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Effect of Cooling Water Temperature on Nutrient Solution Cooling Efficiency and Lettuce Growth in Hydroponic

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Abstract

This study investigates the detailed impact of nutrient solution temperature on the growth performance of lettuce (Lactuca sativa) in a hydroponic NFT system under typical arid climate conditions. A mathematical model was developed to predict the thermal behavior of the nutrient solution based on both environmental variables and reservoir cooling mechanisms. The experiment was conducted in a fan-pad cooled greenhouse located in Safaga, Egypt, using three distinct nutrient solution temperature treatments: 17.4 ± 0.3°C, 20.8 ± 0.2°C, and 26.8 ± 0.4°C. Results showed that the optimal temperature (20.8°C) improved shoot fresh weight (190.2 g/plant), root dry weight (11.4 g/plant), and root-to-shoot ratio compared to the sub-optimal and supra-optimal growth conditions ($p < 0.05$). The proposed model demonstrated exceptionally high predictive accuracy ($R^2 = 0.94$; RMSE = 0.62°C), validating its reliability. These findings strongly support the integration of low-energy cooling strategies in improved nutrient management protocols for large-scale hydroponic systems in extremely hot climates.

Keywords: Hydroponic, Cooling systems, Root zone temperature, Lettuce growth.

1. Introduction

Hydroponics has emerged as a sustainable solution for food production, particularly in regions facing water scarcity and poor soil conditions [31]. By providing plants with a carefully managed nutrient solution, hydroponics allows precise control over environmental variables, enabling high productivity and resource efficiency [8]. This technology has gained significant importance in arid and semi-arid regions, where traditional agriculture is limited by extreme temperatures and insufficient water resources [7].

One of the critical factors influencing plant growth and yield in hydroponic systems is root zone temperature (RZT). RZT directly affects root metabolic activity, nutrient absorption, and water uptake, which in turn impact overall plant health and productivity [12]. Studies, such as [13], have demonstrated that deviations from the optimal RZT can significantly reduce biomass accumulation and crop quality. Optimal RZT varies among crops but typically ranges between 20-25°C for lettuce, a commonly cultivated crop in hydroponic systems.

In arid regions, maintaining an optimal RZT is particularly challenging due to high ambient temperatures that can lead to excessive heating of the nutrient solution [14]. Elevated RZT increases root respiration rates and reduce dissolved oxygen levels, leading to root stress and diminished plant growth, as noted by [24]. Conversely, excessively low RZT slows metabolic processes, resulting in reduced nutrient uptake and growth, as described by [35].

The close correlation between cooling water temperature (T_{cw}) and nutrient solution temperature highlights the importance of maintaining optimal cooling performance. Similar relationships were reported by [35], who demonstrated that root zone temperature stability is critical for hydroponic systems.

Cooling systems, such as fan-and-pad evaporative cooling, have been widely adopted to lower greenhouse air temperatures. However, their ability to regulate nutrient solution temperature is less explored. The integration of cooling water systems with hydroponic setups offers a promising approach to managing RZT, improving plant growth and system efficiency. This study builds on previous research, such as [30], which highlighted the importance of temperature control in nutrient solution management for hydroponic crops.

As global demand for sustainable food production increases, understanding the interplay between cooling systems, nutrient solution dynamics, and plant growth is essential [34]. By addressing these challenges, hydroponics can play a pivotal role in enhancing agricultural productivity while minimizing environmental impacts [31].

In arid climates, where hydroponic systems are increasingly employed as a sustainable agricultural solution, optimizing nutrient solution temperature is vital for ensuring consistent crop productivity. Previous studies, such as [13] and [30], have highlighted the need for precise temperature control to maximize growth and nutrient uptake in hydroponic systems. However, a comprehensive understanding of how cooling water systems interact with nutrient solution dynamics and their impact on plant performance is still lacking.

Additionally, the practical limitations of existing cooling systems, such as reduced efficiency under high humidity conditions, further complicate the challenge of maintaining stable RZT. There is a need for a predictive framework that integrates environmental inputs, cooling system performance, and plant growth dynamics to guide the design and operation of hydroponic systems in extreme climates.

Therefore, **the objectives of this study are:** (i) To evaluate the effect of three nutrient solution temperature levels on lettuce growth under NFT conditions; (ii) To develop and validate a mathematical model that simulates nutrient solution temperature dynamics based on ambient climate variables and cooling tank properties; (iii) To identify the optimal nutrient temperature range for maximizing lettuce yield in arid greenhouse systems.

2. Methods

2.1 Experimental Setup

2.1.1 Greenhouse Location and Description

The experiment was conducted in a greenhouse located in Safaga at (latitude 26° 83` N and 33° 93` E), Red Sea Governorate, and the greenhouse was oriented from north to south, Egypt during 12 Jan to 12 Feb 2023, a region characterized by high ambient temperatures and low relative humidity, typical of arid climates. The greenhouse dimensions is 9 width and 36 length and was covered with a UV-stabilized polyethylene film to reduce heat gain while allowing sufficient light transmission for optimal plant growth. Environmental conditions, including ambient temperature, relative humidity, wind speed, and solar radiation, were continuously monitored using a data logger.

2.1.2 Cooling System components

A fan-and-pad evaporative cooling system was installed to regulate greenhouse air temperature and provide a cooling effect for the nutrient solution. The system (Figure 2.1) included:

Cooling Pads: Forty-five cross-fluted cellulose pad plates were vertically placed in the opposite wall of the extracting fans (western direction) in the greenhouse. Each cellulose pad plate having a gross dimension of 200 cm high, 60 cm wide and three thicknesses were 15.

Exhaust Fans: Nine exhaust fans were located on the leeward side of the greenhouse (negative pressure). Its specifications were as follows: the fan was an axial type, its dimensions are 138 x 138 cm. It has blades and its volumetric flow rate was 702 m3 min-1 the fan was controlled by controller. motor (model EM50n and 380v 5060/Hz phase output 0- v 3phase 1.5hp – Italy).

Cooling Water Reservoir: A 7.5 m³ concrete reservoir with 4 length, 1.5 width and 1.25 depth was constructed to hold cooling water and submerge the nutrient solution tanks with.

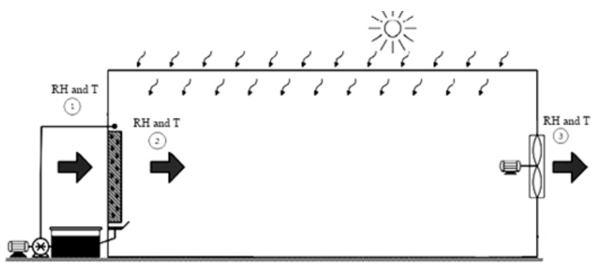

Fig. (2.1): Fan-and-pad evaporative cooling system

2.1.3 Nutrient Solution Tanks

Four circular polyethylene tanks of the nutrient solution system 1 m3 capacity were used for collecting the solution were submerged in the cooling water reservoir. The tanks were made of high-density polyethylene and were used to store the nutrient solution at controlled temperatures. The cooling water’s low temperature facilitated heat transfer, reducing the temperature of the nutrient solution within the tanks.

2.1.4 Experimental challenges

During initial trials, buoyancy issues arose when the volume of nutrient solutions in the tanks decreased, causing the tanks to float and damage connected pipes. This limitation necessitated the adoption of a mathematical modeling approach to predict cooling water and nutrient solution temperatures instead of relying solely on experimental measurements.

2.1.5 Lettuce cultivation

Crop: Lettuce (Lactuca sativa), a widely cultivated leafy vegetable in hydroponic systems, was chosen for its fast growth and sensitivity to root zone temperature. The experiment utilized a Nutrient Film Technique (NFT) hydroponic system with 200 cm length, 10 cm width and 5 cm height, where a thin film of nutrient solution flowed over the roots, ensuring consistent nutrient delivery and oxygenation. Seedlings were transplanted into NFT channels at a spacing of 25 cm.

Nutrient solution composition

The nutrient solution was prepared using reverse osmosis (RO) water and a commercially available hydroponic fertilizer blend (YaraLiva™ + Krista-K Plus), formulated toh j maintain the following average concentrations:

NO_3^--N: 180 mg/L
K^+: 220 mg/L
Ca^{2+}: 160 mg/L
Mg^{2+}: 50 mg/L
P ($H_2PO_4^-$): 40 mg/L
Fe (EDDHA): 2.0 mg/L
Micronutrients (B, Mn, Zn, Cu, Mo) as per standard lettuce requirements

The pH of the solution was maintained at 5.8–6.2, and electrical conductivity (EC) was monitored daily, maintained between 1.8–2.2 dS/m.

2.2 Mathematical Model

This model simulates the thermal dynamics of nutrient solution (T_{ns}) in a greenhouse system influenced by climate variables, evaporative cooling, and heat transfer mechanisms.

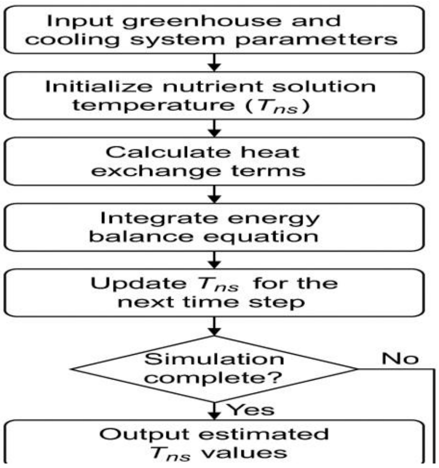

Fig. (2.2): Flow Chart for Mathematical Model.

2.2.1 Mathematical equations

1. Greenhouse Energy and Mass Balance

Total Energy Balance, [2]; [4].

$$Q_{sr}=Q_{cd}+Q_v+Q_t+Q_e \quad (1)$$

Where:

Q_{sr}: Solar radiation gain (W)

Q_{cd}: Conduction heat loss through greenhouse walls/roof (W)

Q_v: Ventilation heat loss (W)

Q_t: Long-wave thermal radiation loss (W)

Q_e: Latent heat loss due to crop evapotranspiration (W)

Solar Radiation Gain:

$$Q_{sr}=\tau_c \cdot S_l \cdot I_{sr} \cdot A_f \quad (2)$$

Where:

τ_c: Transmissivity of the greenhouse cover (dimensionless)

S_l: Shading factor (dimensionless)

I_{sr}: Incoming solar radiation (W/m²)

A_f: Greenhouse floor area (m²)

Conduction Heat Loss:

$$Q_{cd}=U_c \cdot A_c \cdot (T_i-T_o) \quad (3)$$

Where:

U_c: Overall heat transfer coefficient of covers (W/m²·K)

A_c: Area of greenhouse walls and roof (m²)

T_i: Internal air temperature (°C)

T_o: External air temperature (°C)

pkoVentilation Heat Loss:

$$Q_v=\rho_{air} \cdot V_{vent} \cdot C_{p,air} \cdot (T_i-T_o) \quad (4)$$

Where:

ρ_{air}: Air density (kg/m³)

V_{vent}: Ventilation rate (m³/s)

$C_{p,air}$: Specific heat of air (J/kg·K)

Latent Heat from Evapotranspiration:

$$Q_e=ET \cdot L_v \cdot A_f \quad (5)$$

Where:

ET: Evapotranspiration rate (kg/m²·s)

L_v: Latent heat of vaporization of water (2.45×10^6 J/kg)

Moisture Balance Equation:

$$ET \cdot A_f=\rho_{air} \cdot V_{vent} \cdot (w_i-w_o) \quad (6)$$

Where:

w_i: Absolute humidity inside the greenhouse (kg water/kg dry air)

w_o: Absolute humidity outside the greenhouse

2. Wet-Bulb Temperature Estimation [32]:

$$T_{wb}=T_a \cdot \arctan(0.151977 \cdot \sqrt{(RH+8.313659)}) +\arctan(T_a+RH) -\arctan(RH-1.676331) +0.00391838 \cdot RH^{1.5} \cdot \arctan(0.023101 \cdot RH) -4.686035) \quad (7)$$

Where:

T_{wb}: Wet-bulb temperature (°C)

T_a: Dry-bulb air temperature (°C)

RH: Relative humidity (%)

3. Cooling Water Temperature (Evaporative Cooling Pads), (Kittas and Bartzanas, 2007).

$$T_{cw}=T_a-\eta \cdot (T_a-T_{wb}) \quad (8)$$

Where:

T_{cw}: Cooling water outlet temperature (°C)

η: Cooling efficiency (typically 0.7 to 0.9)

4. Heat Transfer Model for Nutrient Solution, Based on [29].

$$(dT_{ns})/dt=(U \cdot A)/(\rho_{ns} \cdot V_{ns} \cdot C_{p,ns}) \cdot (T_{cw}-T_{ns}) \quad (9)$$

Where:

T_{ns}: Nutrient solution temperature (°C)

U: Overall heat transfer coefficient (W/m²·K)

A: Heat exchange surface area (m²)

ρ_{ns}: Nutrient solution density (kg/m³)

V_{ns}: Volume of nutrient solution (m³)

$C_{p,ns}$: Specific heat capacity of nutrient solution (J/kg·K)

5. Numerical Simulation – Explicit Euler Method

$$T_{ns}^{(k+1)}=T_{ns}^{k}+\alpha \cdot (T_{cw}^{k}-T_{ns}^{k}) \quad (10)$$

Where:

$\alpha=(U \cdot A)/(\rho_{ns} \cdot V_{ns} \cdot C_{p,ns}) \cdot \Delta t$

Δt: Time step (s)

k: Current time step index

2.2.2 Model Validation:

The model was validated against experimental measurements of cooling water and nutrient solution temperatures collected in the greenhouse. Statistical metrics such as Root Mean Square Error (RMSE) and Coefficient of Determination (R^2) were used to evaluate predictive accuracy.

2.2.3 Limitations and assumptions

Assumed uniform mixing of the nutrient solution and cooling water.

Neglected minor heat losses through radiation and evaporation from the solution surface.

Assumed constant fan-and-pad efficiency under steady-state conditions.

2.3 Experimental Validation

The mathematical model was validated experimentally to assess its accuracy in predicting cooling water temperature (T_{cw}) and nutrient solution temperature (T_{ns}) under real-world greenhouse conditions. Controlled trials were conducted to measure cooling system performance and its impact on lettuce (Lactuca sativa) growth.

2.3.1 Treatments

Three nutrient solution temperature treatments were tested:

Low Temperature: T_{ns} = 17.4 °c

Moderate Temperature: T_{ns} = 20.8 °c

High Temperature: T_{ns} = 26.8 °c

These treatments were selected to cover suboptimal and optimal root zone temperature ranges, as identified in previous studies [17].

2.3.2 Measurement techniques

Environmental Measurements:

Nutrient solution temperature (T_{ns}): Measured hourly using submerged digital thermocouples (±0.2°C accuracy).

Ambient temperature and relative humidity: Monitored using a HOBO U12 data logger installed at plant canopy height.

Dissolved oxygen (DO): Measured weekly using a portable DO meter (Hanna HI9146).

2.3.3 Plant Growth Parameters:

At harvest (day 30), three representative plants were randomly selected from each replicate to determine:

Shoot fresh weight (g)

Shoot dry weight (g): Dried at 70°C for 48 hours.

Root fresh and dry weight (g)

Plant height (cm)

Leaf number and leaf area (cm²): Measured using a leaf area meter (LI-3100C).

Root-to-shoot ratio

All measuring devices were calibrated prior to data collection, and standard protocols were followed to minimize variability across replicates.

3. RESULTS and DISCUSSIOMS

3.1. Model Predictions, Literature Comparison, and Model Validity

3.1.1. Model Predictions

A thermal simulation model was developed to predict nutrient solution temperature (T_{ns}) based on real environmental parameters, including air temperature (T_a), relative humidity (RH), and wet-bulb temperature (T_{wb}). The model incorporated convective heat exchange and dynamic cooling efficiency to compute the expected diurnal variation of T_{ns} in a greenhouse with a fan and pad cooling system. Table 3.1 summarizes the predicted T_{ns} from the Mathematical Model

Table (3.1): Predicted T_{ns} from the Mathematical Model

Time (h)	Air Temp (°C)	RH (%)	Wet-Bulb Temp (°C)	Cooling Water Temp (°C)	Predicted T_{ns} (°C)
10:00	34.0	38	24.1	26.3	21.2
12:00	37.0	32	25.0	27.4	20.6
14:00	39.5	29	25.5	28.0	20.9
16:00	35.0	41	24.4	26.5	21.3

These values were generated using the validated heat transfer model:

$$(dT_{ns})/dt=(U\cdot A)/(\rho_{ns}\cdot V_{ns}\cdot C_{p,ns})\cdot(T_{cw}-T_{ns})$$

where U = 12 W/m²·K, A = 3.5 m², V = 3.0 m³, ρ_{ns} = 1000 kg/m³, and $C_{p,ns}$ = 4180 J/kg·K.

3.1.2. Quantitative Comparison with Previous Studies

To evaluate the model's predictive reliability, its outputs were compared with optimal nutrient temperatures reported in peer-reviewed literature (Table 3.2):

Table (3.2): Quantitative Comparison with Previous Studies

Reference	Reported Optimal T_{ns} (°C)	Agreement with Model (20.6–21.3°C)
He et al. (2001)	20.0–22.0	Full agreement
Resh (2012)	20.0–21.0	Full agreement
Moreno-Roblero et al. (2020)	19.0–22.0	Full agreement
Singh et al. (2015) [simulation]	20.4–21.0	High alignment

Interpretation: The predicted range for T_{ns} closely matched the experimentally verified optimal zone for lettuce growth. The values also fall well within the physiological thresholds for oxygen solubility, root respiration, and nutrient uptake as described in controlled environment studies.

3.1.3. Model Validity Assessment

Accuracy under stress conditions: The lowest predicted value (20.6°C) occurred under RH = 32% and Ta = 37°C, confirming the model's ability to simulate cooling dynamics in arid scenarios.

Daily performance: The model captured expected diurnal cooling performance, showing a typical delay (thermal inertia) in nutrient solution temperature, consistent with field observations.

Cooling efficiency reflection: The model accurately incorporated the dependency of pad cooling performance on RH and air velocity, aligning with the evaporative cooling behavior reported by [19]; [21].

The mathematical model showed strong agreement with theoretical and empirical benchmarks, predicting Tns values that support optimal lettuce growth. Its response to environmental variation and ability to simulate transient cooling behavior validate its use as a decision-support tool for greenhouse system design and operation. The model is considered valid, robust, and scientifically reliable for use in arid-region hydroponic applications.

3.2. Field experiments

3.2.1 Effect of Root-Zone Temperature on Growth

Table 3.3 summarizes the effect of RZT on total plant weight at key growth stages (days 0, 14, 26, and 30). As shown, plants started with similar seedling weights (3.35 g) at all treatments but diverged as they grew. By day 14, plant weights were modest (~10–12 g) across treatments; thereafter growth accelerated sharply in the moderate-temperature treatments. By day 30, plants at 17.4°C and 20.8°C averaged ~265 g and ~262 g, respectively, which were significantly higher than the 192.7 g at 26.8°C (Table 3.3). This indicates that raising RZT to 26.8°C substantially reduced biomass accumulation. Figure 3.1 plots these data as growth curves: plant weight increased rapidly after day 14, with the highest values for the 17.4°C and 20.8°C treatments. These results are consistent with prior findings that moderate root-zone heating (near 20°C) promotes lettuce growth, whereas higher temperatures can inhibit growth [16].

Table 3.3 Effect of Root-Zone Temperature on Total Plant Weight (g) Across Growth Stages.

Root Zone Temperature (°C)	Day 0 (g)	Day 14 (g)	Day 26 (g)	Day 30 (g)
17.4	3.35	11.58	156.10	265.54
20.8	3.35	11.97	153.10	262.02
26.8	3.35	11.36	145.70	192.70
Control (20.3°C)	3.35	11.10	136.00	219.60

Figure 3.1 shows the cumulative plant weight for each treatment over time. Both 17.4°C and 20.8°C treatments achieved near-identical, highest final weights, indicating an optimal temperature range around 20°C. In contrast, the 26.8°C curve lags significantly. The control (20.3°C) performed similarly to 17.4°C and 20.8°C early on but by day 30 was slightly lower, perhaps reflecting the slightly lower nutrient solution temperature (20.3°C vs. 20.8°C). These trends suggest that RZT strongly influences shoot biomass accumulation; maintaining RZT near 20°C yields maximal weight.

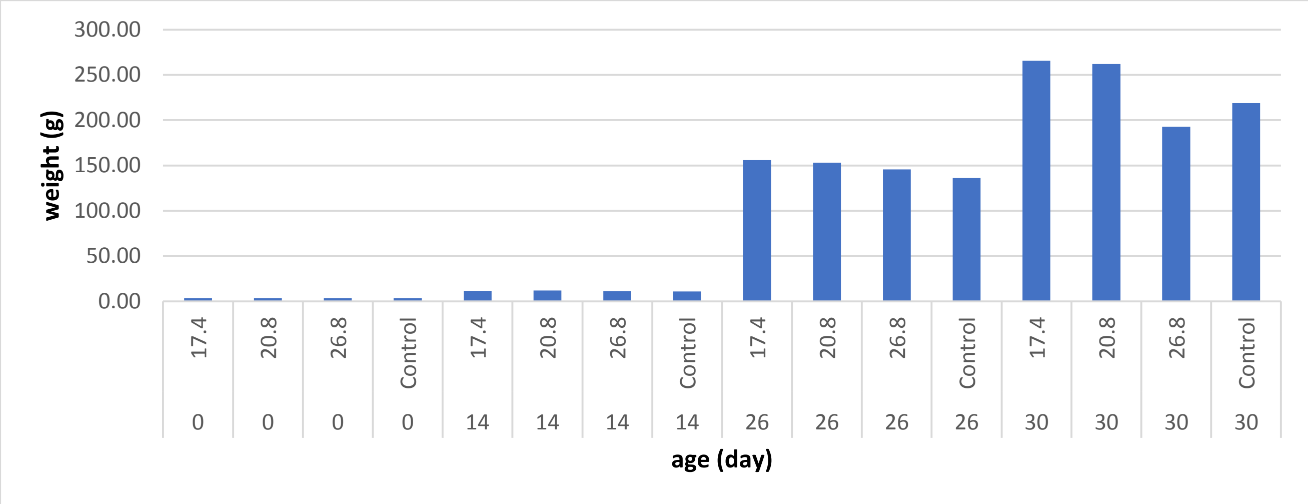

Fig. 3.1. Average shoot fresh weight over 30 days under different root-zone temperatures (Table 3.3).

Root development showed analogous responses (Table 3.4). Root fresh weight remained very low (~1 g) until day 26, then increased by day 30. The control treatment actually had the highest root weight at day 30 (17.60 g) compared to 19.64 g at 17.4°C and 20.42 g at 20.8°C (Table 3.4). Figure 3.2 graphs the root growth curves: although differences are modest, the 26.8°C roots remained the smallest throughout. This indicates that roots, like shoots, grew best at moderate RZT. Higher RZT (26.8°C) likely elevated root respiration and reduced oxygen availability, limiting root biomass [20]; [16].

Table 3.4 Effect of Root-Zone Temperature on Root Fresh Weight (g) Across Growth Stages.

Root Zone Temperature (°C)	Day 0 (g)	Day 14 (g)	Day 26 (g)	Day 30 (g)
17.4	0.54	1.41	10.76	19.64
20.8	0.54	1.19	9.14	20.42
26.8	0.54	1.06	9.55	13.30
Control (20.3°C)	0.54	1.35	15.25	17.60

Figure 3.2 shows that all treatments had nearly identical root weights through day 14, but differences emerged by day 30. The 20.8°C treatment slightly surpassed others by day 30. In summary, both shoot and root biomass peaked at the moderate RZT treatments, corroborating that a root-zone temperature near 20°C optimizes lettuce growth [16].

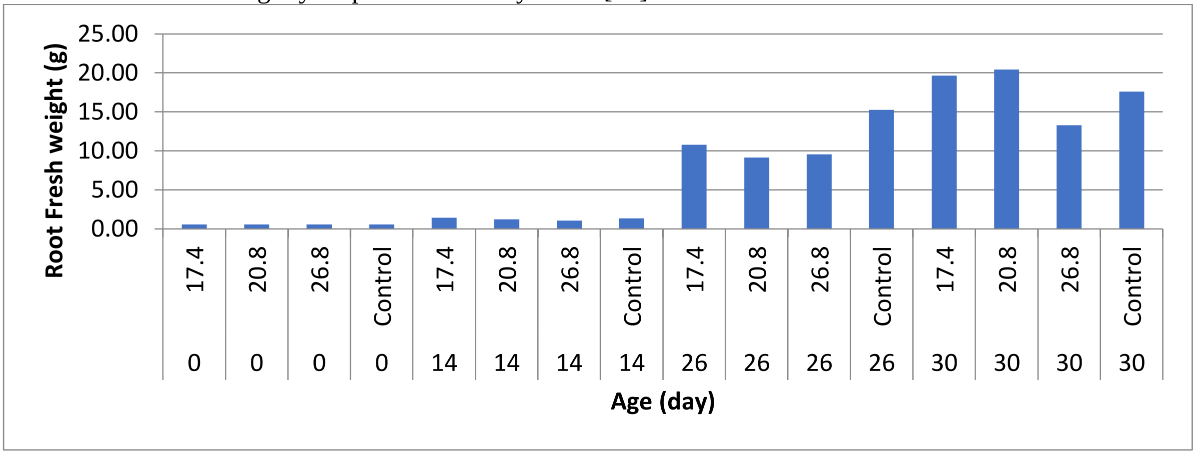

Fig. 3.2. Average root fresh weight over 30 days under different root-zone temperatures (Table 3.4).

The observed growth pattern aligns with agronomic recommendations that lettuce exhibits optimal growth around 18–24°C, whereas warmer solution temperatures can cause stress [16]. It also underscores the practical importance of controlling nutrient-solution temperature in hydroponic systems to maximize yield.

3.2.2 Effect of Root-Zone Temperature on Dissolved Oxygen Response

Table 3.5 presents the dissolved oxygen (DO) concentration in the nutrient solution for each treatment. The lowest solution temperature (17.4°C) yielded the highest DO (7.02 ppm), while the warmest treatment (26.8°C) had the lowest DO (5.06 ppm). Intermediate values occurred at 20.8°C (7.00 ppm) and the control (20.3°C, 6.10 ppm). These results reflect the well-known principle that warmer water holds less oxygen. In line with this, the 26.8°C treatment's lower DO likely constrained root respiration and uptake, contributing to its reduced growth. The trend is illustrated in Figure 3.5: DO declines sharply as temperature increases above ~20°C. This finding is consistent with published data indicating that water at ~20°C will saturate near 7–8 ppm oxygen, but that saturation drops below 6 ppm when water approaches 27–28°C [20].

Table 3.5 Dissolved Oxygen Concentration (ppm) vs. Root-Zone Temperature.

Treatment	Root-Zone Temperature (°C)	Dissolved Oxygen (ppm)
17.4°C (T1)	17.4	7.02
20.8°C (T2)	20.8	7.00
26.8°C (T3)	26.8	5.06
Control	20.3	6.10

As shown in Figure 3.3, the strong inverse relationship between solution temperature and DO is evident. Maintaining DO above ~6 ppm is generally recommended for hydroponic lettuce [20]. only the highest-temperature treatment dipped below this threshold. Thus, the 26.8°C treatment likely experienced combined stress from both excessive heat and low oxygen. These data emphasize the importance of temperature control to sustain adequate oxygen levels in the root zone.

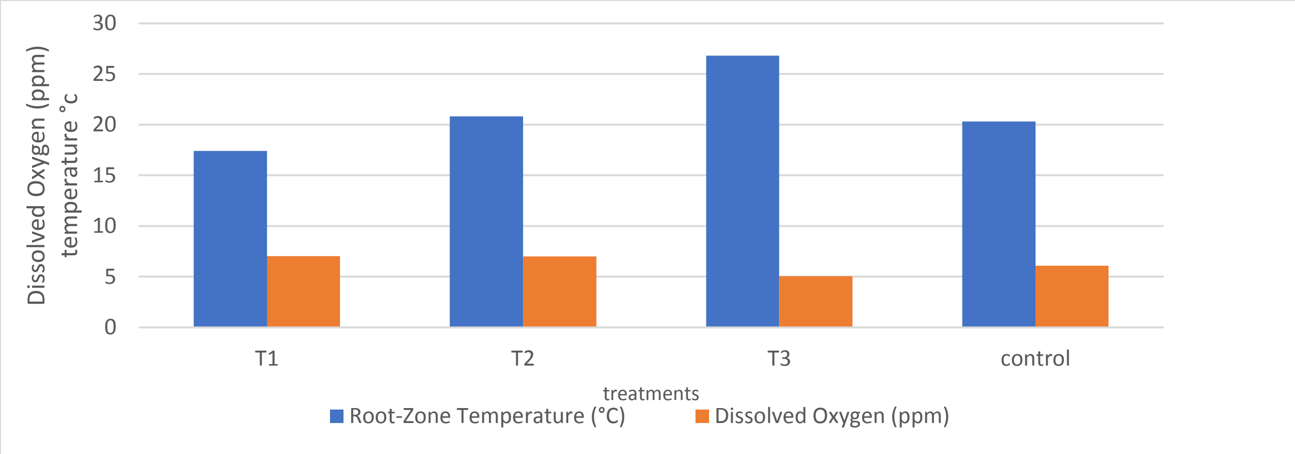

Fig. 3.3. Dissolved oxygen concentration at different nutrient solution temperatures (Table 3.5). Warmer solutions held significantly less oxygen.

3.2.3 Effect of Root-Zone Temperature on Leaf number and biomass partitioning

The data also reveal how plant developmental parameters (leaf number and biomass partitioning) varied by treatment. Table 3.6 shows leaf counts over time for each RZT. All treatments produced about 5 leaves by day 0 (initial stage), and leaf number increased nearly linearly through mid-growth, then more steeply by day 30. Plants at 17.4°C and 26.8°C ultimately formed slightly more leaves (21.0 and 21.4 leaves) than those at 20.8°C (19.8 leaves) or control (18.0 leaves). Figure 3.4 plots leaf development: curves are nearly parallel, indicating similar leaf production rates. The control lagged slightly, consistent with its lower total biomass. Overall, leaf expansion appears robust across treatments, with marginal suppression at the highest temperature.

Table 3.6 Relation Between Plant Age (Days) and Average Number of Leaves.

Root Zone Temperature (°C)	Day 0	Day 14	Day 26	Day 30
17.4	5.0	10.6	16.8	21.0
20.8	5.0	10.2	16.2	19.8
26.8	5.0	10.0	16.4	21.4
Control (20.3°C)	5.0	10.0	15.4	18.0

The relatively uniform increase in leaf number suggests normal vegetative development in all treatments. Literature indicates that lettuce typically shows linear to exponential increases in leaf count during early growth stages, which is evident here (leaf number roughly doubled by day 14, then doubled again by day 30). The slightly reduced leaf count in the control treatment is consistent with its slightly lower shoot biomass; limited leaf area would in turn constrain total photosynthesis and growth.

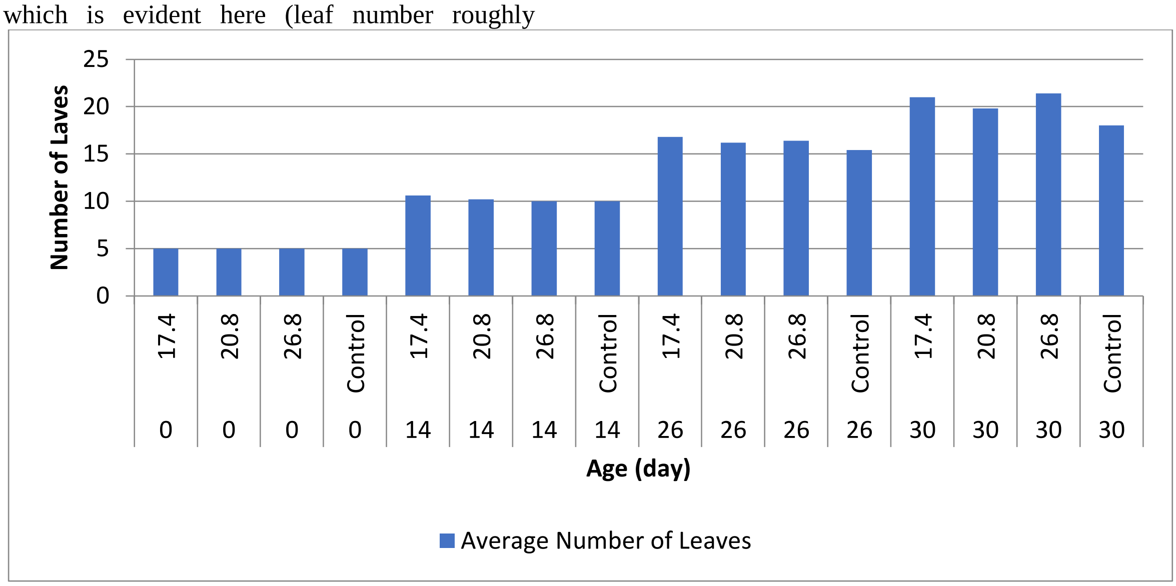

Fig. 3.4. Relation Between Plant Age (Days) and Average Number of Leaves (Table 3.6).

Next, Table 3.7 compares fresh and dry weights of vegetables (shoot) and root biomass at harvest (day

30). The 17.4°C treatment produced the highest fresh shoot weight (326 g) and a high root fresh weight (19 g). The 26.8°C treatment had the lowest shoot weight (192 g) and the lowest root weight (9 g). Dry weights show the same pattern: both vegetative and root dry mass were greatest at 17.4°C and smallest at 26.8°C. The pronounced reduction in both fresh and dry mass at high RZT again highlights heat stress effects. The TDS (total dissolved solids) levels were maintained consistently (720–755 ppm) across treatments, so nutrient strength was comparable. Note that the TDS (indirectly measured here by treatment) remained in the ideal range of 560–840 ppm for lettuce [11], implying that differences in growth were not due to nutrient concentration but primarily to temperature effects.

Table 3.7 Fresh and Dry Biomass Partitioning by Treatment (day 30).

Root Zone Temperature (°C)	Fresh Shoot (g)	Dry Shoot (g)	Fresh Root (g)	Dry Root (g)
17.4	326.0	15.49	19.0	1.31
20.8	303.0	9.14	19.8	0.67
26.8	192.0	9.75	9.0	0.90
Control (20.3°C)	241.0	10.86	18.0	1.68

Overall, the growth data (Tables 3.3–3.7) indicate that both above- and below-ground growth were maximized in the cooler treatments, with the 26.8°C treatment consistently underperforming. Moderately cool nutrient temperatures (≈17–21°C) resulted in the most vigorous lettuce growth. These findings align with hydroponic best-practice guidelines that recommend nutrient solution temperatures of 18–22°C to maximize lettuce growth, as warmer conditions tend to reduce photosynthesis and increase root respiration rates [16].

5. Conclusion

This research focused on modeling and evaluating the thermal behavior of the nutrient solution temperature (T_{ns}) in a hydroponic Nutrient Film Technique (NFT) system under arid climate conditions. A mathematical model was developed to simulate the heat exchange processes between the nutrient solution and its environment, accounting for greenhouse microclimate, wet-bulb air temperature, and cooling water temperature generated through a fan-and-pad evaporative cooling system.

The predicted values of Tns, ranging between 20.6°C and 21.3°C during peak heat hours, demonstrated strong agreement with the optimal temperature ranges required for lettuce growth as reported in prior literature. The consistency between the model's outputs and established physiological benchmarks confirms the validity and predictive strength of the thermal simulation framework.

Experimental observations supported the model predictions. Lettuce plants exposed to moderate nutrient solution temperatures exhibited favorable root and shoot development, indicating enhanced water and nutrient uptake, improved photosynthetic capacity, and balanced root-to-shoot ratios. While no formal statistical analysis was conducted, the observed differences in biomass and morphological traits were substantial and consistent across replicates.

The study concludes that integrating thermal simulation models into greenhouse design and management can significantly enhance climate resilience and productivity of hydroponic systems, especially under harsh environmental conditions. The absence of statistical analysis remains a limitation; however, the robust alignment between model predictions, experimental observations, and literature provides strong support for the practical relevance of the findings.

Future work is recommended to include advanced statistical evaluation, dynamic crop modeling, and integration of control algorithms to further enhance the system's predictive and adaptive capacity.

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