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Root-Zone Cooling in an Arduino-Based NFT Hydroponic System for Enhancing Lowland Strawberry Cultivation

Pendinginan Zona Akar pada Sistem Hidroponik NFT Berbasis Arduino untuk Meningkatkan Budidaya Stroberi di Dataran Rendah

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ABSTRACT

Strawberry cultivation in lowland tropical regions remains challenging due to high temperatures, which negatively affect root-zone processes, reduce nutrient uptake efficiency, and limit plant growth. This study addresses these limitations by developing a controlled Nutrient Film Technique (NFT) hydroponic system integrated with a water chiller and an Arduino-based monitoring unit to replicate the optimal root-zone temperature (17–20°C) typically found in highland environments. The system regulates three key parameters: nutrient solution temperature, nutrient concentration, and water flow rate, to support the growth of Mencir strawberry plants under lowland conditions. The experimental setup consisted of an NFT system equipped with temperature sensors, TDS sensor, and flow sensor, with real-time monitoring conducted via an Arduino Uno microcontroller. Experimental results show that the cooling system effectively reduced the nutrient solution temperature from 27–28°C to approximately 17°C within 19 minutes and maintained this range through automated thermostat control. Nutrient concentration remained within the recommended range (1260–1540 PPM) with average of 1419 PPM, while the flow rate was maintained at approximately 3.29 L/min. These controlled conditions enabled stable plant growth, with flowering initiated at Day 13 and fruit ripening achieved within 19–20 days after transplanting. This growth duration indicates accelerated reproductive development compared to typical strawberry cultivation under non-controlled lowland conditions. The findings demonstrate that stable root-zone conditions contribute to improved strawberry growth under lowland environments. This research provides a practical engineering approach for extending strawberry cultivation to non-traditional agroecological zones and highlights the potential improvements of integrated environmental control systems in hydroponic agriculture.

Keywords: Hydroponics; lowland; Nutrient Film Technique; strawberry; water chiller

ABSTRAK

Budidaya stroberi di wilayah dataran rendah tropis masih menghadapi berbagai kendala akibat suhu tinggi yang mengganggu zona perakaran, menurunkan efisiensi penyerapan nutrisi, serta menghambat pertumbuhan tanaman. Penelitian ini berupaya mengatasi permasalahan tersebut melalui pengembangan sistem hidroponik Nutrient Film Technique (NFT) *yang diintegrasikan dengan sistem pendinginan air (*water chiller*) dan unit pemantauan berbasis* Arduino *untuk mereplikasi suhu zona perakaran optimal (17–20°C) sebagaimana kondisi di dataran tinggi. Sistem hidroponik yang dikembangkan difokuskan pada pengaturan tiga parameter utama, yaitu suhu larutan nutrisi, konsentrasi nutrisi, dan laju aliran air. Pengaturan tersebut ditujukan untuk mendukung pertumbuhan stroberi varietas Mencir di lingkungan dataran rendah. Rangkaian percobaan terdiri atas sistem NFT yang dilengkapi sensor suhu, sensor TDS, dan sensor aliran, dengan pemantauan waktu nyata (*real-time*) melalui mikrokontroler* Arduino Uno*. Hasil penelitian menunjukkan bahwa sistem pendingin (*chiller*) mampu menurunkan suhu larutan nutrisi dari 27–28°C menjadi sekitar 17°C dalam 19 menit dan mempertahankannya melalui siklus kerja termostat otomatis. Konsentrasi nutrisi terjaga pada rentang yang direkomendasikan (1260–1540 ppm) dengan rata-rata 1419 PPM dan laju aliran air berada pada rata-rata 3,29 L/menit. Kondisi terkontrol ini mendukung pertumbuhan tanaman yang stabil, dengan pembungaan mulai terjadi pada hari ke-13 dan pematangan buah dicapai dalam waktu 19–20 hari setelah ditanam. Durasi pertumbuhan ini menunjukkan perkembangan tanaman yang lebih cepat dibandingkan dengan budidaya stroberi pada kondisi dataran rendah yang tidak terkontrol. Temuan ini menunjukkan bahwa pengendalian lingkungan pada zona akar secara presisi dapat meningkatkan kemampuan adaptasi stroberi di kondisi dataran rendah. Penelitian ini memberikan pendekatan rekayasa yang praktis untuk memperluas budidaya stroberi ke wilayah nontradisional dan membuka peluang pengembangan sistem pengendalian lingkungan terintegrasi dalam pertanian hidroponik.*

Kata kunci: *Dataran rendah; hidroponik; Nutrient Film Technique; stroberi;* water chiller

INTRODUCTION

Strawberry (*Fragaria* sp.) is a high-value horticultural commodity in Indonesia with strong economic potential, supported by increasing production and market demand. National strawberry production reached 27,721 tons in 2023, reflecting a substantial increase of 269.56% over the past five years (Badan Pusat Statistik Indonesia, 2024). This growth indicates the rising demand for strawberries, driven by their high nutritional value, particularly vitamin C and antioxidant content (Hernández-Martínez et al., 2023). Despite this positive trend, strawberry production remains highly concentrated in highland regions, particularly West Java (Aryani et al., 2023; Hutauruk et al., 2023; Nugroho et al., 2023). West Java contributed approximately 23,409 tons of the national output in 2023, mainly from areas such as Ciwidey, Lembang, and Tasikmalaya (Romiyadi & Putri, 2024). This geographical concentration creates a supply imbalance, as increasing demand in lowland areas is not matched by local production capacity. At the same time, rapid population growth has reduced the availability of agricultural land, encouraging efforts to expand strawberry cultivation beyond its traditional areas (Abdullah et al., 2023). However, expanding strawberry cultivation to lowland areas is challenging by unfavorable environmental conditions, particularly due to higher ambient temperatures.

Strawberries are typically cultivated in subtropical highland areas at elevations of 1,000–1,500 meters above sea level, with a moderate temperature range between 17–20°C and relative humidity (RH) of 80–90%. They also require approximately 600–700 mm of annual rainfall and 8–10 hours of daily light (Chrysoula et al., 2022; Mahardika et al., 2023). These environmental requirements make strawberry production highly dependent on specific environmental conditions. This highlights the need for technological interventions to enable strawberry cultivation beyond traditional highland areas.

Temperature plays a critical role, especially in the root zone. Optimal root-zone temperatures (17–20°C) support efficient nutrient uptake, root respiration and overall metabolic activity. In lowland tropical areas, where temperatures frequently exceed 27°C, root-zone conditions become less favorable. As a result, plants experience reduced nutrient absorption, increased respiration rates, and slower plant growth. Previous studies have reported that elevated root temperatures can significantly decrease strawberry yield and delay fruit development (Timotiwu et al., 2021; Ullah et al., 2024). Conversely, maintaining optimal root-zone temperatures can enhance growth and accelerate fruit maturation (Naphrom et al., 2025).

Hydroponic cultivation, particularly the Nutrient Film Technique (NFT), offers a promising approach for controlling root-zone conditions (Kalantari et al., 2018; Putri et al., 2020; Yulianti & Manurung, 2017). Unlike conventional soil-based cultivation, NFT allows precise manipulation of nutrient solution temperature and flow characteristics, making it suitable for temperature-sensitive crops (Hutchinson et al., 2025; Oktora et al., 2024; Rani et al., 2023) Several studies have explored that root-zone cooling through nutrient solution temperature control is more effective than ambient air cooling, as it directly targets the plant's physiological processes (Ciptaningtyas et al., 2017; Fazlil Ilahi et al., 2024). Technologies such as vapor-compression chillers and thermoelectric (Peltier) systems have been applied to regulate nutrient temperature in hydroponic systems, primarily for leafy vegetables such as lettuce (Bobi Khoerun et al., 2023), where stable root-zone temperatures are associated with improved plant growth, including increased plant height and faster leaf development.

Despite these developments, existing studies largely focus on general cooling strategies or on crops that are less sensitive to temperature stress (Ciptaningtyas et al., 2017), leaving a gap in research on integrated systems specifically designed for strawberries under lowland conditions. The use of microcontroller-based platforms for real-time monitoring and control also remains relatively underexplored. Integrating key parameters such as temperature, nutrient concentration, and flow rate into a single automated control system is important for maintaining stable growing conditions and reducing environmental stress (Puspitahati et al., 2025).

To address this gap, this study aims to develop and evaluate an integrated NFT hydroponic system equipped with a water chiller and an Arduino-based control to regulate root-zone temperature, nutrient concentration, and water flow rate simultaneously. By maintaining optimal root-zone conditions, this study seeks to improve Mencir strawberry variety growth performance and demonstrate the feasibility of lowland cultivation using controlled-environment agriculture technologies. The system developed in this study was designed at a pilot scale, but it enables scale-up by extending the number of growing channels and adjusting the cooling capacity. However, further investigation is required to evaluate energy efficiency, cost-effectiveness, and system performance under large-scale operational conditions. Therefore, this study serves as a foundational framework for future development of scalable hydroponic cooling systems for commercial strawberry production in non-traditional growing regions.

METHODOLOGY

This study evaluated the performance of a controlled Nutrient Film Technique (NFT) hydroponic system integrated with a water chiller for cultivation on strawberries (*Fragaria* sp.) in lowland conditions The experiment was conducted at Politeknik Negeri Indramayu, West Java, Indonesia, located at 7m above sea level. The site represents a tropical lowland environment (type D) with an average ambient temperature of 24–30°C and relative humidity of 70–80%. Although geographically situated in a coastal region, the experimental site was not directly exposed to strong marine influences such as salt spray or coastal winds.

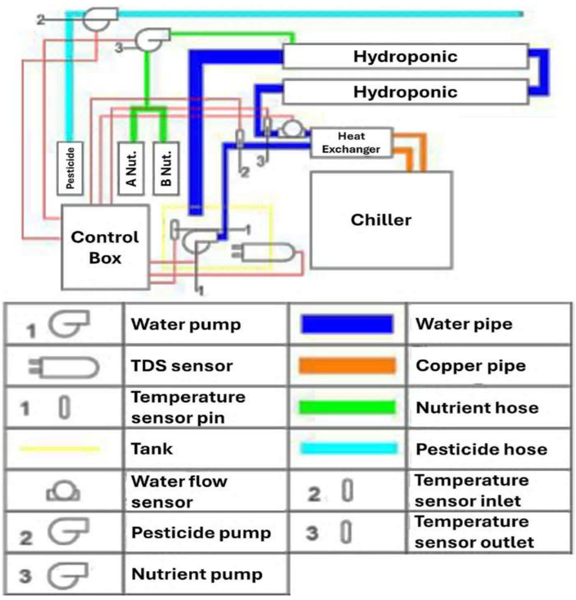

Figure 1. The schematic of the NFT hydroponic system with a water chiller

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Plant Material and Seedling Preparation

The Mencir strawberry variety was selected due to its adaptability and commercial relevance (Nugroho et al., 2023). Seedlings were initially propagated using rockwool cubes as a germination medium to ensure uniform root development. The nursery phase was conducted for approximately 7 days until the seedlings developed sufficient root structures for transplantation. Once the seedlings had developed strong root structures, they were transferred to NFT hydroponic channels for further growth and begin the experimental period. A total of 10 strawberry seedlings with uniform size and developmental stage were selected for the experiment. The system was operated continuously under controlled conditions, and plant growth observations were conducted until the harvesting stage, which occurred on Day 20 after transplantation.

To evaluate the effect of root-zone cooling, a comparative observation was also conducted using a similar NFT hydroponic setup without activating the cooling system (non-cooled condition). This comparison aimed to provide a qualitative assessment of plant response under uncontrolled root-zone temperature conditions in lowland environments.

NFT Hydroponic System Design

The experimental setup consisted of a controlled NFT hydroponic system integrated with a water chiller and an Arduino-based control unit. The system included a nutrient reservoir, circulation pump, PVC growing channels, sensors, and a cooling unit. The nutrient solution was continuously circulated through the channels to maintain a thin film over the plant roots. Figure 1 presents the physical layout of the NFT system integrated with a water chiller.

The cooling process was performed using AQUA (AQA-CR9FQDL) cooling unit with a cooling capacity of 1 HP and a power consumption of approximately 760 W. The system operates based on a vapor-compression refrigeration cycle, which enables efficient heat removal from the circulating nutrient solution (Fatwasauri et al., 2026). This capacity was sufficient to reduce the nutrient solution temperature from 27–28°C to approximately 17°C within 19 minutes.

Control and Monitoring System Architecture

The entire system was monitored and controlled by an Arduino Uno Rev3 SMD CH340 board (Generic Open-Source Manufacturer, Shenzhen, China) equipped with an ATmega328P microcontroller. The board was used for real-time monitoring, data acquisition, and safety control. Figure 2 shows the wiring configuration of the control system placed inside the control box.

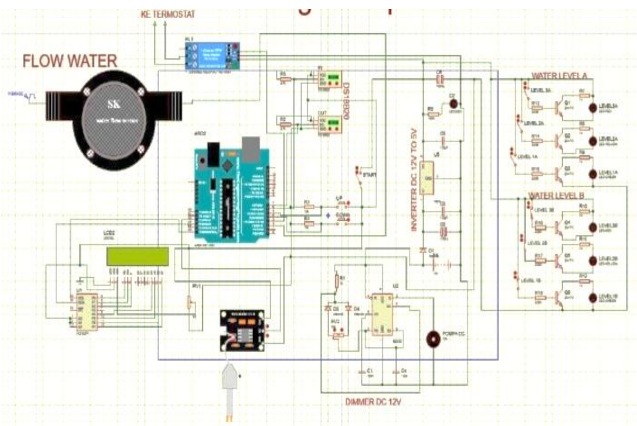

Figure 2. The wiring configuration of the control system

Table 1. Sensors used in the NFT hydroponic control system

Sensor Type	Temperature Sensor	TDS Sensor	Water Flow Sensor	Water Level Sensor
Model / Code	DS18B20	KS0429	YF-S201	Resistive multi-probe
Measurement Parameter	Temperature (°C)	Total Dissolved Solids (PPM)	Flow rate (L/min)	Water Level (cm)
Operating Range	−55–125°C	0–1000 ppm	1–30 L/min	Multi-level detection (2–6 cm)
Operating Voltage	3.0–5.5V DC	3.3–5.5V DC	4.5–18V DC	3.0–5.0V DC
Output Type	Digital	Analog	Digital	Digital
Function in System	Measures inlet and outlet nutrient solution temperature	Monitors nutrient concentration	Measures flow rate and support system safety control	Detects water level and prevents overflow

The sensors used in this study, along with their specifications and functions within the system, are summarized in Table 1. These sensors were selected based on their compatibility with Arduino-based systems and their suitability for real-time monitoring in hydroponic environments.

Power Supply Configuration

Each electronic component in the system operates at specific voltage levels. Figure 3 illustrates the electrical power supply diagram used in this study. The water pump and cooling system operate at 220 V AC, while the Arduino Uno microcontroller and associated sensors (temperature sensor, TDS sensor, and water level sensor) operate at 5 V DC. The YF-S201 water flow sensor operates within a voltage range of 5–18 V DC and is supplied with 5 V for compatibility with the Arduino system.

To accommodate these requirements, the system utilized a 120 W, 12 V Switching Mode Power Supply (SMPS) was used as the primary power source. A DC–DC converter was used to step down voltage from 12 V to 5 V to support low-voltage components such as the Arduino and sensors. This configuration ensures compatibility between components and maintains stable operation within the required voltage range.

System Operation Procedure

System operation began by activating the main circuit breaker (MCB), followed by pressing the start button. Once the system was powered, the water flow rate was manually adjusted to activate the chiller’s thermostat. The thermostat was set to maintain nutrient solution temperature near 17°C, which is optimal for strawberry root function.

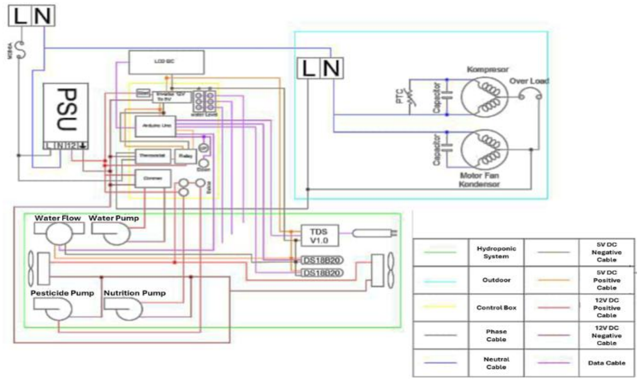

Figure 3.The electrical power supply diagram

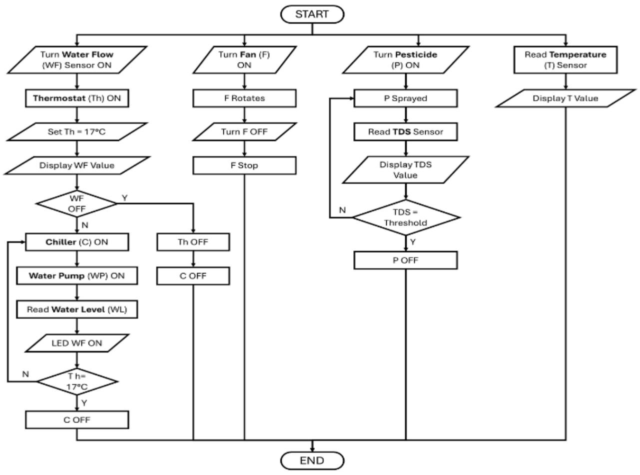

Figure 4. The system's control flowchart

To enhance system safety, a flow-based protection mechanism was implemented. A water flow sensor continuously monitored the circulation of the nutrient solution and transmitted pulse signals to the Arduino microcontroller. When the detected water flow rate stopped entirely, the thermostat automatically shut off and deactivated the chiller by interrupting the electrical supply via a relay module. This mechanism prevents the chiller from operating under no-flow conditions, which may lead to excessive evaporator cooling, resulting in ice formation within the heat exchanger and potential damage to the cooling components.

The cooling process was monitored using temperature sensors installed at the inlet and outlet of the system. The nutrient solution was considered to have reached the chilled condition when the measured temperature decreased to the setpoint value of approximately 17°C, as regulated by the thermostat. Once this temperature was achieved, the cooled nutrient solution was circulated through the NFT channels and returned to the reservoir in a closed-loop system.

A resistive-type water level sensor with multiple probe electrodes was installed inside the NFT channel to monitor the water level. The sensor detects changes in electrical conductivity between probes as the water level rises and activates indicator lights at three predefined levels: Level 1 (2 cm), Level 2 (4 cm), and Level 3 (6 cm).

Additional system functions included cooling fans for air circulation, a pesticide spray pump for pest control, and a nutrient pump to adjust nutrient concentrations were controlled manually using push buttons. Figure 4 illustrates how the control system responds to sensor inputs. The experiment was conducted in a semi-open environment without a fully enclosed greenhouse system. Therefore, manual interventions were applied to maintain environmental stability and plant health. However, the primary control variables were still continuously monitored and regulated using the Arduino-based control system. As a result, the key parameters affecting root-zone conditions remained stable throughout the experiment.

Monitored Parameters

Three primary parameters were monitored continuously throughout the experiment to evaluate system performance:

1. Water Temperature
   Two DS18B20 sensors were positioned at the inlet and outlet of the hydroponic channels to measure the nutrient solution temperature. The chiller was equipped with a thermostat to maintain the temperature within the optimal range of 17°C to 20°C.
2. Nutrient Concentration
   The concentration of the nutrient solution was measured using a KS0429 Total Dissolved Solids (TDS) sensor in parts per million (PPM). Nutrient solutions (designated as A and B mix) were manually added to maintain the desired concentration, and real-time values were displayed on an LCD interface connected to the Arduino.
3. Water Flow Rate
   A YF-S201 water flow sensor was used to measure the nutrient flow rate in liters per minute (L/min). The target flow rate was set at 3 L/min, which falls within the recommended range of 2–4 L/min for NFT systems. Previous studies have reported that flow rates within this range can stimulate root development and increase root surface area, thereby enhancing nutrient uptake efficiency (Baiyin, Tagawa, Yamada, Wang, Yamada, Shao, et al., 2021). A flow rate of 3 L/min was considered sufficient to maintain a thin, oxygen-rich nutrient film without fully submerging the root system. In addition to supporting plant growth, maintaining adequate flow is essential for thermal performance. Before entering the hydroponic channels, the nutrient solution passes through a chiller system, where sufficient flow ensures effective heat transfer and prevents localized freezing within the heat exchanger.

Sensor calibration and stability were confirmed before the experiment to ensure measurement accuracy. Data on temperature, nutrient concentration, and flow rate were recorded at 1-minute intervals during the first 40 minutes of system operation to capture the dynamic response of the cooling and circulation processes. Observations of plant growth were conducted daily, focusing on vegetative development, flowering time, and fruit ripening.

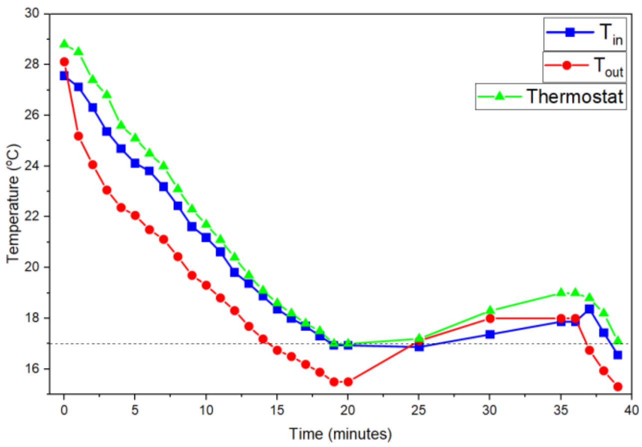

Figure 5. The temperature profiles for inlet water, outlet water, and thermostat readings

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RESULTS AND DISCUSSION

This study demonstrates the effectiveness of a controlled NFT hydroponic system integrated with a water chiller for the successful cultivation of strawberries (*Fragaria* sp. Mencir variety) in lowland conditions. The results show that precise environmental control can mitigate the thermal stress typically observed in lowland strawberry cultivation.

Temperature Control Performance

The performance of the cooling system was evaluated during the initial operation phase to assess its dynamic response. Temperature data were recorded at 1-minute intervals over the first 40 minutes, as shown in Figure 5.

The results indicate that the nutrient solution in inlet temperature decreased from 27.56 °C to 16.94 °C within 19 minutes. The outlet temperature also decreased from 28.12°C to 15.5°C. The thermostat reading in the reservoir reached approximately 17°C, which corresponds to the predefined setpoint.

This observation confirms that the cooling system is capable of rapidly achieving the target temperature required for strawberry root-zone conditions. Maintaining nutrient solution temperature between 17–20°C is essential for optimal strawberry root function (Setiawan et al., 2018). Cooling at the root-zone is known to stabilize plant physiological processes by reducing root respiration rates, allocating more metabolic energy toward growth and fruiting (Naphrom et al., 2025). According to root-zone cooling theory, lower temperatures increase dissolved oxygen (DO) levels, which in turn enhance ion uptake, particularly nitrogen and potassium, essential for both vegetative growth and reproductive development in strawberries.

After reaching the setpoint, the system operated in a cyclic mode, where the thermostat automatically turned on and off the chiller to maintain temperature stability. During the off cycle, the recorded temperatures gradually increase across all measurement points. The inlet temperature rose to 17.87°C, while the outlet temperature reached approximately 18°C. The thermostat temperature demonstrated the highest increase to 19°C. Once the threshold was exceeded, the chiller resumed operation, completing a controlled temperature cycle. This cycling behavior indicates a successful automated regulation mechanism that prevents temperature shock while maintaining optimal conditions.

The 40-minute data represent the transient cooling phase, while during the remaining cultivation period, the system operated continuously under thermostat control to maintain temperature within the desired range.

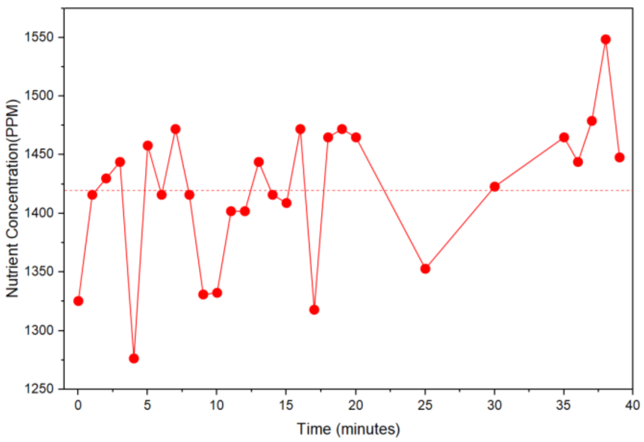

Figure 6. The measured nutrient concentration

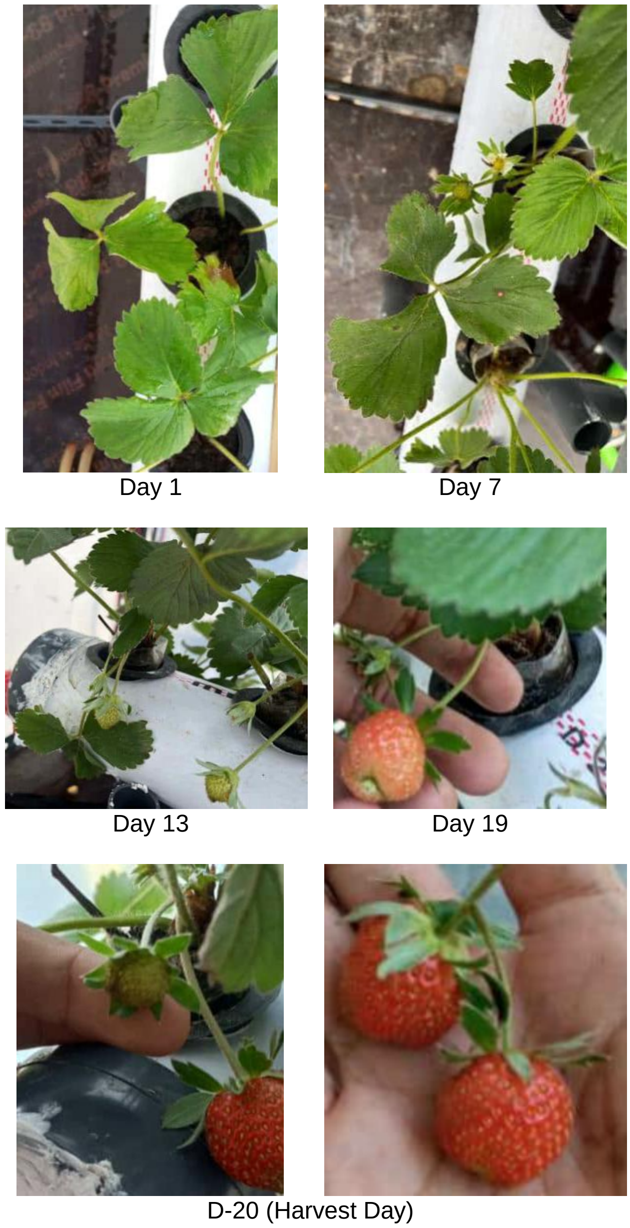

Figure 8. The progression of strawberry plant growth from day 1 to day 20 (harvest day)

Nutrient Concentration Stability

The critical aspect in supplying nutrient solutions within hydroponic systems is determining the appropriate concentration (Oktarina et al., 2017). Nutrient concentration plays a crucial role in maintaining photosynthesis, osmotic balance, and metabolic activities (Rukmi et al., 2017). When nutrient concentration becomes excessively high, this condition hinders the plant's ability to absorb nutrients effectively. It may harm plant health by triggering plasmolysis in plant cells. On the other hand, if nutrient concentrations fall below required levels, the plant may suffer from insufficient nutrient uptake, leading to unmet nutritional needs. Therefore, selecting the optimal nutrient concentration is essential to ensure healthy and balanced plant growth.

Nutrient concentration was monitored throughout the cultivation period using a TDS sensor. During the initial observation period, TDS values ranged from 1276 to 1548 PPM, with an average of 1419 PPM, as shown in Figure 6.

The observed controlled fluctuation reflects normal plant nutrient uptake dynamics. Although short-term fluctuations occurred, the nutrient concentration remained within acceptable limits for strawberry growth across the cultivation period. Manual nutrient addition, supported by real-time TDS monitoring, ensured consistent nutrient availability. The Arduino-based monitoring system effectively reduced the likelihood of sudden nutrient imbalances.

For the entire cultivation period, nutrient concentration was maintained within the recommended range through periodic manual adjustment. The daily average values are presented in Table 2.

Water Flow Rate Dynamics

Adequate water flow rate ensures uniform nutrient distribution, prevents sedimentation, maintains oxygen levels, and reduces the risk of freezing in the chiller's heat exchanger (Balliu et al., 2021). Water flow rate data presented in Figure 7 corresponds to measurements taken at 1-minute intervals during the first 40 minutes of operation to evaluate system stability during initial circulation.

Water flow rate was maintained through a continuous pump operation. The YF-S201 flow sensor provided real-time monitoring, allowing adjustments to be made when deviations from the target flow rate (3 L/min) were observed. The 40-minute dataset represents the system's initial performance flow rate, ranging from 2.42 to 4.36 L/min, with an average of 3.29 L/min. During the cultivation period, the flow rate was maintained, and the daily average values are presented in Table 2.

Maintaining a proper water flow rate is important to prevent waterlogging and to maintain adequate oxygen levels, both of which are vital for root health and nutrient absorption (Rani et al., 2023). Despite some fluctuations, water flow rates are within acceptable limits for NFT systems and beneficial for several reasons. The water flow rates mitigate the risk of root hypoxia by increasing dissolved oxygen availability. Additionally, slightly higher flow rates promote more uniform nutrient-film thickness across channels, enhancing overall nutrient distribution. Continuous circulation prevents stagnant zones, which could harbor pathogens (Balliu et al., 2021).

An appropriate water flow rate helps regulate root cell development, allowing roots to become structurally stronger while remaining efficient in ion absorption. When the flow rate is too low (below 1 L/min), plants may experience water and nutrient deficits due to limited interaction between nutrient ions and the root surface (Abbas et al., 2024) In contrast, excessively high flow rates (above 6–8 L/min) can induce distress (negative stress), leading to more compact and shorter roots, which may ultimately reduce yield (Baiyin, Tagawa, Yamada, Wang, Yamada, Yamamoto, et al., 2021b, 2021a).

Plant Growth Response

The controlled temperature and nutrient environment significantly improved strawberry growth performance. The plants exhibited strong vegetative development, timely flowering, and successful fruiting. Figure 8 presents visual observations of plant development from Day 1 to Day 20 (harvest day).

Plant development was observed throughout the cultivation period. On Day 1, seedlings established themselves in the NFT channels. By Day 7, a noticeable increase in leaf number and plant size. Flowering was initiated on Day 13. The initiation of flower bud formation marked the transition from the vegetative to the reproductive phase. By Day 19, fruits had reached the ripening stage, marked by red pigmentation. Finally, on Day 20, the strawberries attained harvest maturity, signifying the completion of the growth cycle under NFT conditions.

This rapid progression (19–20 days from installation to harvest stage) suggests that optimal root-zone temperatures significantly accelerate physiological processes. Cooling at the root-zone reduces heat stress, promotes hormonal balance (especially auxin and cytokinin), improves carbohydrate allocation to reproductive organs, and enhances the translocation of sugars required for fruit formation.

A comparative observation was also conducted under non-cooled conditions. Under this condition, although nutrient supply was sufficient, plant growth appeared slower, with reduced leaf expansion and less vigorous plant appearance compared to the cooled system. Figure 9 shows the comparison between plants grown with and without root-zone cooling. The comparison indicates that temperature control plays a significant role in maintaining stable root-zone conditions and contributes to improved plant growth under lowland environments.

Figure 9. Comparison of strawberry plants growth with and without root-zone cooling

Table 2. The daily average values for temperature, nutrient concentration, and water flow rate

Day	Temperature (°C)	Nutrient Concentration (PPM)	Water Flow Rate (L/min)
1	18.0	1419	3.29
2	18.9	1318	3.46
3	17.1	1472	3.64
4	22.0	1409	3.64
5	18.0	1400	3.40
6	17.0	1416	3.25
7	17.4	1444	3.25
8	18.0	1400	3.40
9	17.6	1402	3.46
10	17.7	1402	3.14
11	18.4	1332	3.57
12	17.6	1334	4.00
13	18.3	1416	4.36
14	18.3	1420	3.50
15	18.3	1435	3.50
16	17.2	1472	2.81
17	19.0	1416	3.35
18	17.4	1458	3.93
19	18.5	1444	2.77

Table 2 summarizes the daily average values for temperature, nutrient concentration, and water flow rate recorded at late afternoon (15:00–16:00). The data demonstrates that environmental conditions remained within ranges suitable for strawberry cultivation throughout the experiment.

The Arduino-based monitoring system played a crucial role in maintaining stability, serving as a safety net to detect and respond to deviations in real time. The integration of the water chiller and Arduino-based monitoring system successfully replicated highland-like microclimatic conditions in a lowland area, resulting in healthy plant growth and consistent fruit production.

However, challenges such as maintaining perfectly stable flow rates and preventing nutrient concentration drift remain areas for optimization. High light intensity in lowland environments also increased plant transpiration, suggesting future studies should consider shading systems, evaporative cooling, or dynamic climate control.

CONCLUSION

The cultivation of Mencir strawberries in lowland conditions was successful through the integration of a water chiller with an Arduino-based control system in an NFT hydroponic setup. The system was able to reduce nutrient solution temperature from 27–28 °C to approximately 17 °C within 19 minutes, followed by stable cyclic regulation. The nutrient concentration averaged 1419 PPM, while the water flow rate was maintained at 3.29 L/min, ensuring adequate oxygenation and nutrient distribution. These controlled conditions supported healthy vegetative growth, indicated that flowering occurred on Day 13 and fruit ripening was achieved within 19–20 days after transplantation. A comparative observation under non-cooled conditions showed slower growth and less vigorous plant appearance, suggesting that temperature control contributes to improved plant performance in lowland environments. The results indicate that maintaining stable root-zone conditions plays an important role in supporting strawberry growth outside its typical highland environment. This study provides a practical approach for adapting hydroponic systems to lowland environments. Future work should focus on improving system automation, evaluating long-term stability, and conducting quantitative comparisons with controlled experimental designs.

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