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Research Article

Performance Evaluation of a Chiller System for Nutrient Solutions Temperature Control in Lowland Tropical Hydroponic Strawberry Cultivation

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Abstract

Hydroponic strawberry cultivation in tropical lowland regions is constrained by elevated ambient temperatures that increase Nutrient Solution Temperature (NST) beyond the optimal Root-Zone Temperature (RZT) range required for plant growth, leading to thermal stress, reduced nutrient uptake, and yield losses. This study aimed to design and evaluate the performance of a chiller-based cooling system integrated into a recirculating hydroponic setup to maintain the NST within the optimal range of 17–20°C for strawberry cultivation. A laboratory-scale prototype employing a vapor-compression refrigeration system using the R32 refrigerant was developed and tested under tropical conditions. The thermal performance of the system was assessed through cooling load calculations, thermodynamic analysis, and real-time monitoring of temperature, pressure, electrical parameters, and hydraulic conditions, whereas plant growth responses were observed qualitatively. The results demonstrate that the proposed system effectively reduced NST from elevated initial conditions to the target range within 18 minutes and maintained temperature stability using an on–off control strategy. The system achieved a stable actual Coefficient of Performance (COP) of approximately 4.02 with an overall efficiency of approximately 56%, indicating reliable operation under practical conditions. Root-zone temperature control significantly enhanced vegetative growth, leaf quality, and fruit uniformity compared with plants grown without cooling. The findings confirmed that direct nutrient solution cooling using a vapor-compression chiller is a viable and scalable engineering solution for hydroponic strawberry cultivation in tropical lowlands. This study contributes empirical performance data to the limited literature on chiller-integrated hydroponic systems and provides a practical foundation for extending high-value strawberry production into hot climates, while supporting sustainable and controlled agricultural practices.

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1. Introduction

Global food production systems continue to face mounting challenges owing to declining arable land, rapid urbanization, and increasing climate variability (Korbee et al., 2025; Nikolov et al., 2023). These pressures highlight the urgency of adopting innovative agricultural technologies capable of sustaining high productivity under constrained environmental conditions (Erfiana et al., 2025). Hydroponics has emerged as a promising solution, offering efficient water use, precise root zone control, and suitability for both urban and water-limited regions (Alkhalidi et al., 2020; Sahoo et al., 2024; Suarjana et al., 2019; Verma et al., 2025). Among hydroponically cultivated crops, strawberries (Fragaria sp.) are a high-value commodity owing to their fresh consumption and utilization in various processed products, such as jams, syrups, confectionaries, and dairy derivatives (Intawong et al., 2025; Setiawan et al., 2018). Strawberries contain essential nutrients, including vitamins, minerals, and bioactive compounds such as ellagic acid, which are recognized for their antioxidant, anti-inflammatory, and health-enhancing properties (Newerli-Guz et al., 2023).

Despite its economic value, hydroponic strawberry cultivation remains technically challenging, particularly in tropical lowland environments (Abreeza Manap et al., 2022). As a subtropical species, strawberries naturally thrive in cool climates, requiring a narrowly defined root zone temperature (RZT) of approximately 17–20°C for optimal vegetative growth, nutrient uptake, and fruit development (Aa Setiawan et al., 2021; Intawong et al., 2025). In tropical regions, elevated ambient temperatures invariably increase the Nutrient Solution Temperature (NST) beyond the optimal range, imposing thermal stress on the roots (Khan et al., 2025; Sugeng Triyono et al., 2024; Zebro et al., 2025). High NST reduces dissolved oxygen levels, limits the uptake of essential nutrients such as phosphorus, potassium, and magnesium, and ultimately diminishes fruit quality and yield (Nisar et al., 2024; Saputra et al., 2025). Therefore, precise regulation of NST is critical for successful strawberry production in hot climates.

Previous research in controlled environment agriculture (CEA) has explored a variety of thermal management strategies (Amaliah et al., 2019; Hassine et al., 2024; Zulfarosda et al., 2024). Early approaches focused on modifying ambient air temperature through air conditioning or localized zone cooling; however, recent findings indicate that direct cooling of the nutrient solution is considerably more effective for water-based cultivation systems (Catigday et al., 2023; Margiwiyatno & Sumarni, 2014). Passive cooling methods, such as In-Ground Passive Cooling Systems (IGPCS), evaporative wrapping, and earthen-pot heat sinks, can provide moderate reductions in NST but are insufficient for maintaining the consistently low temperatures required for strawberries during periods of extreme heat (Catigday et al., 2023; Nisar et al., 2024). Active cooling technologies, including thermoelectric Peltier devices, have shown promise in small-scale applications; however, they are limited in terms of capacity and long-term stability (Asmbangnirwana et al., 2022; Saputra et al., 2025). In contrast, vapor-compression chiller systems have demonstrated superior cooling performance, operational stability, and energy efficiency, and are widely adopted in aquaculture and controlled horticultural systems (Wardika et al., 2023). Empirical evidence shows that root-zone cooling enhances stem elongation, leaf expansion, photosynthetic vigor, and flower induction in subtropical strawberry cultivars grown hydroponically in tropical environments (Intawong et al., 2025).

Despite these advancements, a clear research gap remains regarding the systematic design, application, and performance evaluation of chiller-based cooling systems specifically optimized for maintaining the precise 17–20°C NST required by strawberries in lowland tropical settings. Existing studies tend to focus on leafy greens or alternative cooling methods with limited capacity, leaving a lack of detailed engineering assessments and performance metrics for chiller-integrated hydroponic systems tailored for strawberry production.

To address this gap, this study developed and evaluated a dedicated water-cooling apparatus based on a vapor-compression chiller integrated into a recirculating hydroponic system. This study pursues two primary objectives: (1) to design and assess the functional effectiveness of a chiller-based cooling system in maintaining the required NST for optimal strawberry growth, and (2) to identify key operational parameters beyond temperature control, such as flow rate and nutrient conditions, that most strongly influence vegetative performance and fruit development. By providing empirical thermodynamic data, system performance indicators (including the Coefficient of Performance and operational efficiency), and plant growth responses, this study contributes to the emerging body of knowledge on climate-engineering solutions for horticulture and offers a practical, scalable approach for achieving sustainable strawberry cultivation in hot, resource-limited environments.

2. Material and Methods

This study employed a design–build–test experimental methodology to develop and evaluate an active cooling system capable of maintaining the Nutrient Solution Temperature (NST) required for hydroponic strawberry cultivation in tropical lowland conditions. The experimental system was constructed at the laboratory scale and integrated with a recirculating hydroponic unit using a vapor-compression chiller.

The primary objective was to maintain NST between 17°C and 20°C, corresponding to the optimal Root-Zone Temperature (RZT) required for strawberry growth. The system performance was assessed through thermodynamic measurements, hydraulic monitoring, and qualitative observations of plant growth responses.

2.1 Materials

Strawberry seedlings (Fragaria sp., Mencir variety) were selected as the plant material due to their high sensitivity to RZT and their economic relevance in tropical horticulture. Plants were cultivated using a commercial AB Mix nutrient solution maintained within the recommended concentration range of 1270–1500 ppm. The nutrient solution pH was targeted between 5.5 and 7.0 to support optimal nutrient uptake by the plants.

The hydroponic cooling system was designed around a vapor-compression refrigeration cycle that directly cooled the nutrient solution in the reservoir. This approach was selected because direct water cooling provides a faster thermal response and greater temperature stability than ambient air cooling in hydroponic systems. Table 1 summarizes the main components and measurement instruments used in this experimental setup.

Table 1. Components and Instruments used in the Hydroponic Water-cooling System.

Component/ Instruments	Specification/Function
Cooling Unit (Outdoor AC)	1 HP capacity, AQUA brand, model AQA-CR9FQDL, R32 refrigerant
Evaporator Coil (Chiller)	1 HP capacity, submerged coil functioning as the chiller heat exchanger
Nutrient Reservoir	Plastic bucket (30 cm in height, 36 cm in diameter)
Circulation Pump	DC 12 V, 800 l/h flow rate, 22 W
Refrigeration Accessories	Accumulator, filter dryer, capillary tube (expansion device)
Temperature Sensors	Digital thermometers were used to measure the air temperature of the environment, reservoir water temperature, evaporator inlet/outlet temperature, and condenser temperature.
Pressure Gauge	Manifold gauge for low (suction) and high (discharge) pressure measurements.
Sensors	Total Dissolved Solids (TDS) sensor for nutrient concentration (ppm), pH sensor, flow meter for measuring the volumetric flow rate (L/min)

2.2 Cooling Load Calculation

Cooling load estimation was conducted to ensure that the selected refrigeration system was capable of rapidly reducing and maintaining the NST within the target range. The cooling system was designed to reduce the temperature of 25 l of nutrient solution from an initial temperature of 30°C to 17°C (ΔT = 13°C) within a target cooling duration of 40 min. An initial temperature of 30°C was selected as the assumed initial temperature of the nutrient solution based on the average ambient temperature measured during the experimental period. The measured ambient temperature fluctuated between 31.5°C and 32.0°C, with an average of approximately 31.8°C, which reflected typical tropical lowland environmental conditions. The cooling load was calculated using Equation 1.

$$Q = m.C_p.\Delta T \tag{1}$$

Q is the heat removal requirement (kJ), m is the mass of the nutrient solution (kg), C_p is the specific heat capacity of water (4.186 kJ/kg °C), and ΔT is the temperature difference (°C). The properties of the nutrient solution were assumed to be identical to those of water, owing to the low concentration of dissolved nutrients. The total mass of the nutrient solution was calculated based on a reservoir volume of 25 l, assuming a density equivalent to that of water ($\varrho \approx 1$ kg/l), which yielded a mass of approximately 25 kg.

The calculated heat removal requirement was approximately 1365 kJ. The required cooling capacity was estimated by dividing the total heat load by the designed cooling time. A target cooling duration of 40 min (2400 s) was selected as the design criterion to ensure that the system could rapidly reduce the nutrient solution temperature under tropical ambient conditions. Using this design cooling time, the required cooling capacity was calculated to be approximately 0.568 kW. A safety factor of 10% was applied, resulting in a final design capacity of 0.625 kW, which is equivalent to approximately 0.85 HP (calculated as 625 W/735 W). Based on this result, a 1 HP refrigeration unit was selected to ensure sufficient cooling margin and operational stability of the system.

2.3 System Assembly and Preparation

The experimental system was assembled on a metal frame with overall dimensions of 120 cm × 50 cm × 100 cm. Two hydroponic pipes were installed in parallel, each measuring 100 cm in length and 2.5 in. in diameter. Each pipe was equipped with ten planting ports to support strawberry growth. The cultivation section was installed inside a partially enclosed training unit equipped with ultraviolet (UV)-protective plastic to reduce direct solar heat gain while maintaining natural light.

The lower section accommodates the outdoor unit, water storage tank, chiller component, and nutrient reservoir. This vertical separation minimizes the thermal interference between the refrigeration components and plant growth area. The design and spatial arrangement of the hydroponic water-cooling system are illustrated in Figure 1.

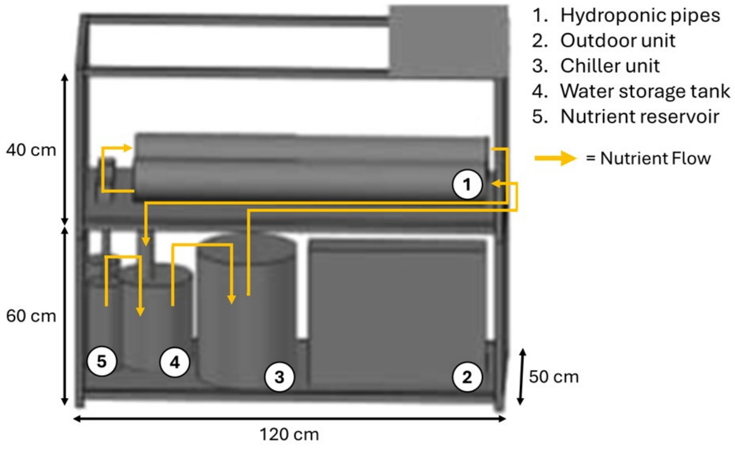

Figure 1. Design of Hydroponic Water-Cooling System.

The cooling system integrated a refrigeration unit with a hydroponic circulation network. Copper pipes were connected to form the vapor-compression cycle (compressor, condenser, accumulator, and evaporator), with diameters of ¼ inch for the discharge line and 3/8 inch for the suction line. For the hydroponic water distribution network, PVC pipes with a diameter of ½ inch were used. Nutrient delivery and water spraying were performed using flexible hoses with an inner diameter of 6 mm. A schematic diagram of the piping configuration of the hydroponic water-cooling system is shown in Figure 2.

Prior to the operation, the refrigeration system was prepared according to standard refrigeration engineering protocols.

1) Leak Testing. The system was pressurized with 150 psi of nitrogen (N2), and all joints were inspected for leaks using the soap-bubble method.
2) Vacuuming. A vacuum pump evacuated the refrigerant lines to 700–750 mmHg to remove air and moisture, ensuring optimal operation and preventing component damage from moisture.
3) Refrigerant Charging. The R32 refrigerant was charged based on the manufacturer specifications (335 g), while monitoring the compressor current, suction pressure, and discharge pressure to achieve proper performance.

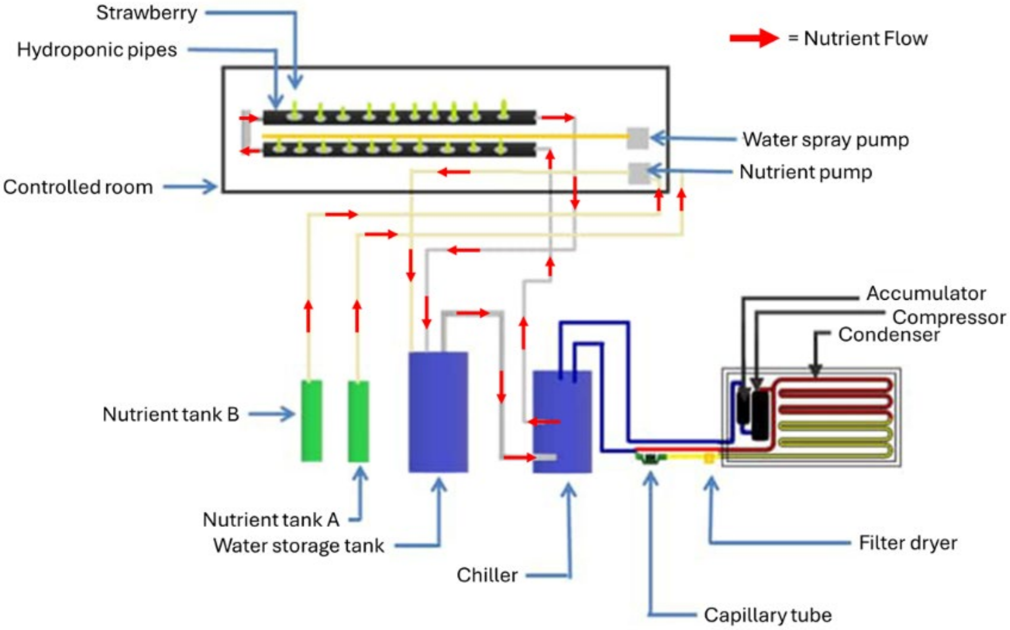

Figure 2. Schematic Diagram of the Piping Configuration for the Hydroponic Water-cooling System

Figure 3 shows the system assembly and preparation processes. These steps ensured that the system operated safely and consistently during the experimental testing.

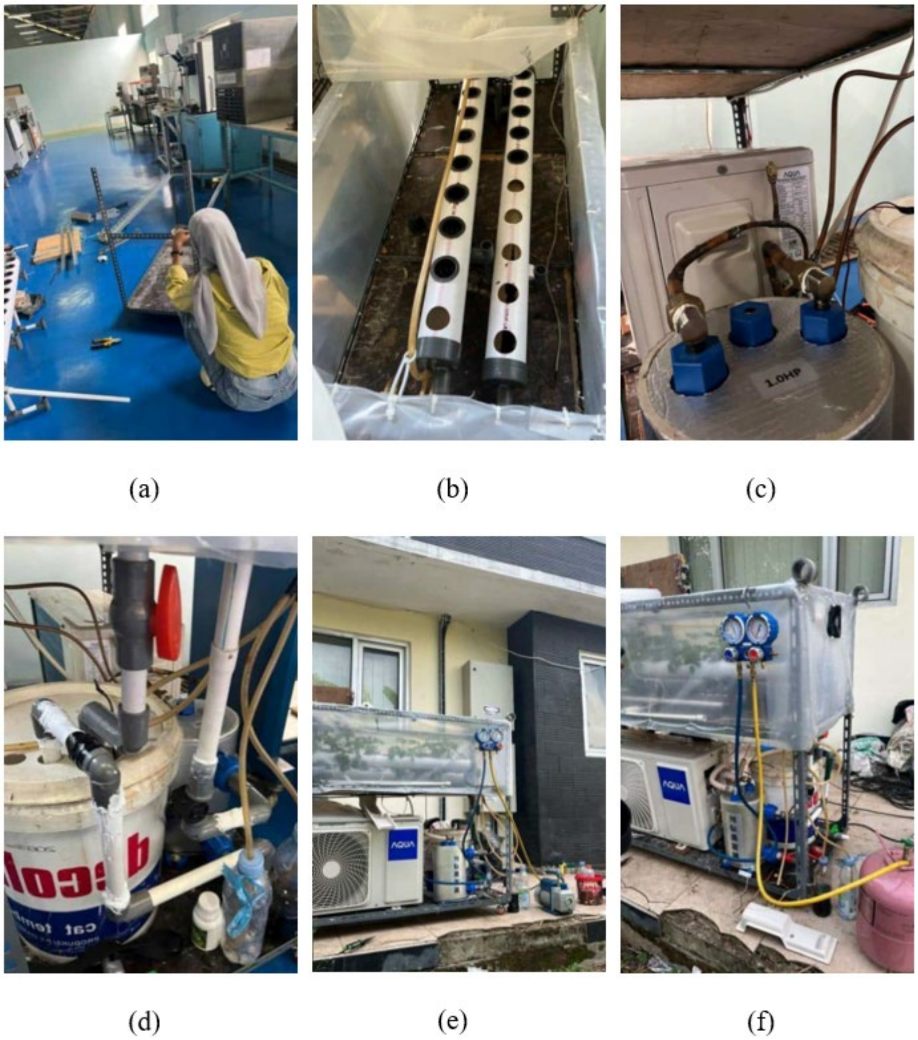

Figure 3. Assembly Process of Hydroponic Water-cooling System: (a) Structural Assembly, (b) Installation of Hydroponic Pipes, (c) Installation of Copper Piping, (d) Installation of PVC Piping, and System Testing Procedures: (e) Vacuum Evacuation, (f) Refrigerant Charging.

2.4 System Operation and Data Collection

During operation, the compressor performs mechanical work to circulate the refrigerant through the vapor-compression cycle. The heat absorbed by the evaporator was extracted from the nutrient solution, lowering the NST to the target set point of 17°C. The system operated using an on–off control strategy: once the NST reached 17°C, the compressor stopped, and cooling resumed automatically when the temperature increased to 19°C.

The water pump operated continuously to maintain nutrient circulation and prevent oxygen depletion in the roots. Nutrient solutions from tanks A and B were delivered to the water storage tank via a nutrient pump to ensure homogeneous mixing before circulation through the hydroponic pipes.

Auxiliary components, including air circulation fans and spray pumps, were operated manually using push buttons to support environmental stability. The experimental data were recorded at one-minutes intervals and included temperatures (T in/out evaporator, T in/out condenser), pressures (suction/discharge), electrical parameters (voltage V and current A), water parameters (T water in storage tank, T in/out hydroponic pipe), nutrient concentration (ppm), pH, and water flow rate (L/min). Strawberry plant growth was visually observed daily to identify the physiological responses to the controlled root zone temperature.

3. Results and Discussion

The primary objective of the developed cooling system was to mitigate excessive Nutrient Solution Temperature (NST) in a hydroponic strawberry cultivation system under tropical lowland conditions. The system performance was evaluated by comparing the theoretical thermodynamic design values with the actual operational measurements obtained during steady-state operations. Table 2 summarizes the comparison between the design values and actual operating conditions using the R32 refrigerant. The experimental results confirmed that the vapor-compression chiller successfully achieved the targeted cooling performance; however, deviations between the theoretical and actual parameters were observed, reflecting the real operating conditions.

Table 2. Comparison of Design Values and Actual Operational Conditions

Variable	Formula	Design Value	Actual Value
Evaporator temperature	T_e	5°C = 278.15 K	-2.6°C = 270.55 K
Condenser temperature	T_c	40°C = 313.15 K	35.6°C = 308.75 K
Enthalpy values	R32 refrigerant properties mapped on a P-h diagram	h_1 = 516 kJ/kg h_2 = 570 kJ/kg h_3 = 275 kJ/kg h_4 = 275 kJ/kg	h_1 = 518 kJ/kg h_2 = 582 kJ/kg h_3 = 261 kJ/kg h_4 = 261 kJ/kg
Compression work (q_w)	$q_w = h_2 - h_1$	54 kJ/kg	64 kJ/kg
Condenser heat rejection (q_c)	$q_c = h_2 - h_3$	295 kJ/kg	321 kJ/kg
Evaporator refrigeration effects (q_e)	$q_e = h_1 - h_4$	241 kJ/kg	257 kJ/kg
Actual COP	$COP_{Actual} = \frac{q_e}{q_w}$	4.46	4.02
COP_{Carnot}	$COP_{Carnot} = \frac{T_e}{T_c - T_e}$	7.95	7.08
Efficiency	$\eta = \frac{COP_{Aktual}}{COP_{Carnot}} x100\%$	56.16%	56.70%

The actual compressor work (qw) was 18.5% higher than the theoretical design value, indicating that the compressor operated under a heavier thermal load than anticipated. This increase indicates that the compressor operated under a heavier thermal load than initially predicted. Such deviations are primarily attributed to environmental heat gains, thermal losses along piping networks, and nonideal heat transfer at evaporator and condenser surfaces. Despite this increased workload, the evaporator absorbed a higher refrigeration effect (qe), demonstrating effective heat extraction from the nutrient solutions.

As a result of the increased compressor workload, the experimentally determined COPActual 10% decreased compared with the theoretical value. The larger operating temperature differential between the evaporator and condenser resulted in a decrease in COPCarnot from 7.95 to 7.08. These reductions are typical in practical refrigeration systems and reflect the performance gap between idealized thermodynamic assumptions and real-world operations, particularly in small-scale systems subjected to fluctuating ambient temperatures. Thus, a lower COP reflects reduced energy efficiency, from 67% to 56%. The observed decrease in the overall system efficiency suggests that further optimization, such as improved insulation, enhanced condenser airflow, or refined refrigerant charge control, could reduce energy losses and improve operational efficiency.

3.1 Cooling Effectiveness and Temperature Stability

Cooling effectiveness is a key indicator of the feasibility of hydroponic systems. Experimental observations revealed that the chiller reduced the NST from an initial temperature of 27.6°C to a target set point of 17°C within 18 min, which was significantly faster than the initial design target of 40 min. Figure 4 illustrates the temporal variation in the NST during the initial cooling process. This nearly linear decline indicates stable and continuous heat absorption by the evaporator. This rapid cooling response is particularly advantageous in tropical environments, where prolonged exposure to high root zone temperatures can rapidly induce physiological stress and inhibit nutrient uptake.

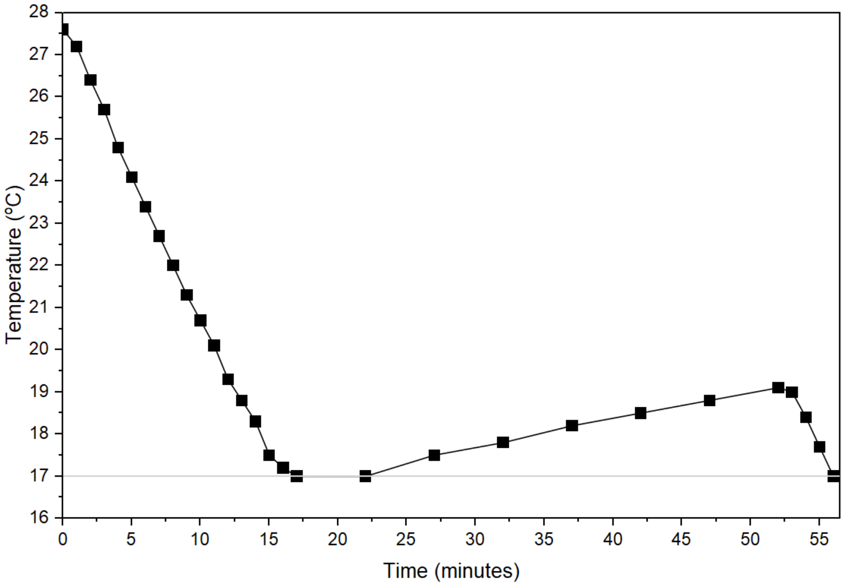

Figure 4. Nutrient Solution Temperature Reduction Over Time During Initial Cooling Phase.

After reaching the setpoint, the system maintained temperature stability using an automatic on–off control strategy. Once the temperature reached 17°C, the compressor was deactivated, and it took approximately 35 min for the temperature to increase to 19°C, triggering reactivation.

This gradual increase in temperature during the off-cycle demonstrates effective thermal retention and limited heat ingress into the reservoir. From a practical perspective, this regulation strategy reduces the compressor operating time, minimizes energy consumption, and prolongs the component lifespan, thereby enhancing the economic feasibility of the system for continuous agricultural use.

3.2 Refrigeration Component Performance Analysis

A component-level analysis further confirmed the system stability. The evaporator refrigeration effect (qe) stabilized at approximately 257 kJ/kg after 7 min of operation, indicating steady-state heat absorption. As shown in Figure 5, the condenser heat rejection (qc) initially increased rapidly as the accumulated thermal energy was released to the environment and then stabilized as the system reached thermal equilibrium. The balanced behavior of both components confirmed that the evaporator and condenser capacities were appropriately matched to the applied thermal load.

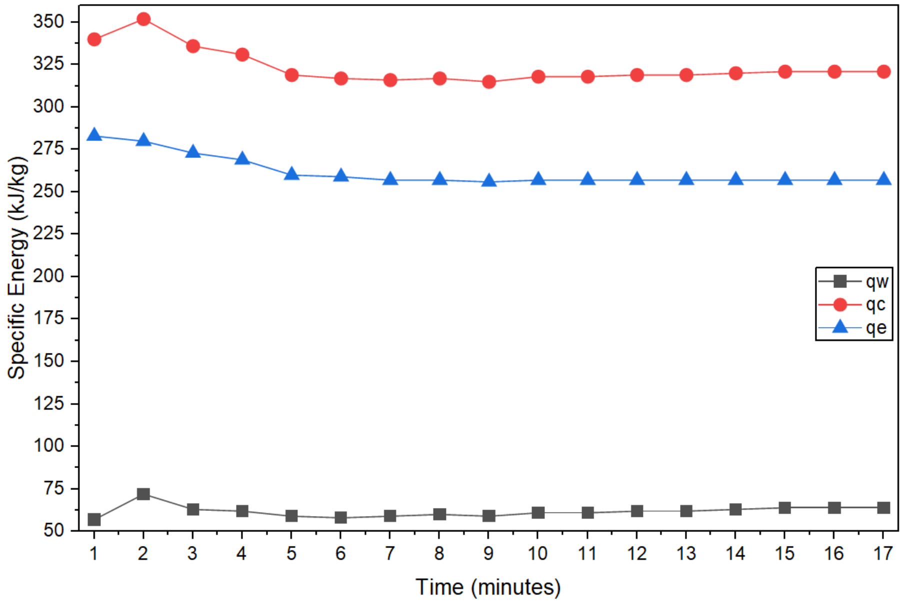

Figure 5. Variation of Compression Work (q_w), Condenser Heat Rejection (q_c) and Evaporator Refrigeration Effects (q_e) During System Operation

The COP trend provides insights into the system efficiency during different operational phases. Figure 6 shows that COPActual decreased sharply from 4.96 to 3.89 during the rapid cooling phase owing to the high compressor power demand. As the system transitioned to steady-state operation, the COP stabilized at an average value, indicating consistent long-term performance. This behavior highlights the importance of evaluating cooling systems beyond transient start-up conditions.

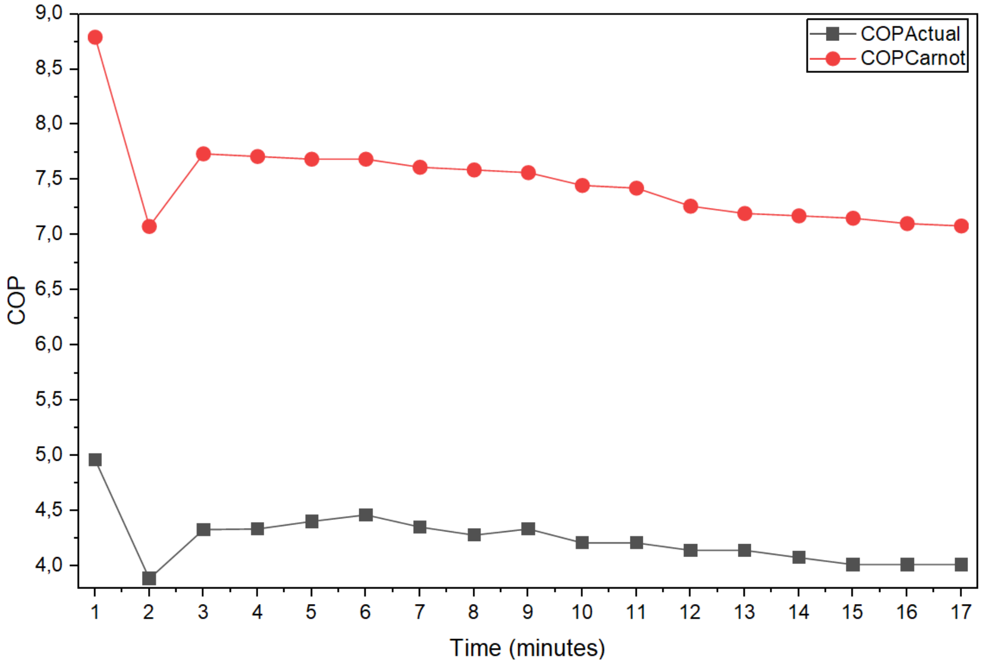

Figure 6. Temporal Variation of Coefficient of Performance

3.3 Influence of Hydroponic Parameters on Plant Growth

Plant growth observations clearly demonstrated the physiological benefits of root zone temperature control. As shown in Figure 7b, plants receiving cooled nutrient solutions exhibited taller stems, larger and darker green leaves, and more uniform development of fruit. These characteristics indicate improved photosynthetic activity and nutrient uptake associated with an optimal root zone temperature (Hooks et al., 2022). In contrast, plants grown without cooling (Figure 7a) showed signs of heat stress, including reduced vigor and leaf-wilting. These findings align with previous reports that emphasize the critical role of root zone cooling in subtropical strawberry cultivation (Intawong et al., 2025).

The hydraulic performance of the system also influences plant growth. Figure 8 shows that the flow rate fluctuated between 3.06 and 3.86 l/min. While higher flow rates can enhance oxygen availability and heat transfer, excessive flow increases energy consumption and nutrient loss. Conversely, insufficient flow may lead to oxygen depletion and root suffocation in the plant. These results indicate that flow rate regulation is essential for complementing temperature control.

(a) (b)

Figure 7. Visual Comparison of Strawberry Plants: (a) Without Cooling and (b) With Water Cooling.

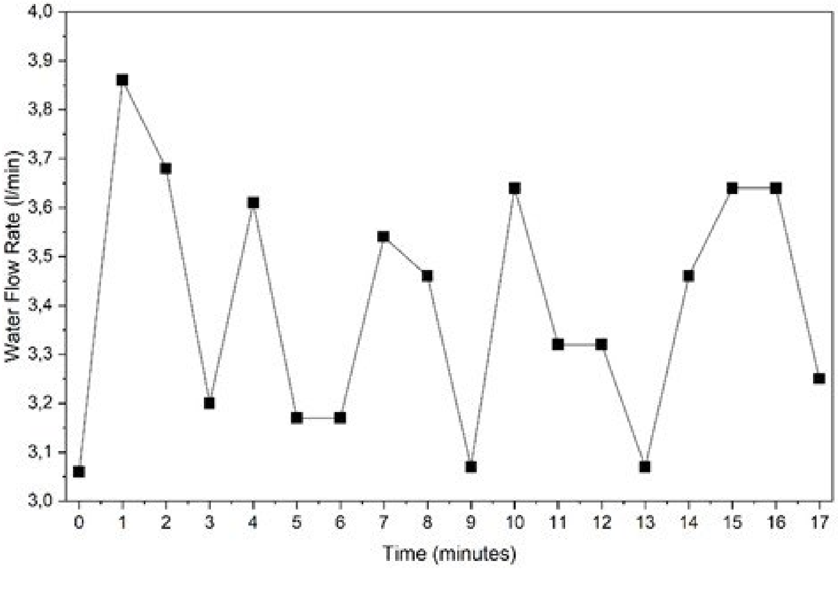

Figure 8. Nutrient Solution Flow Rate Variation during System Operation.

Nutrient concentration was maintained between 1270 and 1500 ppm and was sufficient to support vegetative growth. Figure 9a illustrates nutrient deficiency symptoms, such as chlorosis and stunted growth, whereas Figure 9b shows stress responses under excessive nutrient concentrations, including stem and leaf darkening. These observations confirm that nutrient balance plays a decisive role in plant performance.

(a) (b)

Figure 9. Plant Growth Response to Nutrient Concentration: (a) Insufficient Nutrient Supply and (b) Excessive Nutrient Concentration

Interestingly, strawberry plants exhibited acceptable growth despite the initial acidic pH conditions (pH 4.1). This suggests that stable root zone temperature and adequate nutrient availability may partially compensate for suboptimal pH in the short term. However, prolonged exposure to acidic conditions impairs nutrient absorption and damages root tissues, indicating that pH control is critical for long-term cultivation.

Overall, the results demonstrate that active root-zone temperature control using a vapor-compression chiller is an effective and reliable solution for hydroponic strawberry cultivation in tropical lowland environments with high ambient temperatures. The system achieved rapid cooling, stable temperature regulation, and favorable plant physiological responses.

From an engineering perspective, the findings provide empirical evidence of system performance, highlighting the trade-offs between cooling effectiveness and energy efficiency. From an agronomic standpoint, this system offers a practical and scalable approach for extending strawberry production beyond traditional high-altitude regions. These results confirm that precise thermal management, combined with controlled nutrient and hydraulic conditions, is a key factor for sustainable, high-yield hydroponic strawberry cultivation in hot climates.

4. Conclusion

This study demonstrates that a vapor-compression chiller integrated into a hydroponic system is an effective solution for controlling Nutrient Solution Temperature (NST) in strawberry cultivation under tropical lowland conditions. The developed system successfully reduced NST to the optimal Root-Zone Temperature (RZT) range of 17–20°C within a short period and maintained stable thermal conditions through an efficient on–off control strategy. Although the actual compressor work exceeded the theoretical predictions, the system achieved a stable coefficient of performance and an efficiency of approximately 56%, indicating reliable real-world operation. From an agronomic perspective, controlled root-zone temperature significantly improved vegetative growth, leaf quality, and fruit uniformity compared to plants grown without cooling, whereas nutrient concentration and water flow rate were identified as additional critical factors influencing plant performance. These findings provide empirical evidence supporting the application of chiller-based root-zone cooling as a practical and scalable approach for extending hydroponic strawberry production into hot, lowland regions, while also highlighting opportunities for future optimization through improved energy management and the use of integrated automated control systems.

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6. AI Writing Statement

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