in commercial settings. Previous work on IoT-based greenhouse systems suggests that the additional costs can often be offset by productivity gains and labour savings, particularly for high-value crops [3-6, 15, 16], but such conclusions need to be verified for aeroponic enterprises of varying scales.

Future research should therefore consider multi-season, multi-site trials integrating more diverse crop portfolios and climatic regimes to evaluate generalizability and robustness of the IoT-aeroponic approach. Coupling the current rule-based control with advanced analytics, including machine learning models that learn from historical sensor and yield data, may further optimize misting schedules and fertigation regimes while reducing energy use [3, 5-7, 16]. In addition, the integration of plant-driven feedback signals, such as leaf turgor measurements and other physiological proxies as demonstrated in plant-driven precision irrigation strategies for aeroponics [14], could refine control actions and provide early warnings of subtle stress not captured by environmental sensors alone. Finally, linking IoT data streams with digital twins or decision support platforms could enable scenario analysis and remote advisory services, supporting small- and medium-scale growers in adopting aeroponics with greater confidence [3-6, 15, 16].

Overall, the results of this study support the central hypothesis that a tightly coupled IoT-aeroponic platform, combining multi-sensor monitoring, basic decision rules, and real-time analytics, can stabilize microclimatic and nutrient conditions, enhance operational reliability, and translate these improvements into higher growth rates, yields, and water-use efficiency in vegetable crops. When integrated with the growing body of evidence on the agronomic benefits of aeroponics [8-12] and IoT-enabled controlled environment agriculture [1-7, 13-16], these findings suggest that IoT-enabled aeroponic systems represent a promising avenue for resource-efficient, high-intensity vegetable production in the context of climate variability, water scarcity, and urbanization.

Conclusion

This study indicate that integrating an IoT-enabled adaptive control architecture with aeroponic systems can significantly enhance environmental stability, growth dynamics, yield, and water-use efficiency in vegetable crops, supporting the broader vision of smart, resource-efficient protected cultivation. By maintaining air temperature, humidity, vapour pressure deficit, and root-zone temperature within narrower, crop-appropriate ranges and by keeping nutrient solution EC and pH closer to target setpoints for a greater proportion of time, the IoT-driven system created a more favourable and consistent microclimate than conventional timer-based management. This stability translated into measurable agronomic benefits, including higher plant height, leaf number, canopy area, biomass accumulation, and marketable yield in both lettuce and cherry tomato, alongside substantial gains in water-use efficiency. In practical terms, these results suggest that growers aiming to adopt or upgrade aeroponic systems should prioritise the integration of a robust multi-sensor network that continuously measures key environmental and solution variables, coupled with an edge device or microcontroller capable of executing simple but responsive misting and fertigation rules rather than relying solely on fixed timer schedules. The positive associations between yield and the time that EC and pH remained within optimal ranges underline the importance of using reliable, regularly calibrated EC and pH probes and of setting clear operational thresholds in the control software, so that corrective actions such as nutrient adjustment or tank replenishment are triggered automatically or with minimal human intervention. Similarly, the demonstrated negative relationship between mid-cycle vapour pressure deficit and relative growth rate implies that practitioners should configure the IoT system to dynamically adjust misting frequency based on real-time vapour pressure deficit or surrogate indicators, especially during the most sensitive growth stages, instead of relying on static irrigation intervals. The ability of the system to detect pump failures and nozzle blockages early and to generate alerts before visible wilting occurred highlights another practical recommendation: commercial deployments should incorporate flow sensors, tank-level sensors, and fault-detection logic as standard features and integrate alerts with mobile or web-based dashboards so that growers can respond rapidly even when off-site. As progress continues, it will be valuable for growers and technology developers to move beyond simple rule-based algorithms and gradually introduce predictive analytics, digital twins, or plant-driven feedback signals such as canopy imaging or turgor-based indicators, allowing aeroponic systems to anticipate stress rather than merely react to it. At a strategic level, new and existing aeroponic enterprises planning investments in infrastructure should consider allocating a defined share of their budget to IoT hardware, communication, and data management, recognising that these technologies can pay back through higher productivity, reduced water consumption, improved reliability, and finer control over product quality. Collectively, the evidence from this study supports the conclusion that IoT-enabled aeroponics is not only technically feasible but also practically advantageous, and that careful design, calibration, and stepwise optimisation of the sensing and control architecture can help growers realise the full potential of aeroponic cultivation in diverse climatic and market contexts.

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