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The Influence of Root Zone Temperature of Nutrient Solution on Lettuce Grown in Hydroponic Systems

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UNDER THE GROWING world population and predicted resource depletion, there is a demand for greater and effective food production. Hydroponics is an environmentally friendly technology for growing plants without soil that can achieve sustainable food production. The experiment was conducted in a unheated greenhouse at Cairo University's Faculty of Agriculture in the Giza Governorate of Egypt, under an unheated greenhouse during the two consecutive winter seasons of 2023 and 2024. This study aimed to evaluate lettuce response to different hydroponic cultivation systems and nutrient solution temperatures. A split-plot experimental design was employed, with three hydroponic systems (A-shape nutrient film technique – A-NFT, flat shape NFT – F-NFT, and deep water culture – DWC) assigned to the main plot and three nutrient solution temperatures: 11°C (control), 16°C, and 20°C as the subplot. We estimated the vegetative growth parameter (number of leaves, stem diameter, root length, plant fresh weight), yield, Chlorophyll reading, nitrate level, nutrient contents N, P, and K (%), and water usage efficiency (WUE) of lettuce. Results that were obtained show that the F-NFT system recorded the highest vegetative growth parameter, chlorophyll reading, nitrate content and nutrient contents (N, P and K) as well as water use efficiency followed by A- shape NFT system. While The A-shape nutrient film technique system has the greatest overall yield per m^2. On the contrary, Deep water culture recorded the lowest value for all parameters. Increasing the ambient temperature of the fertilizer solution to 20°C resulted in increased vegetative development and yield parameters. The interaction impact of the F-shape nutrient film technique system combined with a fertilizer solution with a temperature of 20°C resulted in the greatest average plant fresh weight for lettuce. The A-NFT system with a nutrient solution temperature of 20°C produced the highest total yield per m^2 of lettuce due to its higher plant density than the other hydroponic systems. For commercial purposes, the study recommends using an A-shape NFT nutrient film technique at 20 °C for lettuce production.

Keywords: Lettuce, Hydroponic culture, A-shape nutrient film technique (A-NFT), Flat shape, Deep water culture (DWC) and fertilizer solution temperatures.

1. Introduction

The worldwide shortage of food necessitates novel agricultural tactics, making it critical for horticulturists to employ cutting-edge fruit and vegetable production technologies. In the face of food scarcity caused by climate and economic issues, sustainable and efficient agriculture practices are critical (Sousa et al, 2024). Food safety and sustainable production strategies have become more vital in today's rapidly expanding world. Leafy greens production is critical for achieving food scarcity because of its widespread usage and consumer demand.

Hydroponics technology is based on growing plant roots in a nutrient solution that contains the nutrients needed for plant growth, which results in an efficient of water and fertilizers, increases yield and enhances the quality of crops (Lal, 2016). Several techniques are employed to expose plant roots to a nutrient solution such as the Nutrient Film Technique (NFT). In this System a nutrient solution is pumped as a thin layer of 1-2 cm around plant roots that are partially submerged in the solution. Another common system is Deep Water Cultivation (DWC) or Deep Flow Technique (DFT), where plant roots are continuously submerged in an aerated nutrient solution at a depth of 15 to 20 cm (Savvas et al., 2013; Silva et al., 2023). The modified NFT system utilizes tubes made of PVC as culture channels (Flat type), and the pump in the nutrient solution tank controls the recycling of the nutrient solution from the tank to the culture channels, thereby maintaining the availability of water and nutrients in the root growth area (Rodríguez-Delfín et al., 2004). There are many shapes of modified NFT systems, such as the flat-shape NFT (F-NFT) and the A-shape NFT (A-NFT). The F-NFT system design is based on placing the tubes parallel to the ground, while the A-NFT system is based on placing the tubes in the form of a pyramid on the ground which allows for an increase in plants number per unit area (Maharik and Mancy, 2017).

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In hydroponic culture systems, the amount of nutrients plants absorbed from a nutrient solution has a significant impact on yield (Yang, 2021). As a result, nutrient solution management is essential for hydroponic systems to succeed and the primary determinant of crop productivity and quality. One of the major challenges in hydroponic cultivation involves nutrient solution temperature, which directly affects the electrical conductivity (EC), pH, dissolved oxygen concentrations, and nutrient availability (Muthir et al., 2019; Christopher and Mattson, 2021; Silva et al., 2024a). Research indicates that while low root zone temperature treatments improve anthocyanin contents (Islam et al., 2019), controlling root zone temperature increases leaf nutritional components (Moccio et al., 2024). According to Muthir et al. (2019), one of the most important factors influencing crop output and quality in hydroponic production systems is the temperature of the fertilizer solution. Nxawe, et al. (2009) and Thakulla et al. (2021) noted that when the temperature is above or below the ideal range, numerous plant metabolic processes are adversely affected, including the buildup of various metabolites including phenolic substances, nutrient intake, chlorophyll pigmentation, photosynthesis, and eventually plant development and evolution. According to Fazlil et al. (2017), the temperature of the nutrient solution influences the solution's chemical equilibrium, which in turn influences every physiological activity within the plant. Pavel and Fereres, (1998) mention that at lower water temperatures the water density elevate which reduces water permeability in the root system as well as metabolic activity. He and Lee, 2004 found that Photosynthesis is negatively affected by lower root temperatures in lettuce leaves and it has been demonstrated in cucumber (Ahn et al., 1999) and tomato (Willits and Peet, 2001). According to (Calatayud et al., 2008) low temperatures resulted in a decrease in the absorption of nutrient by roots in the majority of plant types. Conversely, higher nutrient solution temperatures are directly correlated with the amount of oxygen that plants take in and inversely correlated with the amount of O2 dissolving in the fertilizer solution. Higher temperatures cause the root respiration rate to significantly increase and the dissolved oxygen levels in the root zone solution to decrease (Masaru et al., 2016; Oliveira et al., 2023; Silva et al., 2024b).

The capacity to regulate the temperature of the root system or nutrient solution using cooling spirals or heaters, respectively, is a characteristic of hydroponics. Root growth can be significantly impacted by very minor variations in the root growth medium's temperature (Thakulla et al., 2021). Conversely, targeted cooling methods, especially root-zone temperature regulation, have shown enhanced energy economy, swift responsiveness, and efficacy in summer lettuce cultivation (Hu et al., 2024). Myung et al. (2024) created a root-zone temperature control system that used an air-source heat pump to improve pepper development and yield by cooling the nutrient solution and circulating chilled water. Although this system significantly lowered root-zone temperatures during culture, it struggled to maintain nutrient solution temperature stability during peak daytime heat, with variances up to 6°C from prescribed values.

When the nutrient solution temperature is above or below optimum, lettuce (*Lactuca sativa* L.) often suffers from growth disorders (Landers, 2017). Lettuce thrives well at ambient temperatures between 15 and 25°C. Elevated temperatures result in diminished leaf growth and abrupt bolting (Zhao et al,. 2022). The effect of cooling the nutrient solution was investigated on butter-head lettuce. Ilahi et al., (2017) found that when the root zone was cooled at 19°C, there were substantial increases in canopy diameter, leaf number, and yield as compared to the no-chilled condition (26°C). On the other hand, Thakulla et al., (2021) studied the effects of different nutrient solution temperatures (18.3°C, 21.1°C, and ambient (20-26°C)) on the growth of five different lettuce types (Batavian, Butter-head, Loose-leaf, Romaine and Salanova) of lettuce. These results indicated that lettuce grown at 21.1°C increased the growth and biomass of lettuce. According to Moccio et al. (2024), maintaining a root-zone temperature of 21.1°C resulted in higher lettuce shoot fresh weight and nutrient uptake than ambient circumstances. Furthermore, high temperatures might diminish dissolved oxygen levels in water, resulting in slower root nutrient updating and growth. Cooling the root zone in hydroponic cultivation systems can improve consistent nutrient uptake, reduce root disease risks, and produce ideal circumstances for plant growth at high temperatures (Kang et al., 2025).

Given these considerations, this study aimed to evaluate lettuce response to different hydroponic systems and nutrient solution temperatures under Egyptian environments.

2. Materials and Methods

2.1. Study site, experimental design, and growth conditions

The experiment was conducted in an unheated greenhouse (9 m wide and 40 m long, with fiberglass sides and net roof) located at Cairo University, Giza Governorate (30°01'02.5"N 31°12'31.9"E), Egypt, during two winter seasons, 2023 and 2024. In the center of the greenhouse, a thermometer and a hygrometer hung (ThermoPro Digital Hygrometer TP53) were installed to record air temperature and relative humidity as shown in Figs (1, 2, 3, and 4).

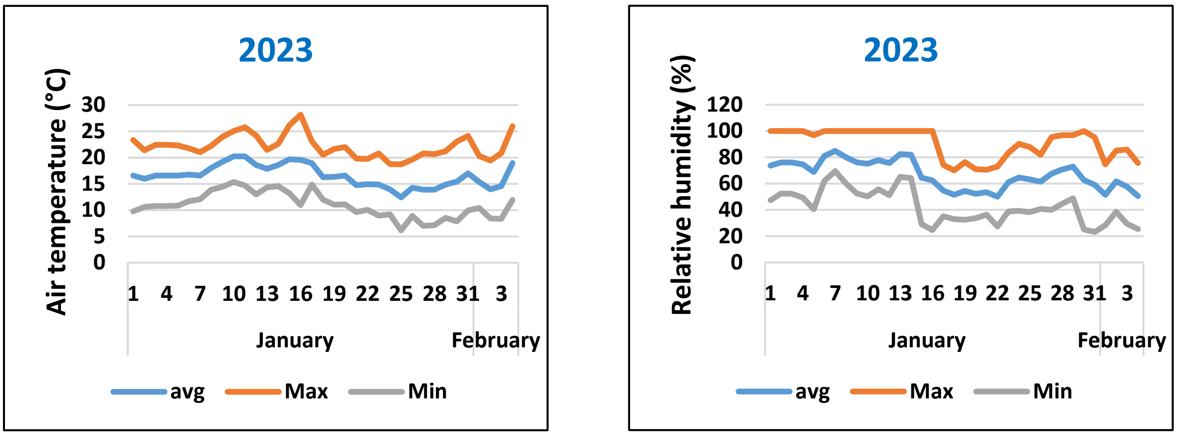

Fig. 1. and 2. Maximum, minimum and average air temperature (°C) and relative humidity (%) under greenhouse during seasons 2023.

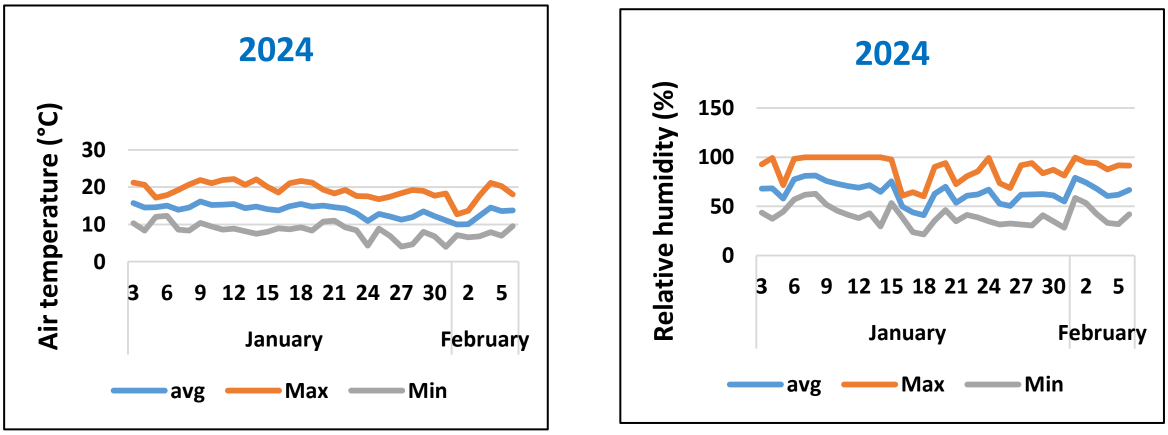

Fig. 3. and 4. Maximum, minimum and average air temperature (°C) and relative humidity (%) under greenhouse during seasons 2024.

A split-plot experimental was employed, with three hydroponic systems (A-shape nutrient film technique (A-NFT), flat shape NFT (F-NFT), and deep water culture (DWC) assigned to the main plot and the three nutrient solution temperatures (11°C (control), 16°C and 20°C) as the subplot.

During the first week of December in both 2023 and 2024. Seeds of the Batavia green lettuce *(Lactuca sativus)* cv. Othilie-RZF1 hybrid were planted in foam trays. Seeds were sown in 209-cell seedling trays filled with a commercial medium of peat moss and vermiculite (1:1 v/v) in the nursery. The seedlings were moved into various hydroponic growing systems after 35 days. 10 seedlings were used in each replication.

2.2. Description of the systems

2.2.1. A-NFT system

An A_shaped iron frame (1.0 × 1.0 × 0.8 m, with a 60-degree angle) was used as a support for 3 m long, 100 mm diameter PVC pipe with a slope 1 cm for every 1 m. The pipes were fixed on the frame at three levels: 40 cm above the rooftop surface (bottom level), with an additional 25cm spacing for the middle level, and another 25 cm for the top level. In these tubes, plants were placed in holes spaced every 25 cm, with a total six pipes in the iron frame. There were 24 plants per square meter.

2.2.2. F-NFT system

The F-NFT system consisted of an iron structure measuring 1.0 m in length and 0.60 m in height above the surface. The system incorporated five 2.5 m long PVC pipes with 100 mm diameter. A 0.25 × 0.25 m distance, respectively, between plants and cultivation pipes was used. There were 20 plants m^{-2}.

2.2.3. DWC system

The DWC system consisted of wooden frame (1.0-m-wide, 2.5-m-long, and 0.3-m-depth). The wooden frame was covered from the inside with a black sheet of polyethylene (1 mm). The structure was filled with nutrient solution up to a height of 25 cm, corresponding to a real water volume of 0.625 m^3. Polystyrene Styrofoam sheet (0.6 x 1.2 m) was placed in tank over the nutrient solution, with holes spaced at 20 cm for planting lettuce seedlings. There were 20 plants m^{-2}.

2.3. Nutrient solution management

In all three hydroponic systems, a nutrient solution with an electrical conductivity (EC) of 2.0 dS m^{-1} was used. In the A-NFT and F-NFT systems, the nutrient solution was pumped into the cultivation channels using a 40 W submersible pump, and then returned by gravity to the tank. For the DWC system, a 40 W submersible pump is installed inside to mix the solution and raise the amount of oxygen in it. The pump runs for 15 minutes every hour of the day for all systems. The nutrient solution was prepared according to El Behairy (1994), as detailed in Table 1. Nutrient solution temperature in the different system's tanks was daily recorded by using (temperature analyzer meter HI98129) throughout the experimental period in 2023 and 2024 seasons as illustrated in Fig.(6 and 7). The temperature were raised up by using a Submersible Heater (200 W) and adjust the temperature for each treatment.

Table 1. The chemical composition of the nutrient solutions.

Macronutrients (ppm)					Micronutrients (ppm)					
N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B	Mo
200	40	300	190	50	5.0	1.0	0.039	0.044	0.17	0.1

N: nitrogen, P: phosphorus, K: potassium, Ca: calcium, Mg: magnesium, Fe: Iron, Mn: Manganese, Cu: Copper, Zn: Zinc, B: Boron, Mo: Molybdenum

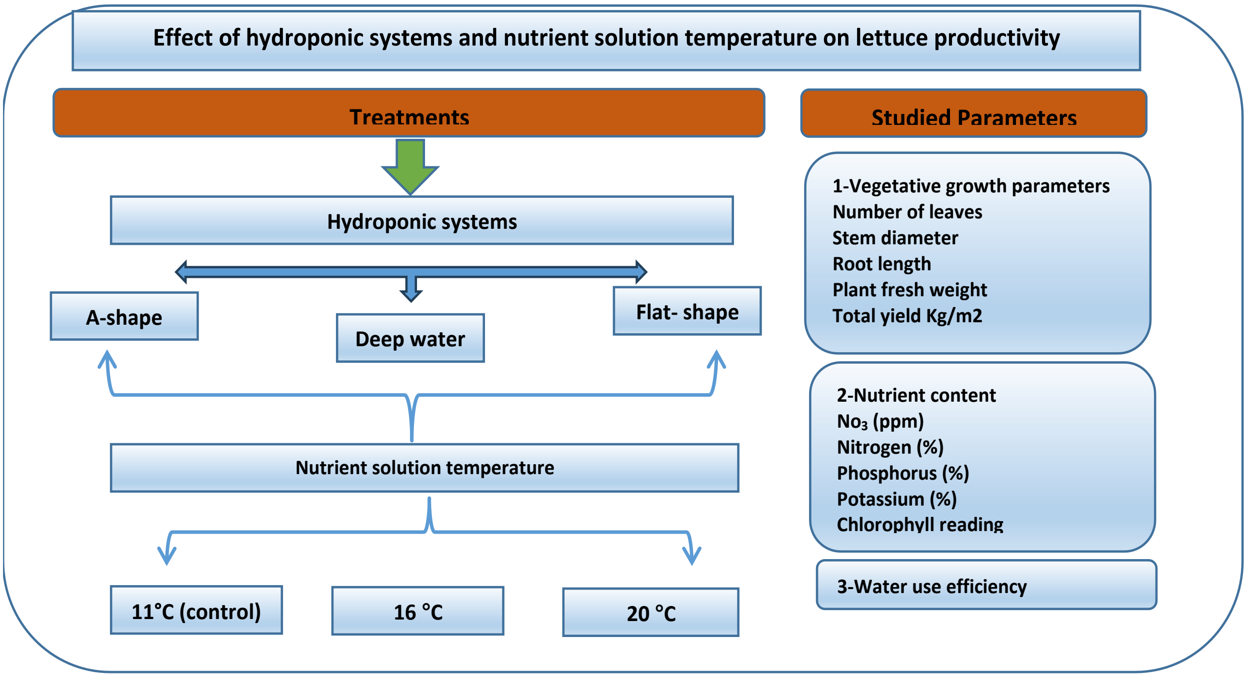

Fig. 5. An outline of the primary interventions and metrics used in the research.

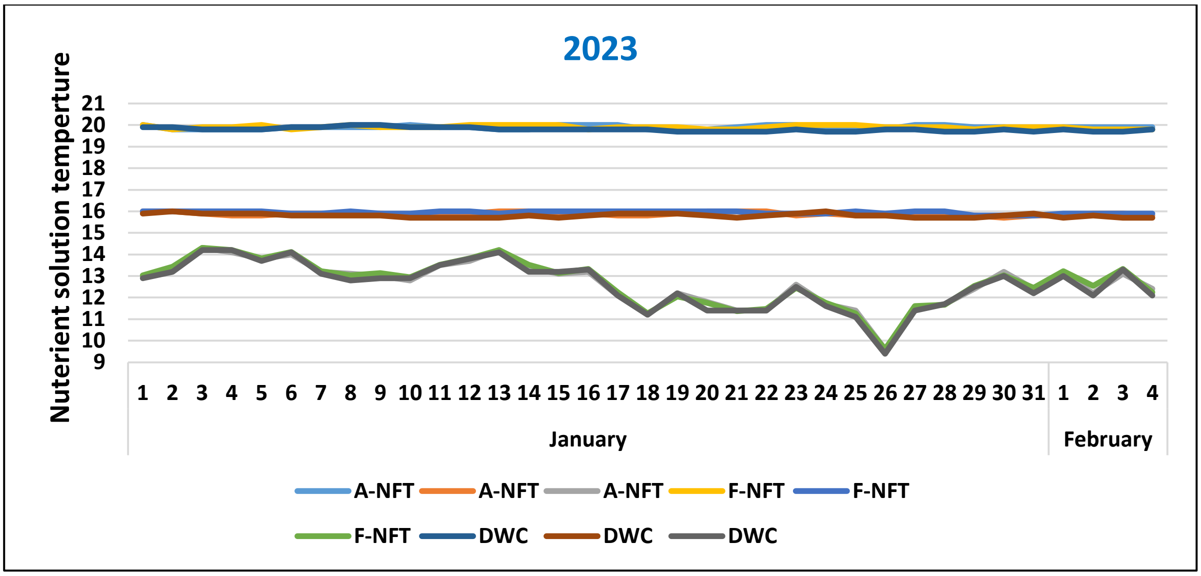

Fig. 6. Nutrient solution temperature (°C) in different hydroponic systems during season 2023.

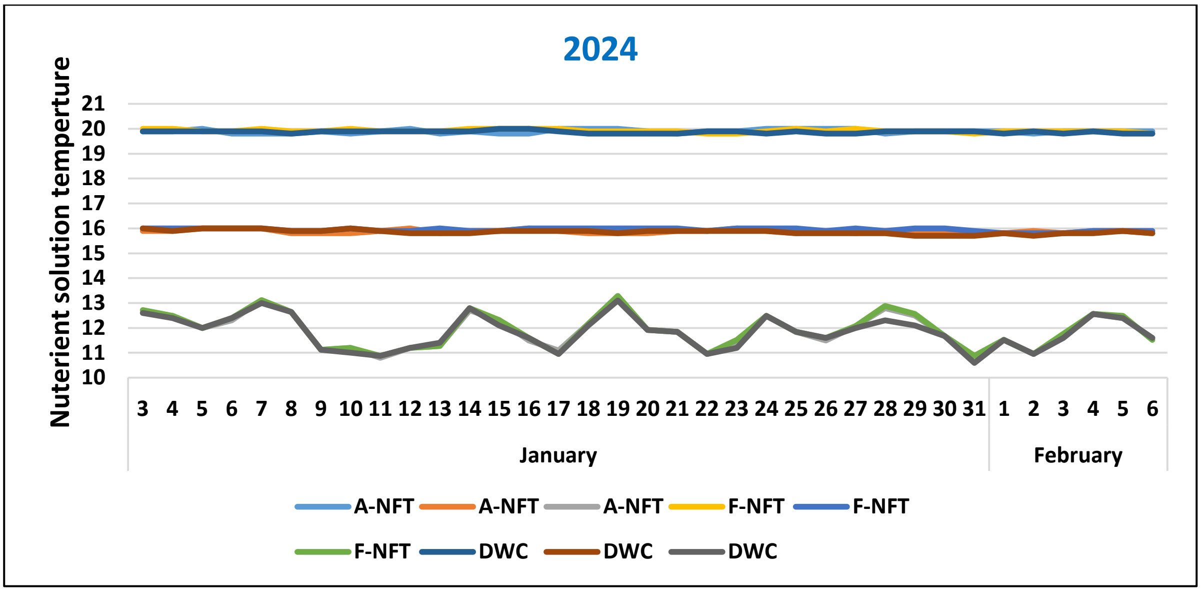

Fig. 7. Nutrient solution temperature (°C) in different hydroponic systems during season 2024.

2.4. Evaluated variables

At the end of growing seasons after 65 days, three plants were harvested from each experimental plot to determine: the number of leaves (NL) by counting, stem diameter (SD, in cm) by vernier caliper, root length (RL, in cm) by meter, and plant fresh weight (PFW, in g plant^{-1}) by digital scales. The data of the three plants provided a mean value. The total yield in kg m^{-2} was calculated from the mean of PFW (PFWY), considering the area occupied by a plant to according with the spacing used in the hydroponic system. The water use efficiency (WUE) was calculated based on the ratio between the crop yield (Y) and the accumulated water consumption (WC) for the growth season, as follows: WUE (kg m^{-3}) = Y (kg)/WC (m^3).

Total leaf chlorophyll inbex was measured using a Minolta SPAD-502 chlorophyll meter. For determination of nutricional content in lettuce leaves, three plant samples from each plot (1 m^2) were collected at harvest phase and dried in a forced-air oven at 70ºC. The nitrate levels were determine according to Holty and Potworowskis (1972). N, P, and K (%) content in plants was determined. The Allen (1974) method was used to digest dried plant samples in a solution of $HClO_4$ and H_2SO_4 acids. Using an UV spectrophotometer and flame photometer, the colorimetric technique (ammonium molybdate) was used to determine the amount of N, P, and K in the acid-digested solution (Chapman and Pratt, 1961). The Kjeldahl method was used to calculate total nitrogen in accordance with the FAO's (1980) protocol. According to Watanabe and Olsen (1965), a spectrophotometer was used to measure the phosphorus concentration. A flame photometer was used to photometrically measure the potassium concentration in accordance with Chapman and Pratt (1961).

2.5. Economic feasibility

The economic impact assessment was calculated concerning the standard system area of 6 m^2

The total cost is determined by the total investment costs (pumps, metal structures, tanks, plastic, substrate, timers, and irrigation network) / annual consumption rate + total production costs (seedling + irrigation + chemicals + electricity +substrate+ others).

Total return is determined by the total yield (kg per system area of 6 m^2) × Average price/ LE per kg

The net profit is determined by the total return – total cost. The returns of each tested treatment were calculated according to Hengsdijk and Van Ittersum (2003**)** and Li et al. (2005).

2.6. Statistical analyses

The statistical analysis system (SAS) software was used to statistically examine the data. According to Waller and Duncan (1969), the significance of the variations in means for all attributes was assessed at the 5% level of probability.

3. Results

Reponse of vegetative growth and yield of lettuce Hydroponic systems and nutrient solution temperature

The information in Table (2) illustrates how the temperature of the nutrient solution and hydroponic systems affected the quantity of leaves, stem diameter, and root length in the 2023 and 2024 growing seasons. Concerning the effect of hydroponic systems, data showed that. The highest results of the number of leaves, stem diameter and root length were recorded by using Flat shape NFT followed by A-shape NFT without significant difference between them in root length or stem diameter but with significant difference in leaves numbers. In terms of leaf count, stem diameter, and root length, DWC obtained the lowest results with a significant difference from the previous systems.

Regarding the temperature of the nutrient solution, it was observed that increasing the temperature of the nutrient solution led to an increase in the number of leaves, stem diameter and root length. The highest values were recorded at 20°C followed by 16°C with a significant difference between them. While the lowest values were estimated with ambient temperature for the nutrient solution. Regarding the relationship between the temperature of the nutrient solution and hydroponic systems. Cultivation of lettuce in a Flat shape NFT followed by A-shape NFT in 20°C gave the highest number of leaves, stem diameter and root Length. On the contrary, cultivation of lettuce in a DWC under ambient temperature for nutrient solution recorded the lowest rates of the number of leaves, stem diameter and root Length with a significant difference from the anther treatments.

Table 2. Effect of hydroponic systems and nutrient solution temperature on the number of leaves, stem diameter and root Length of lettuce plants during 2023 and 2024 seasons.

Hydroponic systems	First season			Second season		
	Root zone temperature					
	Number of leaves per plant					
	20°C	16°C	control	20°C	16°C	control
A-NFT	35.9 b	30.1 cd	25.0 ef	34.7 b	31.3 bc	26.3 de
F-NFT	41.1 a	31.6 c	25.1 ef	38.8 a	32.3 b	27.0 d
DWC	34.1 bc	26.2 de	22.3 f	33.3 b	27.7 cd	22.7 e
F-test	***	**	*	***	**	*
	Stem diameter (cm)					
A-NFT	2.23 a	1.83 abc	1.43 cd	1.83 b	1.57 bcd	1.23 de
F-NFT	2.27 a	2.13 ab	1.57 cd	2.23 a	1.67 bc	1.23 de
DWC	1.73 bcd	1.57 cd	1.33 d	1.63 bc	1.40 cde	1.13 e
F-test	***	**	*	***	**	*
	Root length (cm)					
A-NFT	35.0 a	30.3 ab	26.3 bc	36.3 a	34.7 ab	24.3 f
F-NFT	35.2 a	31.0 ab	26.3 bc	37.7 a	33.3 abc	26.0 de
DWC	33.0 a	26.3 bc	21.7 c	30.7 bcd	28.3 cde	17.3 f
F-test	***	**	*	***	**	*

(A- NFT): A-shape nutrient film technique, (F- NFT): Flat-shape nutrient film technique, (DWC): Deep water culture

Data in Table (3) illustrate how plant fresh weight and total yield per m2 during the 2023 and 2024 seasons are impacted by hydroponic systems and the temperature of the nutrient solution. Concerning the effect of hydroponic systems. With notable variations between the two, the Flat form NFT system produced the best results with plant fresh weight, followed by the A-shape NFT system. However, the maximum overall yield per m^2 was recorded in the A-shape NFT system with a significant difference from the other systems. On the contrary, deep water culture (DWC) recorded the lowest plant fresh weight and total yield per m^2 with a significant difference from the previous systems. Regarding the nutrient solution temperature, it was shown that raising the temperature of the solution led to an increase in the fresh weight of the plant and the total yield per m^2. The highest values were recorded at 20°C with a significant difference with other nutrient solution temperatures. In contrast, the nutrient solution at room temperature (control) produced the lowest values.

Regarding the relationship between fertilizer solution temperature and hydroponic systems. The highest fresh weight of plants was estimated with lettuce plants cultivation in Flat shape NFT under temperatures 20°C with a significant difference with other treatments. While the greatest total yield per m^2 was estimated by using A-shape NFT with a temperature 20°C for the nutrient solution. Whereas, DWC under ambient nutrient solution temperature recorded the lowest fresh weight of the plant and total yield per m^2.

Table 3. Effect of hydroponic systems and nutrient solution temperature on plant fresh weight and total yield /m^2 of lettuce plants during 2023 and 2024 seasons.

.	First season			Second season		
Hydroponic systems	**Root zone temperature**					
	20°C	16°C	control	20°C	16°C	control
	Plant fresh weight / g					
A-NFT	521 ab	499 cd	430 e	483 ab	464 cd	398 ef
F-NFT	537 a	506 bc	446 e	498 a	474 bc	415 e
DWC	507 bc	482 d	407 f	470 bc	447 d	389 f
F-test	***	**	*	***	**	*
	Total yield kg/m^{-2}					
A-NFT	12.5 a	12.0 b	10.3d	11.6 a	11.1 b	9.6 cd
F-NFT	10.7 c	10.1 d	8.9 f	10.0 c	9.5 d	8.3 f
DWC	10.1 d	9.6 e	8.1 g	9.4 d	8.9 e	7.8 g
F-test	***	**	*	***	**	*

(A- NFT): A-shape nutrient film technique, (F- NFT): Flat-shape nutrient film technique, (DWC): Deep water culture

Data in Table (4) show the impact of hydroponic systems and nutrient solution temperature on Chlorophyll reading (spad) and nitrate concentration (ppm) on lettuce plants during 2023 and 2024 seasons. Data pertaining to the impact of various hydroponic systems revealed that the Flat NFT system gives the highest chlorophyll reading with a significant difference from other systems under study. While the lowest reading was estimated from the A-shape NFT system followed by deep water culture without significant difference between them. As for the nitrate content A-shape NFT system followed the Flat NFT system recorded the highest content. Conversely, DWC has the lowest amount of nitrate.

Data showed that the chlorophyll reading was affected by the temperature of the nutrient solution and nitrate content (ppm) increased as the nutrient solution's temperature increased. Where the highest chlorophyll reading and nitrate content was found at 20°C followed by 16°C and the lowest value was found on ambient temperature for nutrient solution whit a significant difference between them. As for the interaction between hydroponic systems and the temperature of the nutrient solution, the maximum chlorophyll reading and nitrate content were recorded by all hydroponic systems when the nutrient solution temperature was 20°C, according to the data. While the lowest values were estimated in DWC and ambient temperature for nutrient solution.

Table 4. Effect of hydroponic systems and nutrient solution temperature on the nitrate content (ppm) and chlorophyll measurement of lettuce plants in the 2023 and 2024 growing seasons.

	First season			Second season		
Systems	Root zone temperature					
	20°C	16°C	control	20°C	16°C	control
	Chlorophyll reading (spad)					
A-NFT	31.7 ab	28.9 bc	25.4 c	34.7 ab	30.1 c	27.3 d
F-NFT	33.4 a	30.1 ab	29.7 b	36.5 a	32.2 bc	31.5 c
DWC	30.4 ab	29.0 bc	25.8 c	34.2 ab	30.0 c	27.0 d
F-test	***	**	*	***	**	*
	No3 / ppm					
A-NFT	1239 a	1161 b	1113 c	1255 a	1180 bc	1113 d
F-NFT	1234 a	1151 bc	1126 bc	1242 ab	1153 cd	1135 cd
DWC	1226 a	1163 b	943 d	1226 ab	1154 cd	1004 e
F-test	***	**	*	***	**	*

(A- NFT): A-shape nutrient film technique, (F- NFT): Flat-shape nutrient film technique, (DWC): Deep water culture

Data in Table (5) show the effect of hydroponic systems and nutrient solution temperature on N, P and K on lettuce plants during 2023 and 2024 seasons. Regarding the effect of different hydroponic systems, data showed that there was a significant difference between the N content under different hydroponic systems. The highest N content resulted from flat shape NFT followed by A- shape NFT during both seasons. While there was no significant difference between flat shape NFT and A- shape NFT in the plant content of PK. On the other hand, the lowest N, P and K % were obtained in a DWC. Regarding the impact of varying nutrient solution temperatures, data showed that rising nutrient solution temperature had an impact on lettuce plants' N, P, and K percentages. The nutrient solution at 20°C had the highest N, P, and K content, followed by 16°C, and the ambient temperature had the lowest value, with no discernible difference between the two. Regarding the relationship between hydroponic systems and nutrient solution temperature, the maximum NPK percentages were obtained when flat shape NFT and nutrient solution temperature of 20°C were combined, followed by A-shaped NFT combined with nutrient solution temperature 20°C without significant difference between them. While the lowest NPK percentages were obtained by deep water culture (DWC) combined with ambient temperature for the nutrient solution.

Table 5. Effect of hydroponic systems and nutrient solution temperature on N, P and K (%) of lettuce plant during 2023 and 2024 seasons.

	First season			Second season		
Systems	Root zone temperature					
	20°C	16°C	control	20°C	16°C	control
	N (%)					
A-NFT	3.26 b	2.91 c	2.62 d	3.31 b	3.00 c	2.70 d
F-NFT	3.54 a	3.25 b	2.64 d	3.57 a	3.34 b	2.76 d
DWC	3.25 b	2.91 c	2.42 e	3.33 b	2.92 c	2.50 e
F-test	***	**	*	***	**	*
	P (%)					
A-NFT	0.91ab	0.86 bcd	0.82 de	0.91 a	0.86 b	0.80 cd
F-NFT	0.95 a	0.86 bcd	0.83 cde	0.96 a	0.86 b	0.85 bc
DWC	0.90 abc	0.84 bcd	0.76 e	0.92 a	0.84 bc	0.78 d
F-test	***	**	*	***	**	*
	K (%)					
A-NFT	1.74 a	1.64 b	1.36 d	1.70 ab	1.68 ab	1.43 c
F-NFT	1.80 a	1.62 b	1.44 c	1.77 a	1.58 bc	1.46 c
DWC	1.61b	1.50 c	1.25 e	1.55 bc	1.49 c	1.17 d
F-test	***	**	*	***	**	*

(A- NFT): A-shape nutrient film technique, (F- NFT): Flat-shape nutrient film technique, (DWC): Deep water culture

Data in Fig (8): show the effect of hydroponic systems and nutrient solution temperature on water use Efficiency (WUE) on lettuce plant during 2023 and 2024 seasons. Without a discernible difference, hydroponic systems (flat and A-shaped NFT) achieved the best water efficiency, whereas deep water culture had the lowest water usage efficiency (WUE). As for nutrient solution temperature, ambient temperature for nutrients gave the highest WUE followed by nutrient solution temperature of 16°C. The lowest WUE was obtained by nutrient solution temperature 20°C with significant difference between them. The relationship between the temperature of the nutrient solution and the hydroponic system showed that flat shape NFT or A- shape NFT combined with ambient temperature for nutrients gave the highest WUE. While nutrient solution temperature 20°C combined with deep water culture (DWC) gave the lowest WUE during both seasons.

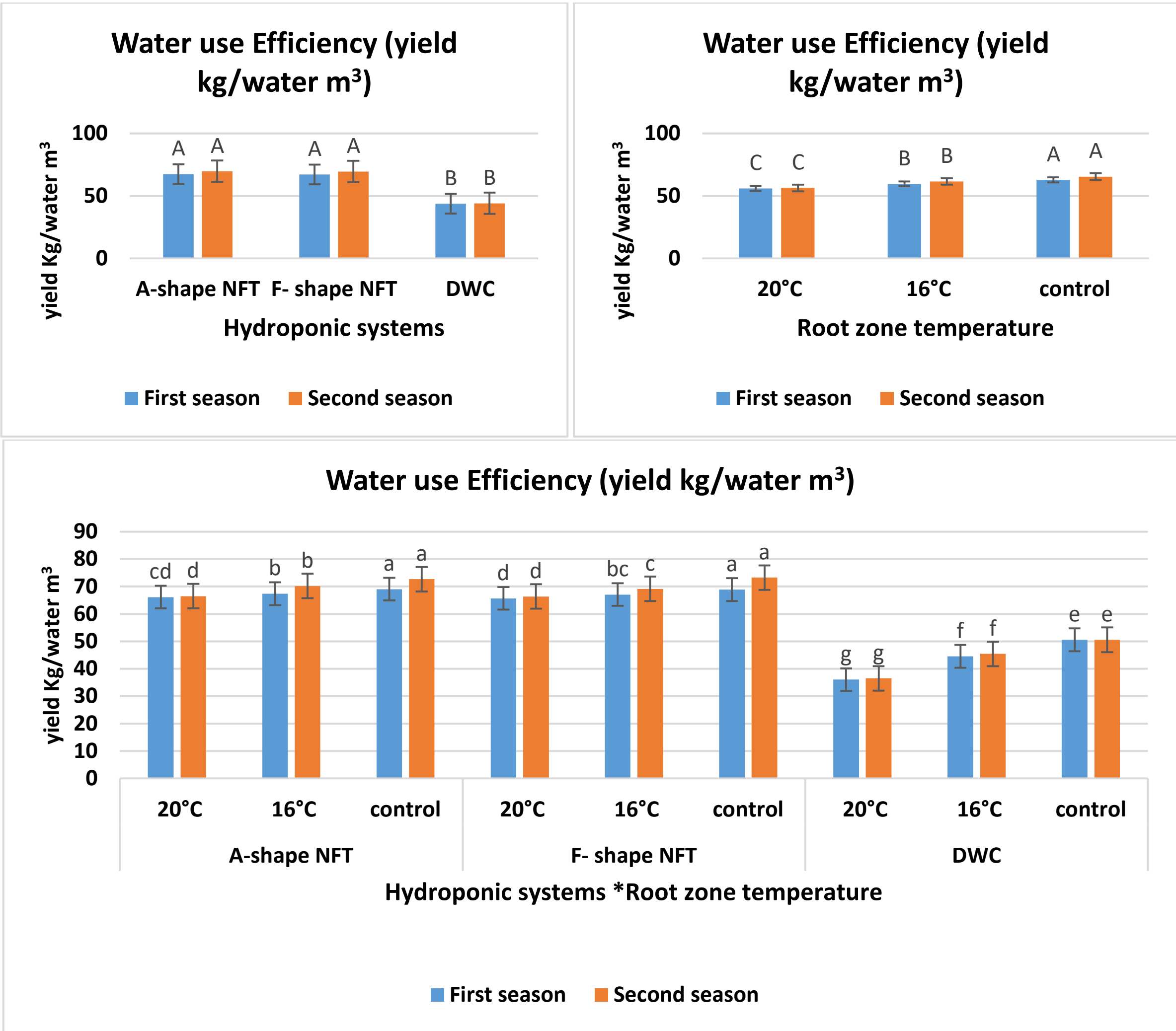

Fig. 8. Effect of hydroponic systems and nutrient solution temperature on water use efficiency (yield Kg/water m^3) of lettuce plant during 2023 and 2024 seasons.

Table 6 shows the economic feasibility of lettuce plant production on different hydroponic systems and different nutrient solution temperatures under Egyptian conditions during the seasons of 2023 and 2024. According to the data, the combined deep water system with ambient nutrient solution temperature (control) had the lowest total cost and return, while the A-shaped NFT system with nutrient solution temperatures of 20°C had the highest (778 and 4337 EL, respectively). Conversely, the deep water system with ambient nutrient solution temperature (control) (2224 EL) was estimated to have the lowest net profit, while the A-shape NFT system with nutrient solution temperatures of 20°C (3559 EL) had the highest.

Table 6. Net profit (LE) of hydroponic systems and nutrient solution temperature as an average of 2023-2024 seasons.

Treatments		Investment costs (EL)	production costs(LE)	Total cost (LE)	Total yield (Kg/ 6m^2)	Price per Kg (LE)	Total return (LE)	Net Profit (LE)
Hydroponic systems	**Nutrient solution temperatures**							
A Shape	**Control**	123	589	712	59.6	60	3577	2865
	16°C	123	612	735	69.3	60	4160	3425
	20°C	123	655	778	72.3	60	4337	3559
Flat	**Control**	117	521	638	51.7	60	3100	2462
	16°C	117	544	661	58.8	60	3528	2867
	20°C	117	585	702	62.1	60	3726	3024
Deep water	**Control**	70	571	641	47.8	60	2866	2224
	16°C	70	595	665	55.7	60	3344	2679
	20°C	70	639	709	58.6	60	3517	2808

4. Discussion

In general, all the measurements under study that included vegetative growth, total yield per m^2, NO_3 content, WUE and N, P and k content in lettuce leaves were higher in nutrient film Technique (A-shape and flat shape) compared to DWC system because different hydroponic systems have varied root growth characteristics and water flow dynamics. Abul-Soud et al. (2019 and 2020) found that in deep water culture, the dynamics of water flow depend on rotating the water in the system, whereas in the nutrient film technique (A-shape and flat shape), the dynamics of water flow depend on pumping the nutrient solution to the end of the tubs and then the drain returning to the tank by gravity. This helps to improve the water flow in the nutrient film technique compared to the deep water culture system which increases the dissolved oxygen in the nutrient film Technique (NFT) solution more than in the deep water culture. According to Velazquez-Gonzalez et al. (2022), the nutrient film technique (A-shape and flat shape) increased the vegetative growth and yield characteristics by growing the roots partially submerged in the nutrient solution, which improved the aeration surrounding the root area. This enabled the roots to expand and develop in an atmosphere that was suitable for their absorption of dissolved oxygen and nutrients. Conversely, in deep water culture, the root was fully submerged in a nutrient solution, which reduced the amount of airflow surrounding the root. These results were in agreement with Jong *et al.* (2014) and Roosta *et al.* (2016) reported that, for a hydroponic system to be successful, there must be adequate dissolved oxygen in the solution, if O_2 demand exceeds supply, oxygen availability to roots grown in hydroponic culture becomes limited resulting in a decline in root growth rate, ion uptake, and water uptake, ultimately diminishing plant productivity. Cherif *et al*. (1997) mentioned that, the sensitivity of roots to low O_2 concentration depends on its effect on mitochondrial respiration because it supplies most of the energy required for root function. The flow rate of the solution around the root zone has a significant impact on the concentration of dissolved oxygen, which in turn impacts the rate of crop growth (Morard and Silvester 1996).

On the other hand, using flat shape NFT gave the highest plant fresh weight per plant compared with A-shape NFT. In contrast to the flat-shaped NFT system, the A-shaped NFT system had the highest total yield per square meter. These results are due to different plant densities (24 plants in A- shape NFT per m^2 and 20 in flat shape NFT per m^2). According to Charlo *et al*. (2007) and Santos *et al.* (2010) clarified that increasing plant space led to higher vegetative growth characteristics and yield per plant but decreased productivity per unit area, whereas the opposite is true. Abul-Soud *et al*. (2018) reported that increase fresh weight per plant under low plant density is due to less overlapping and shading of leaves, better light penetration, less competition for light, water and nutrients and more efficient CO2 fixation. The vegetative properties increased when the nutrient solution's temperature was raised to 20°C, yield per m^2, chlorophyll reading, nitrate content and NPK content are also rised. This may be due to the increased absorption of water and nutrients, which enhanced all the physiological processes in plants. According to Nxawe et al. (2010), raising the temperature of the nutritional solution improved the dissolved oxygen levels and facilitated the dissolution of minerals in the nutrient solution which contributed to the improvement of the physiological process in the root, such as the absorption of water and nutrients. The effects of varying water temperatures (18.3°C, 21.1°C, and ambient) on the vegetative development and TSS of 17 lettuce cultivars cultivated using the nutrient film technique (NFT) were investigated by Dharti et al. (2021), The findings showed that lettuce cultivated at 21.1°C were gave the height value of height, width, shoot fresh weight and root fresh weight than plants grown at 18.3°C or ambient conditions. Sakamoto and Suzuki (2015) found that as the temperature of the nutrient solution increased from 10 °C to 30 °C the nitrate content increased in lettuce.

5. Conclusions

Based on the above discussion, we concluded that using modified NFT systems (A-shape and flat-shape) increases production and improves the quality of lettuce compared to deep water culture. However, the yield of plants cultivated with nutrient solution heating was noticeably higher than that of plants grown with unheated nutrient solution. The previous study recommended using A- shape NFT systems with the nutrient solution heated to 20 °C in lettuce production in unheated greenhouse conditions during the very cold months in winter. The economic feasibility of heating a nutrition solution requires more investigation.

Declarations

Ethics approval and consent to participate

Consent for publication: Not applicable.

Availability of data and material: Not applicable.

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