



Journal of Agrometeorology

(A publication of Association of Agrometeorologists)

ISSN : 0972-1665 (print), 2583-2980 (online)

Vol. No. 28 (2) : 230-236 (June - 2026)

<https://doi.org/10.54386/jam.v28i2.3297>

<https://journal.agrimetassociation.org/index.php/jam>



Research paper

Interactive Effects of IoT-Based Microclimatic Regulation and Nitrogen Supply on Growth, Yield, and Water Productivity of Hydroponically Grown Bokchoy Crop

VIKAS SHARMA*, NITIN M. CHANGADE, VEDIKA DHINGRA and SANCHITA GOSH

Department of Soil Science and Agricultural Chemistry, School of Agriculture, Lovely Professional University, Phagwara, 144411, Punjab, India.

*Corresponding author email: vikas.27227@lpu.co.in

ABSTRACT

IoT-powered climate intelligence is redefining protected hydroponics by delivering dynamic, real-time orchestration of temperature, humidity, and nutrient environments where even subtle micro-variations can decisively shape plant performance, yield potential, and system efficiency. This experiment, conducted in the Hi-Tech polyhouse at Lovely Professional University, Punjab, assessed the combined influence of IoT-regulated microclimate and nitrogen supply on hydroponic bokchoy (*Brassica rapa* var. *chinensis*). The experiment was conducted in a Split-Plot Design (SPD) with three replications, where three microclimatic regimes [MCC₁ (16–18°C; 80–85% RH), MCC₂ (21–23°C; 70–75% RH), and MCC₃ (26–28°C; 60–65% RH)] were assigned to the main plots, and three nitrogen levels [N₁ (100 ppm), N₂ (150 ppm), and N₃ (200 ppm)] were allocated to the sub-plots, resulting in nine treatment combinations. The IoT-based monitoring system demonstrated high precision ($R^2 > 0.90$), ensuring reliable environmental control. Growth, yield, and water productivity were significantly influenced by both factors and their interaction. A moderate regime of 21–23°C and 70–75% RH combined with 150 ppm nitrogen consistently delivered superior outcomes, including earlier maturity, enhanced vegetative growth, higher yield (370 g plant⁻¹), and improved water productivity (118 g L⁻¹). In contrast, suboptimal combinations reduced productivity by nearly half. The findings emphasize that synchronized climate automation and balanced nitrogen management are essential for maximizing efficiency and sustainability in smart hydroponic systems.

Keywords: IoT-based climate control, Hydroponics, Bokchoy, Microclimatic regulation, Nitrogen concentration, Water productivity, Precision fertigation.

Intelligent sensor-based systems are increasingly transforming modern agriculture by enabling continuous monitoring and automated regulation of microclimatic variables. In hydroponics, fluctuations in temperature, humidity, or light instantly activate fans, foggers, or cooling pads to maintain optimal growth conditions. With rising global population and pressure on food systems, innovative controlled environment technologies are essential to enhance productivity and sustainability (Vinod Kumar *et al.*, 2024; Hasan *et al.*, 2025). Traditional soil-based agriculture faces constraints such as land scarcity, soil degradation, climate variability, pest pressure, labor demand, and excessive water use, while open-field cultivation suffers from uncontrolled environmental variability that reduces yield and quality (Kumar *et al.*, 2024; Sharma V, 2025). These limitations emphasize the need for climate-resilient and resource-efficient systems (Toit & Labuschagne,

2007). Hydroponics, a key component of controlled environment agriculture (CEA), offers a soil-free system where plants receive nutrient solutions within regulated conditions. Sensor-based automation enables real-time adjustment of ventilation, fogging, and evaporative cooling, stabilizing the microclimate, reducing labor dependency, and improving crop productivity (Mahesh *et al.*, 2025). The expansion of hydroponics is increasingly viewed as a solution for food and nutritional security, particularly in regions facing climatic stress and limited land and water availability (Kano *et al.*, 2021). Bokchoy (*Brassica rapa* var. *chinensis*) is a short-duration leafy vegetable valued for its high biomass production and nutrient-rich profile, including antioxidants and anticancer bioactive compounds (Bhat *et al.*, 2025). Its rapid growth, sensitivity to the environment, and shallow root morphology make it well suited for hydroponic production systems. Nitrogen is a key determinant of

Article info - DOI: <https://doi.org/10.54386/jam.v28i2.3297>

Received: 08 December 2025; Accepted: 26 March 2026; Published online : 04 June 2026

"This work is licensed under Creative Common Attribution-Non Commercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) © Author (s)"

leafy vegetable performance, influencing chlorophyll formation, photosynthesis, leaf expansion, and metabolic activity (Sharma *et al.*, 2025). In hydroponics, nitrogen uptake efficiency is closely linked to microclimate: high temperatures and low humidity elevate vapor pressure deficit, reducing stomatal conductance and nutrient transport, whereas cooler and more humid conditions favor transpiration and nitrogen use efficiency. The integrated optimization of nitrogen management and sensor-controlled microclimate in hydroponic systems remains inadequately explored. Most previous studies have examined these factors independently, overlooking their interactive effects under defined temperature humidity regimes and graded nitrogen levels. Addressing this gap, the present study systematically evaluates the combined influence of IoT-driven microclimate regulation and differential nitrogen supply on growth, physiology, and yield of hydroponic bokchoy to develop a precision-based climate–nutrient management framework for controlled-environment agriculture.

MATERIAL AND METHODS

Experimental Site and Design: The experiment was conducted in a Hi-Tech polyhouse (fan pad cooling based) at the Research Farm of Lovely Professional University, Jalandhar, Punjab (31.25°N, 75.70°E; 280 m AMSL). The facility featured a fan–pad evaporative cooling system for hydroponic cultivation, with temperature and relative humidity regulated using fogging, forced ventilation, and evaporative cooling based on treatment requirements. Bokchoy was evaluated during the same seasonal window in two consecutive years (Cycle 1: 01 Sept–03 Nov 2024 and Cycle 2: 01 Sept–03 Nov 2025) to minimize seasonal variability and ensure uniform microclimatic conditions. Although the controlled system allows multiple cycles per year, a single cycle per season was maintained to ensure environmental consistency and improve the reliability of treatment comparisons across years. Future studies may include multiple crop cycles within a year to further strengthen statistical robustness and assess seasonal interactions under controlled environments. The study followed a split-plot design with three microclimatic levels as main factors and three nitrogen concentrations as sub-factors, generating nine treatment combinations (Table 1), each replicated three times for statistical validity.

The treatments were selected to represent realistic microclimatic regimes commonly encountered under protected cultivation. The combinations of low temperature with high humidity and high temperature with low humidity reflect natural environmental gradients and enable the assessment of plant responses under contrasting physiological conditions. The high temperature low humidity regime was specifically included to evaluate heat and evaporative stress effects on growth, whereas the low temperature high humidity regime represents comparatively favorable yet distinct conditions. These treatment combinations ensured agronomic relevance and experimental validity. During the experimental period, the mean ambient temperature outside the protected structure ranged from 27 to 35 °C, while the corresponding relative humidity varied between 58 and 72% in the study area.

Development of the Hydroponic System: A nutrient film technique (NFT) hydroponic system was established in a climate-controlled greenhouse for Bokchoy (*Brassica rapa* var. *chinensis*). The

structure consisted of a painted, corrosion-resistant square iron–frame design, supporting food-grade PVC NFT channels arranged in 8 rows. Channels were spaced 35 cm apart, with 15 cm plant spacing, and seedlings were placed in 75-mm UV-stabilized net pots to support aerated root development. A 100-L underground reservoir supplied the nutrient solution, maintained at 22–27°C. Continuous circulation was provided by a 55-W submersible pump, ensuring uniform nutrient delivery, water-use efficiency, and adequate root-zone aeration through a closed-loop system. This configuration enabled a controlled and sustainable growth environment.

Sensor based Microclimate Monitoring and Control: Microclimatic regulation within the hydroponic structures was implemented according to the respective treatments using aIoT Based automated monitoring and control system. The system dynamically activated or deactivated the exhaust fan, cooling pad pump, and fogging units in response to fluctuations in air temperature and relative humidity relative to preset thresholds, thereby maintaining the desired growth environment. Relative humidity was monitored and controlled using an Arduino-based system integrated with a DHT-11 sensor and relay module to automate the exhaust fan and cooling pad pump. However, because the DHT-11 has limited temperature accuracy and resolution, an independent XH-W1219 (12 V) digital temperature controller equipped with a high-accuracy waterproof NTC 10K thermistor (–30 °C to 110 °C) was used for precise air temperature regulation. The additional temperature sensor ensured greater accuracy, stability, and reliable feedback control, which was critical for maintaining the defined microclimatic regimes. The controller included a temperature sensor, a control algorithm, and an output mechanism to regulate fogger pump operation via a relay. A carbon dioxide concentration was recorded at ambient levels (350–380 ppm), as no external enrichment was applied. Supplemental lighting was not provided; crop growth was entirely dependent on natural solar radiation. Incident light availability was quantified using a quantum sensor, with average daytime photosynthetic photon flux density (PPFD) ranging from 205 to 410 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during the experimental period, a range previously reported to be sufficient for optimal Bokchoy growth (Lee & Lee, 2015).

Nutrient Management in Hydroponic: To get optimal growth in hydroponic systems, electrical conductivity (EC) and pH were closely monitored and maintained. The target pH range was 5.5–6.5, while EC was kept below 2.5 dSm^{-1} (Budiman *et al.*, 2022). Both parameters were recorded four times daily, and the nutrient solution was renewed every five days to ensure stability. The nutrient solution was formulated following Hoagland’s protocol (Hoagland and Arnon, 1950), with nitrogen concentrations adjusted between 100 and 200 ppm according to treatment requirements. Macronutrients were prepared by dissolving calcium nitrate tetrahydrate and potassium nitrate (as per nitrogen specification), along with 136.1 g mono-potassium phosphate and 246.5 g magnesium sulfate heptahydrate per liter of distilled water. Micronutrient supplementation comprised 2.8 g boric acid, 1.8 g manganese chloride tetrahydrate, 0.2 g zinc sulfate heptahydrate, 0.1 g copper sulfate pentahydrate, and 0.025 g sodium molybdate per liter. Iron was supplied in chelated form, prepared by dissolving 56.1 g potassium hydroxide in distilled water, followed by sequential addition of ethylenediaminetetraacetic acid (EDTA) and iron sulfate

Table 1: Details of treatments

Main plot factor: IoT Based Microclimatic condition (MCC)		Sub plot factor: Nitrogen concentration in nutrient solution	
MCC ₁	16 to 18°C Temp & 80 to 85% RH	N ₁	Low (100 ppm N)
MCC ₂	21 to 23°C Temp & 70 to 75% RH	N ₂	Medium (150 ppm N)
MCC ₃	26 to 28 °C Temp & 60 to 65% RH	N ₃	High (200 ppm N)

heptahydrate, ensuring optimal bioavailability for plant uptake.

Seedling germination and transplanting: Bokchoy (*Brassica rapa* var. *chinensis*, Choko F1 hybrid) seeds were procured from a local market and germinated in a soilless substrate composed of cocopeat, vermiculite, and perlite in a volumetric ratio of 3:1:1, respectively, as recommended by Hasan *et al.*, (2018). Seedlings were initially raised in plastic trays under controlled greenhouse conditions to ensure uniform germination and to prevent nutrient solution leaching from the hydroponic system.

Performance Evaluation of the Sensor-Based Model: The Arduino-based sensor system was calibrated before deployment to verify accuracy in measuring temperature and humidity. Readings from the DHT11 and NTC 10K thermistor were compared with those from a calibrated digital thermo-hygrometer (Fig. 1). After confirming strong agreement, the system was installed in the polyhouse for continuous monitoring of temperature and relative humidity throughout both cropping cycles.

Observation to be recorded: To achieve the research objectives, growth and productivity parameters were systematically recorded by randomly selecting five representative plants from each treatment. Observations included days to maturity, plant height, number of leaves per plant, and leaf area measured using an automatic leaf area meter (Model 211, Systronics). Chlorophyll content was assessed using a SPAD meter to evaluate physiological status, while marketable yield was recorded on a per-plant basis. Water productivity, a key efficiency indicator, was calculated as the ratio of biomass produced to total water consumed and expressed as kg of bokchoy per unit of water applied (Sharma *et al.*, 2025).

Statistical Analysis: The experimental data from two consecutive

growing seasons were analyzed using analysis of variance (ANOVA) with CVSTAT, an MS Excel-based statistical package. All statistical tests were evaluated at a significance level of $p \leq 0.05$. A two-factorial ANOVA model was applied to examine the main effects of treatment combinations, growing season, and their interaction ($GS \times T$).

RESULT AND DISCUSSION

The accuracy of the developed sensing system was evaluated by comparing the recorded temperature and humidity values with those obtained from standard reference instruments. For temperature validation, readings from the NTC 10K thermistor-based sensor module were correlated with a calibrated digital temperature meter, resulting in a strong linear relationship (Fig. 1). The regression equation ($Y = 0.952x + 2.372$) with a coefficient of determination ($R^2 = 0.965$) confirms that the sensor output closely matches the standard measurements, indicating high precision in temperature detection. Similarly, humidity data recorded through the DHT11-driven model were statistically compared with a digital hygrometer (Fig. 1), yielding a regression equation of $Y = 0.983x + 1.998$ and an R^2 value of 0.978. The high correlation coefficient demonstrates reliable agreement between both datasets, validating the efficiency of the developed model for real-time humidity monitoring. The high degree of concordance observed may be attributed to appropriate sensor calibration prior to experimentation, stable power input, and optimal sensor positioning within the controlled environment, which minimized measurement drift and external interference. The near-unity regression slopes indicate negligible systematic bias, while the high R^2 values reflect strong predictive accuracy and consistency across the measurement range. Collectively, these findings confirm that the integrated low-cost sensing system provides dependable and

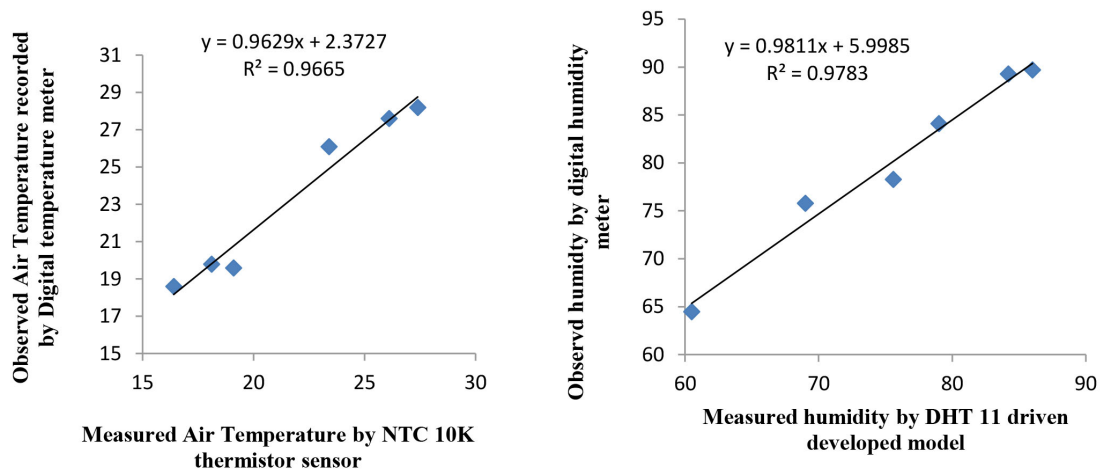


Fig. 1: Correlation of air temperature and humidity measured by sensors with standard instruments: air temperature measured by NTC 10K thermistor sensor versus digital temperature meter, and humidity measured by DHT11-driven model versus digital humidity meter.

Table 2: Effect of Sensor-Driven Microclimate and Nitrogen Levels on Growth of Hydroponic Bok Choy

	Growth parameters								
	Day taken to Harvesting			Plant height (cm)			Leaf area (cm ²)		
	C ₁	C ₂	Pooled	C ₁	C ₂	Pooled	C ₁	C ₂	Pooled
MCC ₁ x NC ₁	59	56	57.5	14.3	14.9	14.6	113	119	116
MCC ₁ x NC ₂	56	53	54.5	17.6	17.6	17.6	129	132	130.5
MCC ₁ x NC ₃	62	59	60.5	W14.1	15.2	14.65	117	123	120
MCC ₂ x NC ₁	55	52	53.5	19.1	20.3	19.7	132	135	133.5
MCC ₂ x NC ₂	44	42	43	25.9	27.4	26.65	151	156	153.5
MCC ₂ x NC ₃	49	47	48	21	21.8	21.4	143	149	146
MCC ₃ x NC ₁	61	60	60.5	16	17.1	16.55	124	127	125.5
MCC ₃ x NC ₂	54	51	52.5	20.1	19.8	19.95	146	151	148.5
MCC ₃ x NC ₃	58	55	56.5	18	18.6	18.3	134	135	134.5
CV (%)	6.1	5.2	5.8	7.1	5.2	5.4	5.2	5.7	6.1
CD at 5%	0.59	3.7	1.9	ns	1.1	1.3	2.4	1.7	1.8
GS X T(MCC x NC)	**			NS			**		
MCC X NC	**	**	**	NS	**	**	**	**	**
MCC	**	**	**	**	**	**	**	**	**
NC	**	**	**	**	**	**	**	**	**

GS: Growing Seasons (C₁ and C₂), T: Treatment combination (MCC X NC), MCC: Sensor Driven Micro-climatic conditions, NC: Nitrogen concentration in nutrient solution, CV: Coefficient of variation, **: Significant (p ≤ 0.05), NS: Non Significant

precise environmental parameter monitoring suitable for controlled agricultural applications and experimental research.

Effect of different treatment combination on plant growth of bokchoy:

The pooled data revealed that the days required for harvesting of Bokchoy were significantly affected by microclimatic conditions (MCC), nitrogen concentration (NC), and their interaction (Table 2). Among the individual effects of MCC, the maximum number of days to harvest was recorded under MCC₁ (57 days), followed by MCC₃ (56 days), while the minimum duration was observed under MCC₂ (48 days). The favorable microclimatic range of 21–23 °C temperature and 70–75 % relative humidity (MCC₂) likely enhanced metabolic activity and accelerated physiological processes, resulting in shorter crop duration, whereas exposure to extreme conditions (high temperature and low humidity) may have induced greater transpiration losses and partial leaf senescence, thereby delaying harvest under MCC₁. With respect to nitrogen concentrations, NC₁ required the longest period to harvest (57 days), followed by NC₃ (55 days), while the shortest duration was observed under NC₂ (50 days). The reduction in growth period at the medium nitrogen level (150 ppm) may be attributed to improved vegetative vigor and faster canopy development, which facilitated early attainment of harvestable maturity. The interaction effect showed that MCC₃ × NC₁ (60.5 days), similar to MCC₁ × NC₃, required the maximum time to reach harvestable stage, whereas MCC₂ × NC₂ (43 days) resulted in the earliest maturity. This confirms that moderate temperature–humidity conditions combined with optimum nitrogen concentration substantially accelerated growth and reduced crop duration. Plant height was also significantly influenced by MCC, NC, and their interaction in pooled analysis, although the interaction effect was non-significant during the first crop cycle. Among MCC levels, the tallest plants were recorded under MCC₂ (22.58 cm), followed by MCC₃ (18.25 cm), while the shortest plants were

observed under MCC₁ (15.62 cm). The moderate temperature regime of 21–23 °C with 70–75 % RH likely provided favorable conditions for shoot elongation through enhanced cell expansion. Regarding nitrogen concentrations, plant height increased with nitrogen level up to NC₂ (150 ppm), beyond which a decline was recorded. The maximum height was noted in NC₂ (21.41 cm), followed by NC₃ (18.10 cm), while the lowest height occurred under NC₁ (16.94 cm). The improvement in plant height at medium N level may be associated with higher chlorophyll formation and enhanced photosynthetic efficiency. The similar result was reported for nitrogen effect by Sharma *et al.*, 2025. The pooled interaction data indicated that the tallest plants (26.65 cm) were produced under MCC₂ × NC₂, followed by MCC₂ × NC₃ (21.4 cm), whereas the shortest plants (14.6 cm) were recorded under MCC₁ × NC₁, demonstrating the synergistic role of moderate microclimate and balanced nitrogen supply in promoting shoot elongation. The variation in crop duration and plant height under different treatments is attributed to the combined effects of microclimate and nitrogen on physiological processes. The moderate regime (21–23 °C and 70–75% RH) likely enhanced photosynthesis, stomatal regulation, and metabolic activity, resulting in faster growth and earlier maturity. In contrast, extreme conditions induced stress, delaying harvest and reducing growth (Mahesh *et al.*, 2025). Nitrogen at 150 ppm promoted optimal chlorophyll synthesis and canopy development, whereas lower or higher levels caused nutrient limitation or imbalance. The significant interaction effects indicate that balanced nitrogen supply under favorable microclimatic conditions synergistically improves growth performance and crop duration in protected cultivation.

Leaf area was significantly influenced by MCC, NC, and their interaction, with season × treatment effects also being significant. Under individual effects, the maximum leaf area was

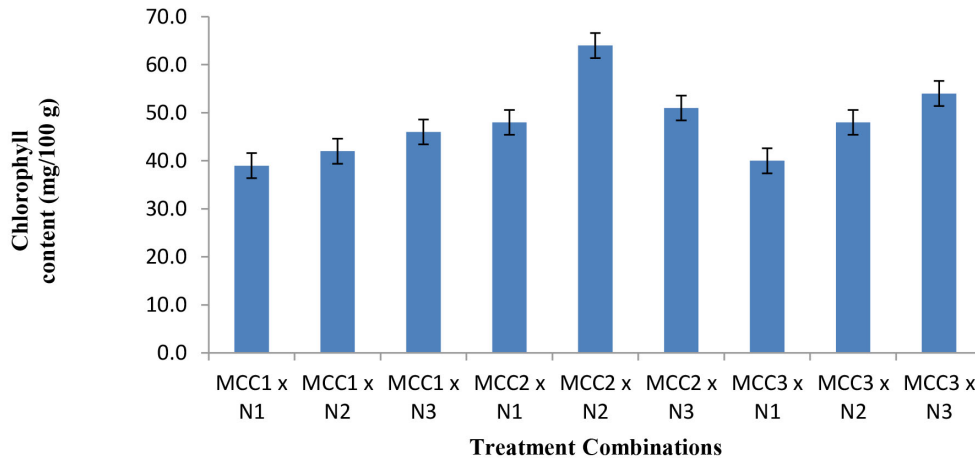


Fig. 2: Effect of different treatment combination on chlorophyll content in leaves.

recorded under MCC_2 (144.33 cm²), followed by MCC_3 (136.17 cm²), while the smallest leaves were recorded under MCC_1 (122.17 cm²). The moderate temperature range (21–23 °C) appeared to support optimal cell expansion and photosynthetic activity, resulting in greater leaf area. Among nitrogen treatments, the maximum leaf area was observed under NC_2 (144.17 cm²), followed by NC_3 (133.50 cm²), whereas the minimum value (125.00 cm²) occurred under NC_1 . The enhanced leaf area at medium nitrogen concentration may be attributed to increased chlorophyll synthesis (Table 3) and improved nutrient assimilation. In the interaction response, $MCC_2 \times NC_2$ recorded the highest leaf area (153.5 cm²), closely followed by $MCC_3 \times NC_2$ (148.5 cm²), while the lowest value (116.00 cm²) was noted under $MCC_1 \times NC_1$. Overall, the growth attributes days to harvesting, plant height, and leaf area were strongly governed by both microclimatic regimes and nitrogen levels in the nutrient solution. The results clearly demonstrate that Bokchoy achieved superior vegetative performance under MCC_2 (21–23 °C, 70–75 % RH) in combination with NC_2 (150 ppm N), which significantly enhanced plant height and leaf expansion while moderately reducing the crop duration. Thus, the optimum treatment combination $MCC_2 \times NC_2$ ensured balanced physiological functioning and improved crop establishment under controlled hydroponic conditions. Fig. 2 illustrates the effect of the interaction between IoT Based Microclimatic Conditions (MCC) and Nitrogen concentrations (N) in the nutrient solution on the chlorophyll content of bokchoy. A noticeable variation was observed across both main and sub-treatments, indicating that chlorophyll synthesis was strongly influenced by microclimate and nitrogen availability. Among the microclimatic treatments, MCC_2 (21–23°C and 70–75% RH) recorded the highest chlorophyll content across nitrogen levels, with the maximum value observed under $MCC_2 \times N_2$ (150 ppm N). The results are inline with Vinod *et al.*, 2024.

This treatment showed a substantial increase compared to all other combinations, suggesting that a moderately warm and moderately humid microclimate favored optimal physiological functioning and photosynthetic pigment formation. In contrast, MCC_1 (16–18°C and 80–85% RH) and MCC_3 (26–28°C and 60–65% RH) exhibited comparatively lower chlorophyll content across

treatments, indicating that both excessively low temperatures with high RH and high temperatures with lower RH were less favorable for chlorophyll accumulation. Across nitrogen treatments, medium nitrogen concentration (N_2 ; 150 ppm) consistently performed better within each MCC group than both low (N_1 ; 100 ppm) and high (N_3 ; 200 ppm) concentrations. The decline observed at N_3 in some MCC combinations suggests that excessive nitrogen may have triggered oxidative or metabolic stress, reducing chlorophyll synthesis efficiency. This aligns with findings from Gobilik *et al.*, (2021) for bokchoy. Overall, the trend highlights a clear synergistic effect between microclimatic control and nitrogen optimization, where MCC_2 combined with N_2 demonstrated the most conducive environment for maximum chlorophyll development in bokchoy.

Effect of different treatment combination on yield, growth and water productivity of bokchoy:

The pooled analysis (Table 3) revealed that the growth, yield, and water-use efficiency of hydroponically cultivated bokchoy were significantly modulated by IoT Based microclimatic conditions (MCC), nitrogen concentrations (NC), and their interactive effects (MCC \times NC), underscoring the critical role of integrated environmental and nutrient management in controlled cultivation systems. Among the microclimatic treatments, MCC_2 consistently outperformed the others, producing the highest number of leaves per plant (11.33), marketable yield (0.30 kg/plant), and water productivity (93.37 g/l), whereas MCC_1 exhibited the lowest values, indicative of suboptimal environmental conditions that limited vegetative growth and biomass accumulation. Nitrogen application at 150 ppm (NC_2) similarly optimized plant performance, enhancing leaf initiation (10.17 leaves/plant), assimilate partitioning into harvestable biomass (0.30 kg/plant), and water-use efficiency (89.07 g/l), relative to both deficient (NC_1) and supra-optimal (NC_3) levels, highlighting the importance of precise nitrogen nutrition in promoting cellular division, shoot elongation, and efficient resource utilization. The interaction between MCC and NC revealed a pronounced synergistic effect, with the $MCC_2 \times NC_2$ combination achieving the highest values for leaves (11/plant), yield (0.37 kg/plant), and water productivity (118.0 g/l), whereas combinations such

Table 3: Effect of Sensor-Controlled Microclimate and Nitrogen Levels on Yield Parameters of Hydroponic Bok Choy.

	Yield Contributing parameters and overall yield								
	Number of leaves/plant			Marketable Yield (kg/plant)			Water Productivity (gm/lit)		
	C ₁	C ₂	Pooled	C ₁	C ₂	Pooled	C ₁	C ₂	Pooled
MCC ₁ x NC ₁	7	7	7	0.17	0.19	0.18	60.7	61.3	61.0
MCC ₁ x NC ₂	7	8	7	0.19	0.23	0.21	73.1	76.7	75.0
MCC ₁ x NC ₃	8	9	8	0.22	0.23	0.23	84.6	80.5	82.4
MCC ₂ x NC ₁	8	9	8.5	0.21	0.29	0.25	65.6	86.3	76.3
MCC ₂ x NC ₂	13	14	11	0.35	0.39	0.37	112.9	122.9	118.0
MCC ₂ x NC ₃	10	11	12	0.26	0.31	0.28	78.8	92.9	85.9
MCC ₃ x NC ₁	7	9	9	0.21	0.22	0.22	51.2	51.2	51.2
MCC ₃ x NC ₂	10	12	9.5	0.29	0.33	0.31	69.0	79.4	74.2
MCC ₃ x NC ₃	8	10	10	0.25	0.27	0.26	58.1	62.8	60.5
CV (%)	7.2	6.3	6.4	5.2	5.4	4.1	5.2	5.6	4.1
CD at 5%	1.1	1.1	1.0	0.02	0.03	0.02	6.7	7.5	5.4
GS X T (MCC x NC)	NS			**			**		
MCC X NC	**	**	**	**	**	**	**	**	**
MCC	**	**	**	**	**	**	**	**	**
NC	**	**	**	**	**	**	**	**	**

GS: Growing Seasons (C₁ and C₂), T: Treatment combination (MCC X NC), MCC: Sensor Driven Micro-climatic conditions, NC: Nitrogen concentration in nutrient solution, CV: Coefficient of variation, **: Significant ($p \leq 0.05$), NS: Non Significant

as MCC₁ × NC₁ and MCC₃ × NC₁ recorded the lowest performance, emphasizing that optimal nitrogen-mediated growth is contingent upon favorable microclimatic conditions. The results also highlight the pivotal role of IoT-based microclimatic control in hydroponic systems. By continuously monitoring and adjusting environmental parameters such as temperature, humidity, and light intensity, IoT-enabled sensors can create precise growth conditions that optimize plant physiological responses and resource use efficiency.

These results are consistent with the findings of Hasan *et al.*, (2025), who reported that sensor-based microclimate regulation significantly improves crop growth and performance under controlled cultivation conditions. The superior performance observed under MCC2 suggests that dynamic, IoT Based regulation allows for rapid correction of suboptimal conditions, minimizing stress and promoting consistent vegetative and reproductive growth. This real-time environmental modulation, combined with precise nutrient management, not only maximizes yield and water-use efficiency but also reduces wastage of resources and enhances the sustainability of soilless cultivation systems. Collectively, these findings underscore that integrating IoT-based microclimatic control with optimized nutrient regimes provides a robust strategy to enhance hydroponic crop productivity and efficiency, demonstrating a transformative approach for modern controlled-environment agriculture.

CONCLUSION

This study establishes that hydroponic productivity is maximized only when microclimate automation and nitrogen

management operate in synergy rather than isolation. A precisely regulated environment of 21–23°C with 70–75% RH combined with 150 ppm nitrogen emerged as the optimal operational benchmark, delivering earlier harvests, superior vegetative growth, higher yield, and markedly improved water productivity. The significant interaction effects confirm that nutrient efficiency is strongly dependent on environmental precision. Accordingly, smart hydroponic systems should prioritize integrated climate–nutrient calibration, maintaining moderate thermal humidity regimes alongside balanced nitrogen supply as a standard management protocol. Future system design should incorporate adaptive nutrient algorithms and predictive climate automation to further enhance resource-use efficiency and scalability in precision-controlled cultivation.

ACKNOWLEDGEMENT

The authors are thankful to the Dean, School of Agriculture, Lovely Professional University for providing the opportunity to complete the research experiment.

Author's certificate: The manuscript or its part is not under consideration for publication elsewhere and the same has been approved by all co-authors.

Conflict of Interests: The authors declare that there is no conflict of interest regarding the publication of this article.

Funding: This research did not receive any specific funding.

Authors Contribution: Vikas Sharma (VS), Nitin M. Changade (NMC), Vedika Dhingra (VD) and Sanchita Gosh (SG) have contributed to the study conception and design. Original draft writing was performed by VS. The material preparation and data collection along with the analysis was done by NMC, VD and SG.

Data availability statement: The authors confirm that the data supporting our findings are available within the article.

Disclaimer: The contents, opinions, and views expressed in the research article published in the Journal of Agrometeorology are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

Publisher's Note: The periodical remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

- Bhat, A. G., Hasan, M., Singh, D. K., Sahoo, R. N., Yeasin, M., & Shukla, V. K. (2025). Design, development and testing of an IoT-based smart vertical hydroponic system for optimized nutrient management in a controlled environment. *Irrigation and Drainage*, 1–17. <https://doi.org/10.1002/ird.4002>
- Budiman, M., Partogi, E., Kristi, A. A., Anggara, P., & Aminah, N. S. (2022). Study of the effect of physical parameters on commercial hydroponics based on Internet of Things: A case study of bokchoy (*Brassica rapa*) and water spinach (*Ipomoea aquatica*). *Journal of Mathematical and Fundamental Sciences*, 54(2), 275–289.
- Gobilik, J., Rechard, C. T., Maludin, A. J., Alam, M. A., & Benedick, S. (2021). Efficacy of column hydroponic system for increasing growth and yield of pak-choi (*Brassica rapa* L.) per unit area. *Transactions on Science and Technology*, 8(1), 7–24.
- Hasan, M., Sabir, N., Singh, A. K., Singh, M. C., Patel, N., Khanna, M., & Pragnya, P. (2018). *Hydroponics technology for horticultural crops* (Tech. Bull. TB-ICN-188/2018, p. 30).
- Hasan, M., Bhat, A. G., Shukla, V. K., et al. (2025). IoT-based smart fertigation scheduling and wireless microclimate monitoring for a greenhouse Dutch bucket hydroponic system. *Irrigation and Drainage*, 74, 1–15. <https://doi.org/10.1002/ird.70012>
- Hoagland, D.R. & Arnon, D.I. (1950) The Water-Culture Method for Growing Plants without Soil. Circular & California Agricultural Experiment Station, 347, 32. <https://archive.org/details/watercultureme3450hoag>
- Kano, K., Kitazawa, H., Suzuki, K., et al. (2021). Effects of organic fertilizer on bokchoy growth and quality in hydroponic cultures. *Agronomy*, 11, 1–17.
- Kumar, V., Singh, C. D., Rao, K. R., Rajwade, Y. A., Kumar, M., & Asha, K. R. (2024). Development and evaluation of smart drip irrigation system for eggplant using Internet of Things. *Journal of Scientific and Industrial Research*, 83(3), 300–308. <https://doi.org/10.56042/jsir.v83i3.2471>
- Lee, S., & Lee, J. (2015). Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of hydroponic food production methods. *Scientia Horticulturae*, 195, 206–215.
- Mahesh, R., Hasan, M., Singh, D. K., Sahoo, R. N., Kumar, S. N., & Yeasin, M. (2025). Effect of LED spectra (red:blue ratios) on morphological and physio-biochemical performance of pakchoi (*Brassica rapa* var. *chinensis*) grown under controlled environment multi-tier hydroponic production system. *Plant Physiology and Biochemistry*, 226, 110054.
- Sharma, V. (2025). Climate-smart irrigation strategies for drip-irrigated exotic vegetables: An analysis of bokchoy, Chinese cabbage, zucchini and broccoli in Jalandhar, Punjab. *Journal of Agrometeorology*, 27(1), 117–120. <https://doi.org/10.54386/jam.v27i1.2861>
- Sharma, V., Changade, N. M., & Madane, D. A. (2025). Impact of integrated water and nutrient management on growth, yield and water use efficiency of drip-irrigated capsicum in the sub-tropical region of Punjab. *Journal of Plant Nutrition*, 48. <https://doi.org/10.1080/01904167.2025.2458836>
- Toit, A. G. A., & Labuschagne, M. T. (2007). A comparison between hydroponics systems and pots for growing wheat in the greenhouse. *South African Journal of Plant and Soil*, 24(2), 120–123.
- Vinod Kumar, S., Singh, C. D., Rao, K.V.R., Rajwade, A.Y., Kumar, M., Jawaharlal, D., Asha, K. R. (2024). IoT-based smart drip irrigation scheduling and wireless monitoring of microclimate in sweet corn crop under plastic mulching. *Irrigation Science*, 11, 1–20. <https://doi.org/10.21203/rs.3.rs-4234762/v1>