Egypt. J. Soil Sci. **Vol. 65**, No. 1. pp: 135- 148 (2025)

Egyptian Journal of Soil Science

http://ejss.journals.ekb.eg/

Improving fertilization management for increasing heat stress tolerance of Plants under Irregular High Temperature

Dina M. Omran, Manal Mubarak, Shimaa Y. Oraby, Ahmed A. Ibrahim and **Mona I. Nossier***
Soils and water Dept., Agric. Fac. Ain Shams Univ., Cairo, Egypt

FIELD experiments were conducted to study the possibility of reducing the negative effects of irregular high temperatures (IHT) >30^{o}C on the growth of hard head lettuce and pea plants during growing season by reducing fertigation solution concentration (FSC) to minimize the chance of plants being exposed to salt accumulation in the plant root zone. The experimental area was divided into six plots to receive the following FSC treatments: 100, 90, 80, 70, 60, and 50 % of the recommended fertilization rate (RFR) for each crop. A significant increase was revealed in the yield, fresh weight and diameter of marketable lettuce heads as affected by reducing FSC levels to 70 % from RFR of the lettuce crop. Similar trends were obtained for pea crops in some of its growth parameters such as seed weight and pod production. The contents of N, K, Ca and Mg in lettuce and pea leaves decreased with decreasing FSC treatments. Chlorophylls (A, B and total), and β-carotene contents increased with decreasing FSC treatments to 70 % of RFR. Data showed a significant reduction in the concentrations of superoxide dismutase (SOD), peroxides (POD), Polyphenol oxides (PPO) and proline in both lettuce and pea with decreasing FSC treatments to 70 % then decreased with decreasing FSC treatments lower than 70 % of RFR. It could be concluded that the reduction in FSC to 70% from the RFR led to an increase in plant resistance to IHT, improved crop yield and economical benefit/cost ratios of lettuce and pea crops grown under IHT.

Keywords: Irregular high temperature, Abiotic stress, Antioxidant defense, Crisphead lettuce, Green pea.

Introduction

Climate change has taken a lot of attention from the world due to the noticed risks to human life. Human activity via chopping down forests, burning fossil fuels, and farming livestock is one of the primary causes of gas emissions and worldwide warming, which is often known as the "greenhouse effect" **(SharafEldin et al., 2023)**.

High temperatures due to climate change caused by global warming led to a serious threat to crop yield worldwide (**Wang et al. 2018**). With a 1°C increase in average temperatures, yields of the major food and cash crop species can decrease by 5 to 10 percent (**Hatfield et al. 2011**). In general, the term "heat stress" often refers to a period in which plants are subjected to high temperatures for long enough to permanently change their ability to function or grow normally (**Tuteja et al. 2012; Wahid et al. 2007**). At the same time, rising air temperatures because of climate changes considered real safety threatens agrarian production. Hence, to cope with these challenges, particularly in some regions, it is vital to modify current agricultural practices **(Mohamed et al. 2024**)

High temperature, salinity-induced osmotic stress and ionic stress lead to the overproduction of reactive oxygen species (ROS) and, ultimately, result in oxidative damage to cell membrane components, and may cause cell and plant death. The antioxidant defense system protects the plant from abiotic stress-induced oxidative damage by detoxifying the ROS, also by maintaining the balance of ROS generation under abiotic stress (**Motsa et al. 2015**). Some of scientific investigations have demonstrated that heat stress has a variety of negative effects on plant development, , physiological traits, growth and productivity-both in terms of quality and quantity **(Shalaby et al., 2021).**

Excessive fertilizer application beyond crop needs particularly at high temperatures may result in soluble salt buildup and phytotoxic effects on plant growth. Lettuce has a moderately low salt tolerance. Soluble salt injury results in a reduction in head size. Lettuce yield losses can occur when the electrical conductivity of the soil

*Corresponding author e-mail: mona_nossier@agr.asu.edu.eg
Received: 05/10/2024; Accepted: 08/11/2024
DOI: 10.21608/ejss.2024.326207.1874

solution exceeds 1.3 dS/m (**Moretti et al. 2010, Xu and Mou 2015**). In hot dry areas where temperatures are relatively high, the transpiration rate is also high. As expected under such conditions, the accumulation of salts dramatically increased in the active plant root zone. This increase in salt accumulation may reach a level that causes severe damage to the cell membranes of the roots loseing their selective ability to control the entry of dissolved materials and ions and chooseing the appropriate ones (**Ibrahim 2013**). Therefore, it is a good idea to reduce nutrients added through fertilization during a heat wave (**Wahid et al. 2007**). Crisphead lettuce crop is adapted to cool growing conditions with the optimum temperatures for growth of 15.6-18.3^{o}C and 21.1-26.7^{o}C for flower and produce seed. Lettuce can tolerate a few days of temperatures from 26.7 to 29.4^{o}C (**Sanders 2019**). Pea crops are particularly sensitive to heat stress at the bloom stage; only a few days of exposure to high temperatures (30–35^{o}C) can cause heavy yield losses through flower drop or pod abortion **(Wahid et al. 2007**).

Improving plant nutrition can successfully mitigate the adverse effects of high temperature stress. Where, the efficient use of nutrients including the proper fertigation solution concentration (FSC) under heat stress conditions may help in activate the metabolic and biological processes to increase the heat stress tolerance. The application of plant nutrients like N, K, Ca, and Mg was also found to reduce the toxicity of reactive oxygen species (ROS) by increasing the amount of antioxidant enzymes (**Waraich et al. 2012**). In fact, there is a scarcity of information about the appropriate FSC for crops under (IHT) conditions that may influence plant tolerance to heat stress (**Bita and Gerats, 2013**). Therefore, there is an urgent need to study possibilities to enhance plant tolerance to high temperatures by improving nutritional management. Hence, the main purpose of this research is to evaluate the possibility of increasing plant tolerance to (IHT) that causes heat stress by improving nutritional management by reducing the FSC added during the growing season of lettuce and pea crops which varied in their heat stress sensitivity.

2. Materials and Methods

2.1. Field experiment

Due to climate changes, it has been observed that the average temperature during one year differs from the year before and from the following, and therefore the fertilizer needs of plants will differ depending on these changes.

It was noted that during growing season the plant is exposed to varying temperatures between high and low, which affects the efficiency and natural growth rate of the plant during the various stages of its growth and thus the final crop. A procedure field experiment was conducted in the experimental area of Soil and Water Department, Faculty of Agriculture, Ain Shams University to study the possibility of reducing the negative effects of IHT on the growth and development of crisphead lettuce and green pea crops by adjusting FSC to reduce the chance of plants being exposed to the accumulation of salts and drought stress in the plant root zone In these experiments, crisphead lettuce was planted at different dates in order to reach the highest economic production of the crop outside the known marketing window, where supply is low for local marketing or export, and thus the economic return is as high as possible.. The experimental area was divided into six main plots. Two drip irrigation lines of 16 mm were installed for each experimental plot, including a dripper of 4 L/h every 30 cm, with a total of about 52 drippers for each experimental plot of 1×8 m (**Figure 1)**. Plants irrigated according to the tracking of the readily available water in the root zone as described by **Allen et al. (2002).**

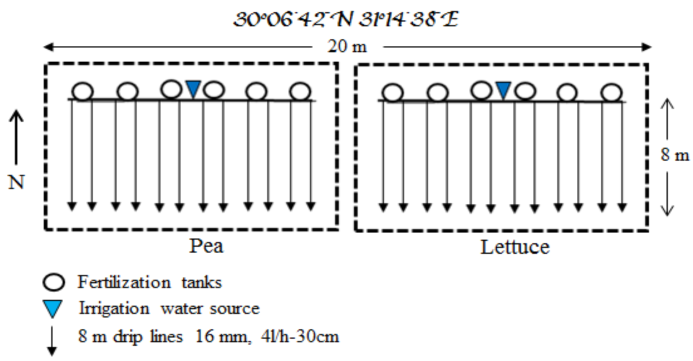


Fig. 1. A sketch of the experimental area including location, drip irrigation lines and fertilization tanks.

Lettuce *(Lactuca sativa L. Crisphead palsam CV.*) seedlings were planted on April 14, 2023, at a rate of 78 plants per terrace (30×30 cm per plant). Pea seeds, (*Pisum sativum L. Master B CV.*) were planted on March 21, 2023, at a rate of 39 plants per terrace (30×60 cm per plant). Plants grown under such conditions are exposed during growth seasons to IHT which may cause heat stress.

2.1.1 The climatic conditions surrounding the plants under study

Data in **Fig. 2.** shows the daily average values of air temperature (T) and relative humidity (RH) during the growth season. In this work crisphead lettuce and green pea grown through the period from April 14 to June 10, 2023, for lettuce and from March 21 to June 4, 2023, for pea plants. The temperature conditions to which plants were exposed during the different growth stages can be summarized as follows:

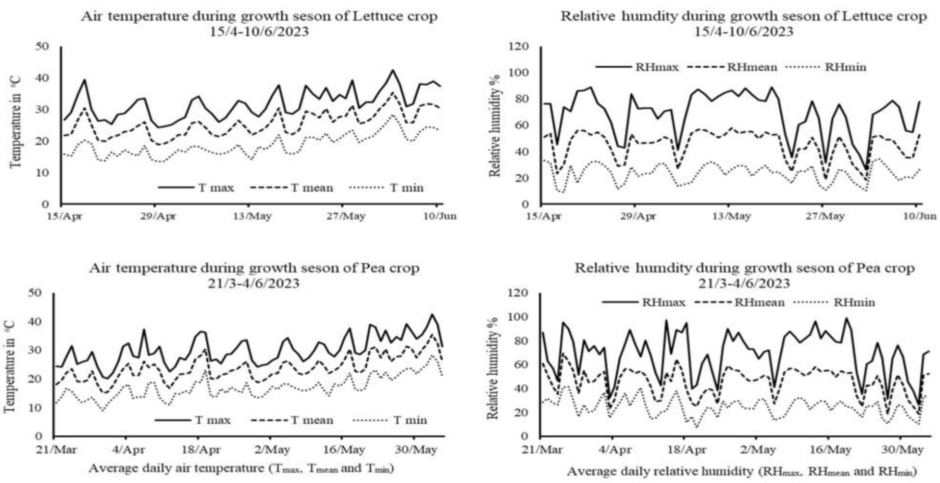


Fig. 2. The average air temperature and relative humidity at the experiment area during different growth seasons of lettuce and pea crops.

- **During the vegetative growth stage of lettuce "A"** (from transplanting, to 75% plant cover), which lasted for about 30 days (720 hrs.), lettuce plants were exposed to 71 hrs. at T_{mean}>30 °C (5.19 %), 291 hrs. at T_{max}>30°C (21.3 %), and 90 hrs. at T_{max}>37°C (6.58 %).
- **The heading lettuce growth stage "B"** (from the beginning of the formation of heads until the harvest), which lasted for about 27 days (648 hrs.), plants were exposed to 242 hrs. at T_{mean}>30°C (17.7 %), 436 hrs. at T_{max}>30°C (31.9 %), and 242 hrs. at T_{max}>37°C (17.7 % of the total number of hrs. of growth season (1368 hrs.).
- **During the vegetative growth stage of pea plants "A"** (from the appearance of the first true leaf until 20% of the flowers emerge), which lasted for about 30 days (720 hrs.), pea plants were exposed to 43 hrs. at T_{mean}>30°C (2.36%), 186 hrs. at T_{max}>30°C (10.2%), and 62 hrs. at T_{max}>37°C (3.4%).
- **The pea flowering stage "B"** (from 20% flowering until 20% of pods are formed), which lasted for about 30 days (648 hrs.), lettuce plants were exposed to 82 hrs. at T_{mean}>30°C (4.5%), 303 hrs. at T_{max}>30°C (16.6%), and 97 hrs. at T_{max}>37°C (5.32%).
- **During the pea-pod emergence stage "C"** (after 20% of the pods are formed, until the harvest), which lasted for about 16 days (384 hrs.), pea plants exposed to 161 hrs. at T_{mean}>30°C (8.83%), 270 hrs. at T_{max}>30°C (14.8%), and 161 hrs. at T_{max}>37°C (8.83% of the total number of hrs. of growth season i.e. 1824 hrs.).

Also, the number of hours where lettuce and pea plants were exposed to the high temperature during different growth stages (<T_{mean}>30^{o}C, T_{max}>30^{o}C, T_{max}>37^{o}C) were calculated and presented in **Table 1**

Table 1. Air temperature during different growth stages of lettuce and pea crops.

Crop	Planting Date	Growth stage	Growth stage Duration		Temperature during growth season in °C					
					T_{mean}>30^{o}C		T_{max}>30^{o}C		T_{max}>37^{o}C	
			Day	hrs.	hrs.	%	hrs.	%	hrs.	%
Lettuce	15/4-14/5	A	30	720	71	5.19	291	21.3	90	6.58
	15/5-10/6	B	27	648	242	17.7	436	31.9	242	17.7
	15/4-10/6	Total	57	**1368**	**312**	**22.8**	**727**	**53.1**	**332**	**24.3**
Pea	21/3-4/6	A	30	720	43	2.36	186	10.2	62	3.40
	21/3-19/4	B	30	720	82	4.50	303	16.6	97	5.32
	20/4-19/5	C	16	384	161	8.83	270	14.8	161	8.83
	21/3-19/5	Total	76	1824	282	15.5	758	41.6	319	17.5

2.1.2 Electrical conductivity of fertigation solutions (EC $_{fert}$)

To evaluate the possibility of increasing the tolerance of plants to IHT during the different growth stages using nutrient management (mainly by reducing the FSC). The experimental areas were divided to receive the following 6 fertigation solution concentrations (FSC) treatments: 100, 90, 80, 70, 60 and 50 % of the RFRs (RFR) for each crop. These FSC treatments were used only when plants needed fertilization during exposure to high temperatures (T_{mean}>30°C). The FSC treatment of 100 % was used for all growing plants when they needed fertilization at T_{mean}<30°C. The average electrical conductivity values (EC_{fert}) of the different FSC treatments used during different growth stages for the tested crops were determined and presented in **Table 2**.

Table 2. Average electrical conductivity of fertigation solutions (EC_{fert}) used during different growth stages of the lettuce and pea crops.

Crop	Growth Season	Electrical conductivity of fertigation solutions) EC fert)in dS/m					
		100	90	80	70	60	50
Lettuce	A	1.10	0.99	0.88	0.77	0.66	0.55
	B	1.04	0.94	0.83	0.73	0.63	0.52
Pea	A	1.10	0.99	0.88	0.77	0.66	0.55
	B	1.18	1.06	0.94	0.83	0.71	0.59
	C	1.24	1.12	1.00	0.87	0.75	0.62

2.1.3. Nutrients added under different temperature and FSC treatments.

Crop fertilizer requirements for any of the tested crops were divided to add through the fertigation system twice a week. The different FSC were made using water soluble fertilizers such as NH_4NO_3 (33% N), H_3PO_4 (60% P_2O_5), KNO_3 (13% N, 46% K_2O), Ca $(NO_3)_2$ (15% N and 26% CaO), $MgSO_4$ (16% MgO), $FeSO_4$ (19% Fe), $ZnSO_4$ (13 % Zn), $MnSO_4$ (14 % Mn), Na_3BO_3 (10% B). The amount of nutrients added for the tested crops under different temperatures and FSC treatments were recorded and presented in **Table 3** for lettuce and **Table 4** for pea crops **Ibrahim (2013)**.

Table 3. The amount of nutrients added for lettuce crop under different temperatures and fertigation solution concentration(FSC).

Lettuce 15/4-10/6	Fertigation times	Nutrients added during growth season in kg/Fad					
		N	P_2O_5	K_2O	CaO	MgO	Mic $_{Mix}$
Nutrients added at T mean< 30°C							
100	10	15.7	2.98	14.8	2.60	2.27	1.60
Nutrients added at T_{mean}>30°C							
100	6	5.99	0.79	10.8	1.91	0.60	0.56
90		5.39	0.71	9.75	1.71	0.54	0.50
80		4.31	0.57	7.80	1.37	0.43	0.40
70		4.19	0.55	7.59	1.33	0.42	0.39
60		3.59	0.47	6.50	1.14	0.36	0.34
50		2.99	0.40	5.42	0.95	0.30	0.28

Fad = Fadden = 4200 m^2=0.42 hectare (ha)

Table 4. The amount of nutrients added for pea crops under different temperatures and fertigation solution concentration(FSC) treatments.

Pea 21/3-4/6	Fertigation times	Nutrients added during growth season in kg/Fad					
		N	P_2O_5	K_2O	CaO	MgO	Mic $_{Mix}$
Nutrients added at T_{mean} < 30°C							
100	15	24.1	5.38	26.5	5.84	3.54	2.37
Nutrients added at T_{mean} >30°C							
100	6	9.58	1.58	14.9	2.79	1.13	0.91
90		8.62	1.42	13.4	2.51	1.01	0.82
80		7.66	1.27	11.9	2.24	0.90	0.73
70		6.70	1.11	10.5	1.96	0.79	0.64
60		5.75	0.95	9.00	1.68	0.68	0.55
50		4.79	0.79	7.50	1.40	0.56	0.46

2.2 Growth and yield measurements

Some parameters of growth and development of lettuce plants were measured at harvest, on June 10, 2023, 58 days after planting lettuce seedlings, especially fresh weight, size, diameter and crop yield of the marketable lettuce head (MLH). Some growth parameters of peas plants were also measured at harvest on June 4, 2023, 76 days after planting such as the number of pods per plant, weight of pods per plant, Pod weight in g/ pod, and the pod crop yield per ha.

2.3 Chemical analyses

2.3.1 Soil, and water analyses

Representative soil samples were collected at 0-30 cm depth from the experimental area before cultivation for some physical and chemical analyses. Soil physical characteristics (i.e. SP, FC and PWP, $CaCO_3$, Real particle density (P_d), bulk density (B_d) and soil texture were determined using the methods described by **Black et al., (1965)**. Soil organic matter (OM) was determined based on the Walkley-Black chromic acid wet oxidation method as described by **Walkley (1947)**. Electrical conductivity ($EC_{1:2.5}$) was determined in 1:2.5 soil: water extract using an EC meter (Model YSI 32). In the 1:2.5 soil: water extract, pH, water - soluble K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, HCO_3^- and $CO_3^=$ were determined using the standard methods of analysis as described by **Jackson (1973)**. The soil in this area was not saline and almost light alkaline. The results were presented in **Table 5**.

Table 5. **Some soil physical and chemical properties and irrigation water in the experimental area.**

Some soil physical properties of the experimental area										
$CaCO_3$ %	OM %	P_d g/cm^3	B_d g/cm^3	SP %	FC %	PWP %	Sand %	Silt %	Clay %	Soil texture
1.85	0.82	2.16	1.36	36.3	22.4	14.5	63.9	16.0	20.1	Sandy clay loam

Some soil chemical properties for the experimental area										
Soil sample 30 cm depth	$pH_{1:2.5}$	$EC_{1:2.5}$ ds/m	Ca^{++}	Mg^{++}	K^+	Na^+	HCO_3-	$CO_3^=$	Cl^-	$SO_4^=$
			meq/l in 1:2.5 soil: water extract							
	7.94	0.63	4.40	0.80	0.51	0.56	3.20	ND	2.04	1.02

Some chemical properties of irrigation water										
Irrigation water	pH	EC ds/m	Ca^{++}	Mg^{++}	K^+	Na^+	HCO_3-	$CO_3^=$	Cl^-	$SO_4^=$
			meq/l							
	7.36	0.71	1.00	1.20	0.03	5.52	4.80	ND	1.68	1.28

2.3.2 Determination of N, K, Ca, and Mg contents

The collected samples of lettuce and pea leaves were prepared for chemical analysis. Plant samples were dried in a drying oven at 70°C for 24 h and digested with a mixture of H_2SO_4/H_2O_2. The nitrogen, potassium, calcium and magnesium contents were determined using the methods described by **Walinga et al., (2013); Chapmann and Pratt (1961).**

2.3.3 Determination of some biochemical compounds (chlorophyll's, β-Carotene, antioxidant defense compounds and proline)

- **Chlorophyll and β-carotene** concentrations in lettuce and pea leaves were determined according to the method described by **Ruth G. Alscher and Alan R. Wellburn (1994).**
- **Peroxidase activity (POD)** was determined by the method described by **Hammerschmidt et al. (1982).** The assay mixture (100 ml) contained 10 ml of 1% (v/v) guaiacol, 10 ml of 0.3 % H_2O_2 and 80 ml of 50 mM phosphate buffer (pH=6.6). A volume of 100 µl crude enzyme was added 2.9 ml of the assay mixture to start the reaction. The absorbance was recorded every 30 s for 3 min at 470 nm using spectrophotometer. The rate of change in absorbance per minute was calculated and one unit of enzyme was expressed as ^OD= 0.01. The G-POD activity was expressed as unit.mg-1 protein.
- **Polyphenol oxidase (PPO) activity** was measured according to **Oktay et al. (1995)**. The reaction mixture consisted of 100 µl crude enzyme, 600 µl catechol and 2.3 ml phosphate buffer (0.1 M, pH=6.5). The absorbance at 420 nm was recorded zero time and after 1 min using a spectrophotometer. One unit of PPO activity absorbance of 0.001 per min at 420 nm.
- **Superoxide dismutase (SOD)** assay was based on the method described by **Beyer and Fridovich (1987)**. The reaction mixture with a total volume of 3 ml contained 100 µl crude enzyme, 50mM phosphate buffer (pH=7.8), 75 µM NBT,13 mM L-methionine, 0.1 mM EDTA and 0.5 mM riboflavin. The reaction was initiated by the addition of riboflavin then the reaction mixture was illuminated for 20 min with a 20 W fluorescent lamp. One unit of enzyme activity was defined as the amount of enzyme required to result in a 50% inhibition in the rate of nitroblue tetrazolium reduction at 560 nm using spectrophotometer. The enzyme activity was expressed as µg g^{-1} FW.
- **Proline concentration** was determined using a ninhydrin colorimetric method of **Troll and Lindsley (1955)** as modified by **Petters et al. (1997)**. Frozen tissues of leaves were ground using mortar and pestle and homogenized with 100 mM sodium phosphate buffer pH=6. The extraction ratio was 10 ml for each one gram of plant tissue. Afterward, the homogenate was centrifuged for 10 min at 4500 rpm then 200 µl of the extract was reacted with1 ml of ninhydrin solution (2.5 g dissolved in 100 ml of orthophosphoric acid. acetic and water 15:6:25, V: V: V) for 1 h in boiling water. Thereafter, the developed dye was extracted with 1 ml of toluene and vigorously vortexed for 15 s. The toluene phase was sucked using micropipette and the color was measured at 515 nm using a spectrophotometer. The proline concentration was calculated from the standard curve of L-proline. Proline concentration was expressed as µg proline. g^{-1} Fresh weight (FW).

2.4 Profitability

The economic evaluation based on the Benefit/Cost ratio was estimated according to **Cimmyt (1988)** by calculating the cost of cultivation for different agro-inputs, i.e., labor, fertilizers, irrigation, insect control, harvesting, and other necessary experimental requirements. The returns of each tested treatment were calculated on the basis of the local market price of crisphead lettuce and green pea crop yield (about 200 US$/Ton each):

Benefit/Cost ratio was determined by dividing the proposed total cash benefit of a project by the proposed total cash cost of the project.

2.5. Statistical Analysis

The data on Lettuce and pea were analyzed according to the following two General Linear Models and the means were separated by Duncan's test using of SAS (2011).

3 Results

Evaluation of Lettuce Genotypes for
Salinity Tolerance
Chenping Xu and Beiquan Mou

Evaluation of Lettuce Genotypes for
Salinity Tolerance
Chenping Xu and Beiquan Mou

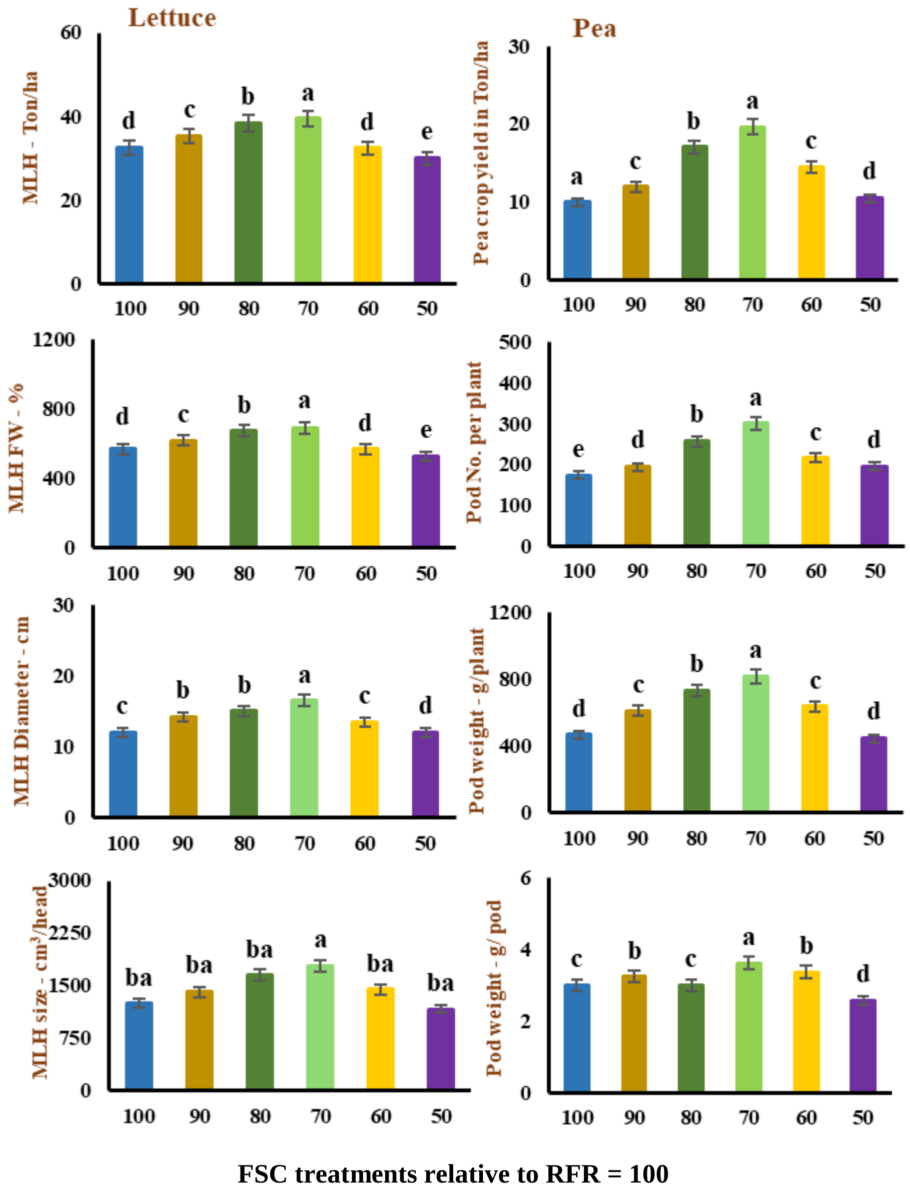


Fig. 3. Some growth parameters of lettuce and pea crops as affected by irregular high temperature (IHT) under different fertigation solution concentration(FSC) treatments.

Means with the same letters are not significantly different.

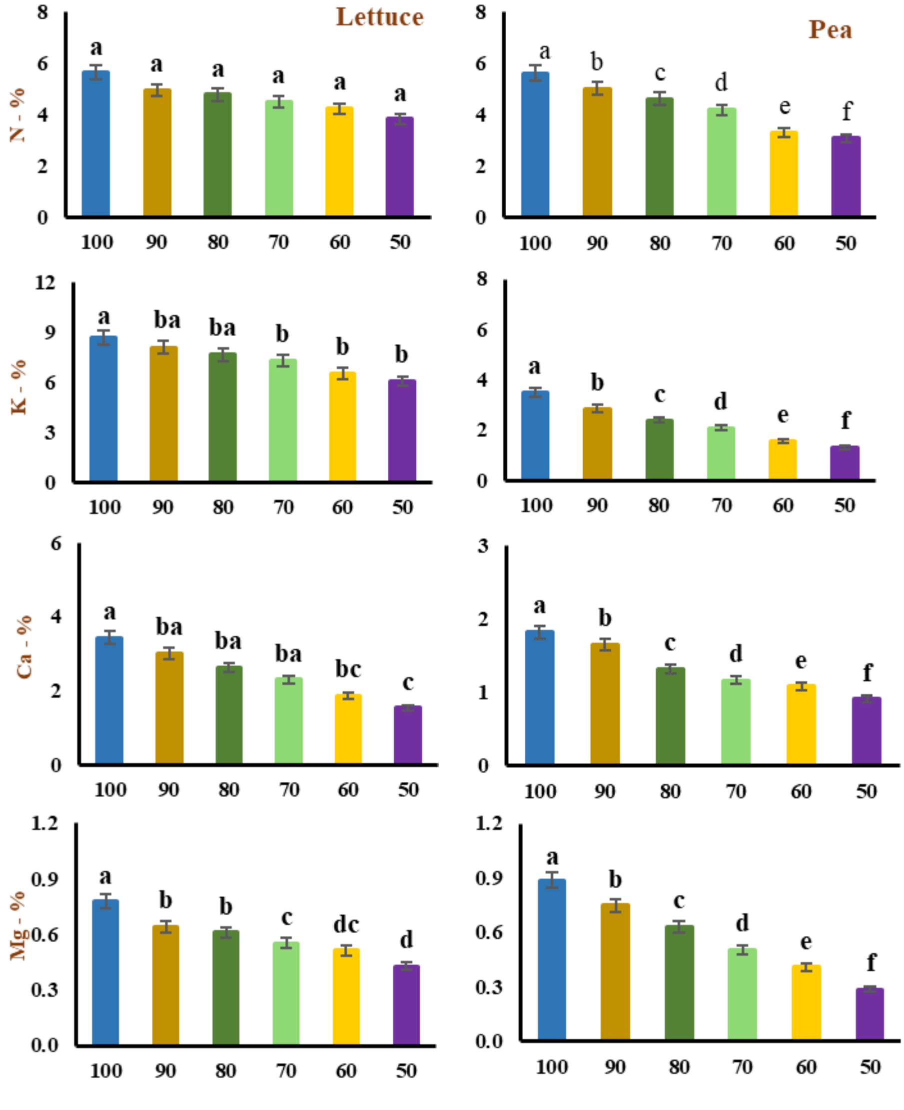
3.1 Growth parameters of lettuce and pea crops as affected by IHT under different FSC treatments.

Data in **Figure 3** Showed significant increases in fresh weight (FW), size and diameter and yield of MLH as affected by FSC treatments to 70 % from the RFR of lettuce and peas. The relative increase in these growth parameters were 118-132-125-118% and 121-142-125-121% for lettuce at FSC of 80 and 70 % from RFR respectively. Similar trends were also obtained for Pes crop. It could be also observed slight decreases in some growth parameters of lettuce and peas such as MLH FW, size, yield, pod weight per plant, and pod No. per plant with reducing the FSC treatments to 50 % from the RFR under IHT.

3.2 N, K, Ca and Mg contents in lettuce and pea crops as affected by irregular high temperature under different FSC treatments

Data in **Fig. 4.** indicated that N, K, Ca and Mg contents in lettuce and pea leaves were significant decreased except N in lettuce with decreasing nutritional levels treatments from 100 to 50 % of the recommended rate of

fertilization. These decreases were more pronounced for K and Ca particularly at nutritional level less than 70 % from the RFR of lettuce and pea crops. The decreases in K and Ca at 60-50 % of the tested nutritional treatments reached to about 75-75 and 56-48 % for lettuce and 57-55 and 61-51 % for pea plants respectively.



FSC treatments relative to RFR = 100

Fig. 4. Some nutrients contents in lettuce and pea crops as affected by irregular high temperatures (IHT) under different fertigation solution concentration (FSC) treatments.

Means with the same letters are not significantly different.

3.3 Chlorophyll (A, B and Total), and β-carotene contents in lettuce and pea plants as affected by IHT under different FSC treatments

Results in **Figure 5** showed a significant increases in chlorophyll A, chlorophyll B, chlorophyll A+B, and β-carotene particularly with reducing FSC treatments from 100 to 70 % of RFR under IHT. These increases were about 134, 149, 141, 145% and 146, 167, 155, 182 % for lettuce and 152, 151, 179, 144% and 164, 180, 187, 161% for pea crops at FSC treatments of 80 and 70 % from RFR respectively (**Figure 5**). It could be also observed marked decreases in all the tested biochemical compounds contents in leaves of lettuce and pea plants with decreasing FSC treatments particularly to 50 % from the RFR.

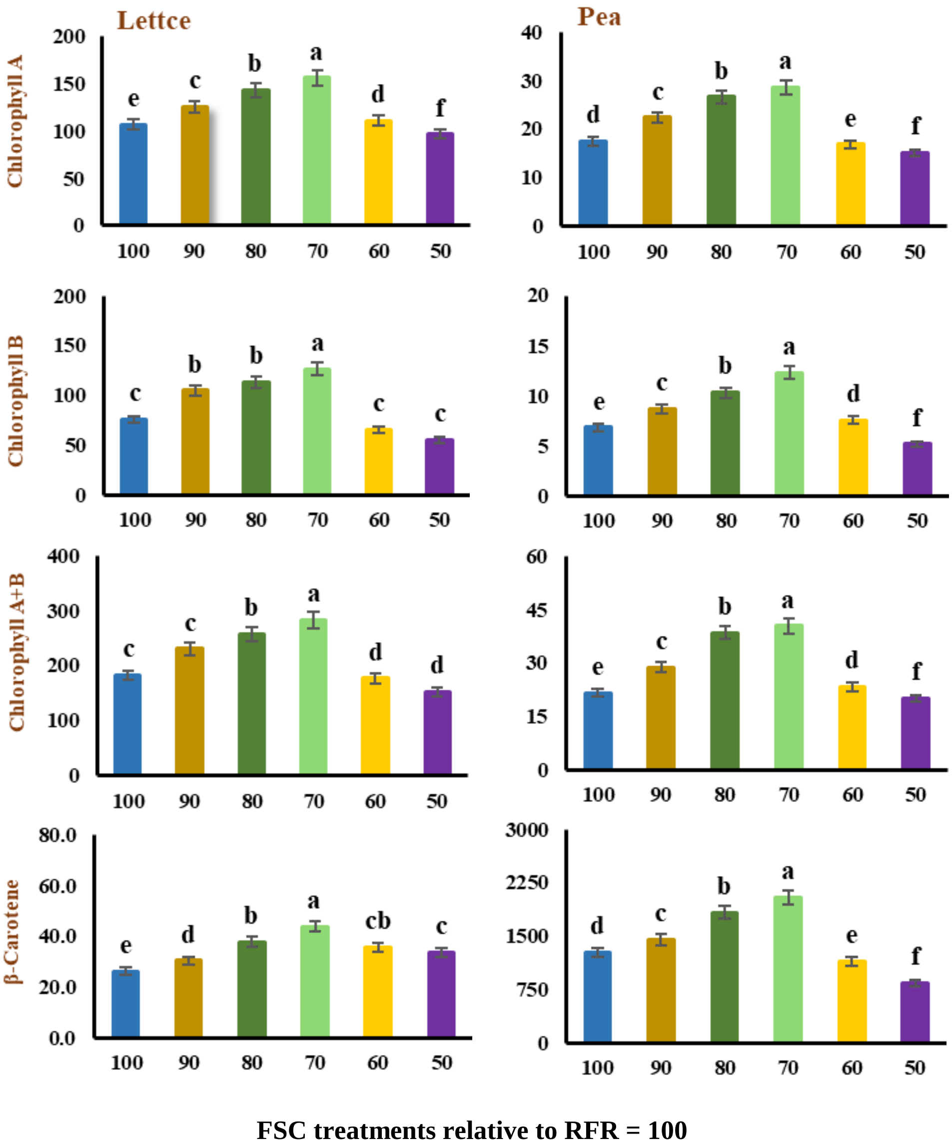


Fig. 5. Chlorophyll (A, B and Total), and β-Carotene contents in lettuce and pea plants as affected by irregular high temperature(IHT) under different fertigation solution concentration (FSC) treatments.

Means with the same letters are not significantly different.

3.4 Antioxidant defense compounds and proline contents in lettuce and pea plants as affected by IHT under different FSC treatments

Results in **Figure 6** showed significant reduction in the concentrations of peroxidase (POD), Polyphenol oxidase (PPO), superoxide dismutase (SOD), and proline in both lettuce and pea plants to 70 % then increased with decreasing the FSC lower than 70 % of from the RFR for both crops under IHT. The relative decreases in POD, PPO, SOD and proline were 73, 77, 64, 69% and 61, 61, 53, 62 % for lettuce and 70, 82, 53, 72% and 44, 67, 48, 58 % for pea at FSC of 80 and 70 % from RFR respectively. While the relative increases in POD, PPO, SOD and proline with reducing FSC to 60 and 50 % from RFR were 74, 58, 73, 70; and 81, 66, 85, 82 % for crisphead lettuce and 74, 71, 61, 67% and 55, 73, 69, 76 % for green pea respectively.`

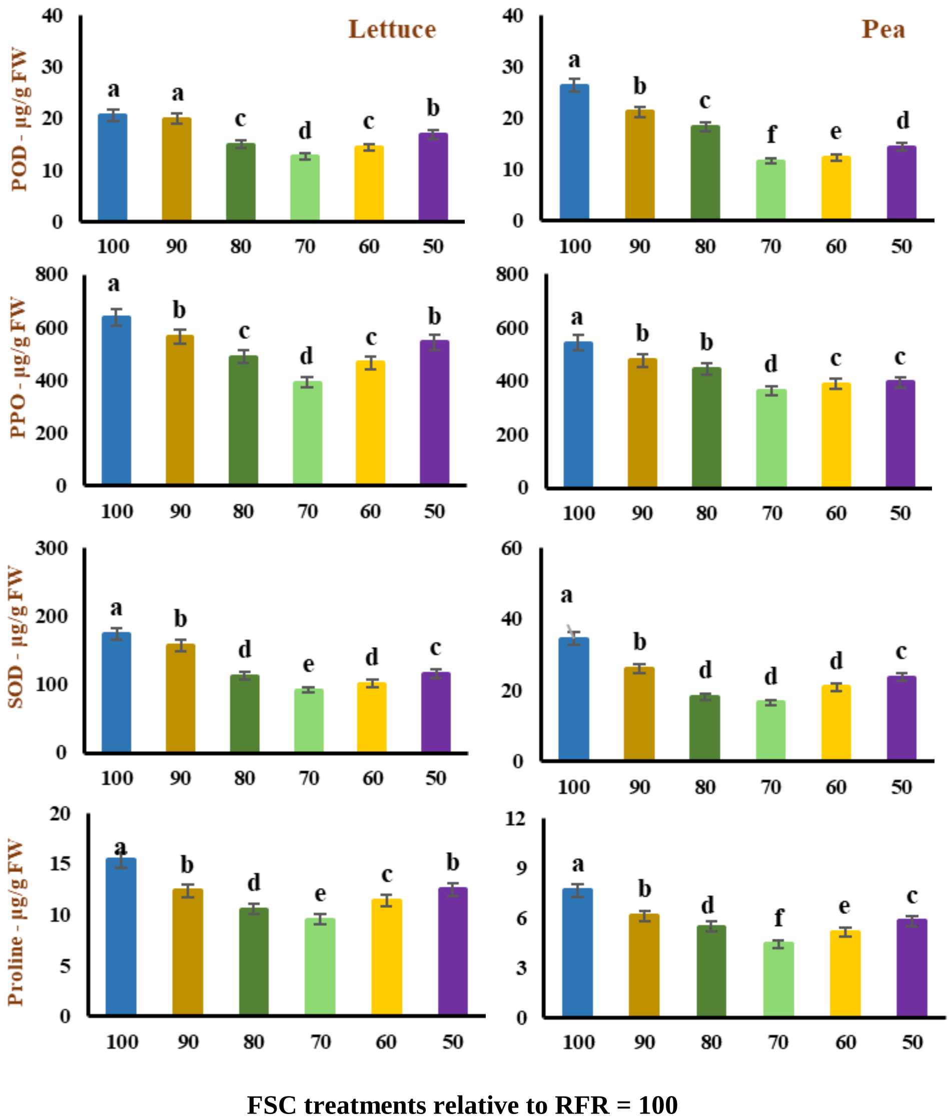


Fig .6. **Concentrations of peroxidase (POD), polyphenol oxidase (PPO), superoxide dismutase (SOD), and proline in lettuce and pea plants as affected by different fertigation solution concentration (FSC) levels under irregular high temperature(IHT).**

Means with the same letters are not significantly different.

3.5 The economic benefit/cost ratio for the proposal to alleviate the negative impact of IHT

From agribusiness feasibility point of view, data in **Figure 7** show the economic benefit/cost ratio for crisphead lettuce crop as affected by reducing FSC from 100 to 50 % of the RFRs as a tool for alleviate the negative impact of heat stress under irregular high temperature. Data revealed that the maximum benefit/cost ratio was obtained by reducing the FSC to 80 and 70% from RFR. The relative economic benefit/cost ratio at FSC levels of 80 and 70 % were 133 and 138 % for crisped lettuce and 171 and 203 % for green pea crops respectively. It worthies to mentioned that these increases were calculated as relative to control FSC treatment which received 100 % from the RFR for each of the tested crops.

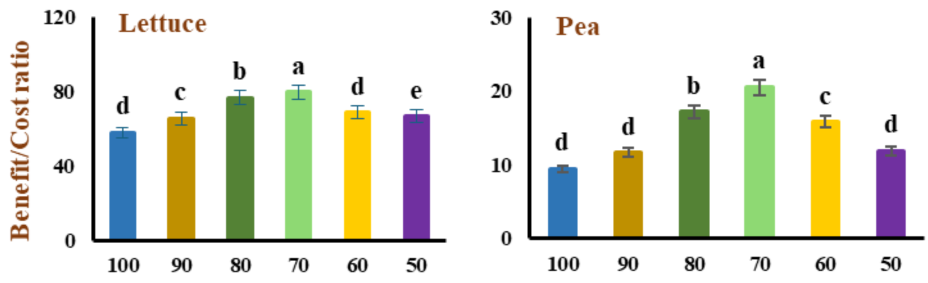


Fig. 7. The economic benefit/cost ratio of lettuce and pea crops affected different fertigation solution concentration (FSC) levels under irregular high temperatures (IHT).

Means with the same letters are not significantly different.

4. Discussion

Concerning climatic conditions surrounding the tested plants presented in **Figure 2** and **Table 3**, it could be observed that crisphead lettuce exposed to high temperatures (T_{mean}>30°C) during different growth stages which may consider as heat stress for quite a lot of hrs. According to **Sanders (2019)** who reported that crisphead lettuce grows best **at 15 to 18°C**. Germination takes place at an optimum range of **16 to 20°C**, (depending on the cultivar and type of lettuce). It could be also observed that pea plants may exposed to high - temperature (T_{mean}>30°C) during different growth stages which may consider also as heat stress for some hours according to **Mahoney, (1991)** who reported that the ideal temperature for vegetative growth in pea crop is **15-20°C** and the heat stress consequences are determined by intensity, duration and timing of heat exposure to the plant.

From the previous results, it has become clear to us that reducing the fertilization rate from 100% to 70% of the recommended fertilization rates according to (**Ibrahim 2013**) is appropriate for plant growth under heat stress because it works to reduce the overall stress that the plant can feel due to the high temperature and the increase in the rate of evapotranspiration, such as water stress resulting from rationalizing the use of irrigation water and resorting to drip irrigation instead of flood and saline irrigation due to the accumulation of excess salts from fertilization.

The conscious decreases in the FSC treatments were implemented and evaluated as a mitigator for the negative effects of heat stress and the associated abiotic stress such as salt and drought stresses stresses (**Riham , et al. 2023; El-Hamdi, et al., 2020); Khalifa, 2019)**. Lettuce and pea crops received the FSC treatments at different growth stages during exposure to high temperatures (T_{mean}>30°C). **Nikolić et al., (2023)** reported that abiotic stress such as salt, drought and heat stress causes a significant threat to photosynthesis in plants, which can be attributed to various mechanisms including changes in enzymatic activities, suppression of chlorophyll biosynthesis, and damage of the photosynthetic apparatus, dissipation of heat energy through non-photochemical processes, and reduced CO_2 influx due to stomatal closure. In addition, they concluded that the injurious effects of salinity and drought can be more stress with increasing temperature. Similar results of lettuce growth parameters shown in **Figure 3** were also obtained by **Song et al. (2020)** who documented that the rise in temperature adversely affects plant development, and limits plant growth and productivity mostly by reducing photosynthesis.

These results of pea growth parameters confirm the importance of reducing the FSC to increase the tolerance of plants to irregularly high temperatures particularly those that cause heat stress. Meanwhile, **Sadras et al., (2013**) found that pea crop productivity usually declines when the maximum day temperature during flowering exceeds 25°C. The decreases in some growth parameters such as MLH FW, size, yield and ENR of lettuce and pod weight per plant, and pod seeds No. per plant with reducing the FSC treatments to 50 % from the RFR under IHT mainly attributed to the reduction in the applied fertilizers at these treatments of FSC to 50 % from the RFR of lettuce and pea crops (**Waraich et al., 2012)**.

Concerning N, K, Ca and Mg contents in lettuce and pea crops as affected by IHT under different FSC treatments, , **Abou-Amer, 2013**; **Younis, 2021. Bhowmick et al., (2013)** conclude that salinity and rising temperature is a threat for growing vegetables. Excessive uptake of the macronutrients than normal can cause even death of the vegetables. They also noted that due to excessive salinity some tissue of plant was damaged. So much awareness is required for salinity and rising temperatures for vegetable cultivation.

Concerning Chlorophyll (A, B and Total) and β-carotene contents in lettuce and pea plants as affected by IHT under different nutritional treatments. **Crafts-Brandner et al., (2002**) concluded that photosynthesis is one of the most heat - sensitive physiological processes in plants. However, the observed decreases in Chlorophyll (A, B and Total) particularly at control treatment (100 %) compared with the FSC of 90, 80 and 70 % from the RFR under IHT may ascribed to the expected closure of stomata under high temperature in impairing photosynthesis due to the decrease in the concentration of the intercellular CO_2 (**Ashraf and Hafeez, 2004**). Moreover, such decreases in chlorophyll's and β-Carotene contents in both lettuce and pea plants may attributed to high temperature stress through the eradication of enzymes involved in the mechanism of chlorophyll biosynthesis as mentioned by **Ashraf and Harris, (2013).**

The increases in chlorophyll and β-Carotene contents in lettuce and pea plant leaves grown under (IHT) with nutritional treatments of 90, 80 and 70 % may be mainly due to reducing FSC levels added from 100 to 90, 80 and 70 % of the FSC. Where, the reduction in FSC levels led to alleviating the negative impact of high temperatures by reducing drought and salt stress associated with the high FSC levels (**Shin et al., 2020**).

The decreases in the tested biochemical contents (chlorophyll and β-Carotene) in the leaves of both lettuce and pea plants with decreasing FSC lower than 70 % from the RFRs may ascribed to the expected negative effects of reducing FSC level in the fertigation system particularly to 60 or 50 % from the RFR on nutrient uptake and contents in leaves of both lettuce and pea crops .However, **Waraich et al., (2012)** mentioned that improving plant nutrition including FSC can successfully mitigate the adverse effects of high - temperature stress.

The high concentrations of oxygen radicals and their derivatives, known as reactive oxygen species, (ROS), may cause oxidative stress (**Munns and Gilliham, 2015**). Many abiotic stresses such as high temperature, salinity-induced osmotic stress lead to the overproduction of ROS and, ultimately, result in oxidative damage to cell membrane components, and may cause cell and plant death. The antioxidant defense system as either enzymes or amino acid forms protects the plant from abiotic stress induced oxidative damage by detoxifying the ROS and by maintaining the balance of ROS generation.

It is well known that superoxide dismutase (SOD), peroxidase (POD), Polyphenol oxidase (PPO) and amino acid proline are among the most important components which act in reducing reactive oxygen species (ROS) under abiotic stress including heat stress (**Hasanuzzaman et al. 2020**). induced by stress, such as the activation of the antioxidant defense system to neutralize ROS **(Farooq et al., 2012;Ali et al., 2021**). Proline, an essential non-enzymatic antioxidant, holds a key role in the neutralization of ROS that are produced due to a lack of water **(Loudari et al., 2023).** Additionally, it strengthens the plant's antioxidant systems and enhances their survival capacity during periods of water scarcity **(Desoky et al., 2021**) Therefore, the decreases in the concentrations of such antioxidant defense compounds in plants demonstrate the ability of plants to tolerate abiotic stress conditions particularly with reducing salinity-induced osmotic stress by lowering the FSC from 100 to 70% of the RFR for both the tested crops. The increases in the tested antioxidant compounds (SOD, POD, PPO and proline) with lowering FSC from 70 to 50 % of the RFR may attributed to the additional abiotic stress caused by the nutrient's deficiencies at the FSC treatment of 60 or 50 % from the RFR. The accumulation of antioxidant components by plants under stress conditions is a significant defense mechanism against drought stress **(Elsherpiny et al. 2023)**, which protects plant cells from negative impacts of drought stress and preserves membrane integrity **(Hegazy et al., 2015;Desoky et al., 2023).**

Success in growing some crops under irregular temperatures that are not suitable for plant growth is important in terms of increasing its economic feasibility due to the higher purchase price and the opportunity to export it abroad than that crop growing under its optimal temperatures.

Concerning the economic benefit/cost ratio, it worthy to mentioned that feasibility studies are an important tool for evaluating the viability and potential success of an agricultural technology such as that suggested in this work to alleviate heat stress (**Tolinggi et al., 2018**). Therefore, according to the above calculated feasibility study, it could be concluded that reducing FSC to 70 % from the RFR for the tested crops increases the benefit/cost ratio to the highest significant values.

5. Conclusion

From the aforementioned results, it could be concluded that plants have been exposed to heat stress in the past few years due to the rise in temperatures as a result of climate change. However, exposure of plants to heat stress is usually accompanied by exposure of plants to other types of abiotic stresses such as drought and salt stress. These types of abiotic stresses closely lead to damage to the water relations of plants, including even the closure of stomata thus reducing the photosynthesis process and the growth and development of plants. Therefore, this research can be considered as an attempt to alleviate the negative impact of high temperatures (heat stress) by reducing the negative effects of the accompanying abiotic stresses, especially those resulting from salt stress. These results were confirmed by increasing the concentrations of some biochemical compounds, particularly those related to photosynthesis. In addition, to the reduction in the concentrations of antioxidant defense compounds, decreasing the fertigation solution concentration (FSC) to 70% of the recommended fertilization rate (RFR) for lettuce and pea crops.

Author Contributions:

Dina M. Omran: Conducting practical work, the necessary analysis and statistical analysis, and participating in writing and reviewing the research, **Manal Mubarak**: Conducting the necessary analysis and reviewing the research, **Shimaa Y. Oraby**: Conducting the necessary analysis, **A.A. Ibrahim**: Establishing the main idea of the research, writing and reviewing the research, **and Mona I. Nossier**: Participate in developing the main idea of the research, writing and reviewing the research, and following up on publication.

Funding: This research was technically supported by the Faculty of Agriculture, Ain Shams University, Egypt.

Declarations

Conflict of interest: The authors declare that they have no conflict-of-interest

References

Abou-Amer AI (2013). Effect of rates and methods of N application on growth, fruit yield and mineral content of Manzanillo olive trees. Egypt. J. Soil Sci., 53(2), 161-173.

Ali, M.M., Mansour, E., and Awaad, H.A. (2021). Drought tolerance in some field crops: State of the art review. Mitigating Environmental Stresses for Agricultural Sustainability in Egypt. Springer Nature Switzerland AG., 17-62

Allen RG, Pereira LS, Raes D and Smith M (2002) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements; FAO Irrigation and Drainage Paper 56. FAO: Rome, Italy, 15 p.

http://www.fao.org/3/X0490E/X0490E00.htm

Ashraf M, Harris PJC (2013) Photosynthesis under stressful environments: An overview. Photosynthetic. 2013; 51:163-190. DOI: 10.1007/S11099-013-0021-6

Ashraf M, Hafeez M (2004) Thermotolerance of pearl millet and maize at early growth stages: Growth and nutrient relations. *Biol. Plant.* 2004; 48:81–86.

Beyer Jr WF, Fridovich I (1987) Assaying for superoxide dismutase activity: some large consequences of minor changes in conditions. Analytical biochemistry, 161(2), 559-566.

https://plantstress.com/wp-content/uploads/2020/03/Proline-analysis.pdf

Bhowmick AC, Salma U, Siddiquee TA, Nikhil RM, Bhoumik C (2013) Effect of Temperature on the Uptake of Na^+, K^+, Ca^{2+} and Mg^{2+} By the Various Anatomical Parts of the Vegetable Amaranth Gangeticus. Journal Of Environmental Science, 3(6):2319-2399

file:///C:/Users/Ibrahim/Downloads/EnvironmentAmaranth.pdf

Bita CE, Gerats T (2013) Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. Frontiers in Plant Science. 2013; 4:1-18.

DOI: 10.3389/FPLS.2013.00273

Black, C.A. (1965) Methods of Soil Analysis: Part 1, Physical and Mineralogical Properties. American Society of Agronomy, Madison.

Chapmann HD, Pratt PF (1961). Methods of Analysis for Soils, Plants and Waters. Div. Agric. Sci., Univ. of California, Berkeley.

Cimmyt (1988) From agronomic data to farmer recommendation: an economic workbook DF, pp 31–33

Crafts-Brandner SJ, Salvucci ME (2002) Sensitivity of photosynthesis in a C_4 plant, maize, to heat stress. *Plant Physiol.* 2002; 129:1773–1780.

Desoky, E.-S.M., Mansour, E., El-Sobky, E.-S.E., AbdulHamid, M.I., Taha, T.F., Elakkad, H.A., Arnaout, S.M., Eid, R.S., El-Tarabily, K.A., and Yasin, M.A. (2021). Physio-biochemical and agronomic responses of faba beans to exogenously applied nano-silicon under drought stress conditions. Frontiers in plant science 12, 637783.

Desoky, E.S.M., Alharbi, K., Rady, M.M., Elnahal, A.S., Selem, E., Arnaout, S.M., and Mansour, E. (2023). Physiological, biochemical, anatomical, and agronomic responses of sesame to exogenously applied polyamines under different irrigation regimes. Agronomy 13, 875

El-Hamdi, Kh. H.; AS. Khair and HM Ishwayrib (2020). Simulation of water stress and climate change impacts on canola yield, seed quality and water productivity at north delta, Egypt. J. of Soil Sciences and Agricultural Engineering, Mansoura Univ., Vol 11 (8): 377-383.

Elsherpiny, M. A. (2023). Role of compost, biochar and sugar alcohols in raising the maize tolerance to water deficit conditions. Egyptian Journal of Soil Science, 63(1), 67-81.

Farooq, M., Hussain, M., Wahid, A., and Siddique, K. (2012). Drought stress in plants: an overview. Plant responses to drought stress: From morphological to molecular features, 1-33.

Hammerschmidt R, Nuckles EM, Kuć J (1982) Association of enhanced peroxidase activity with induced systemic resistance of cucumber to Colletotrichum lagenarium. Physiological Plant Pathology, 20(1), 73-82.

Hasanuzzaman M, Bhuyan MHMB, Zulfiqar F, Raza A, Mohsin SM, Mahmud JA, Fujita M, Fotopoulos V, (2020) Reactive oxygen species and antioxidant defense in plants under abiotic stress: Revisiting the crucial role of a universal defense regulator. Antioxidants 2020, 9, 681.

Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D et al. (2011) Climate impacts on agriculture: Implications for crop production. Agron. J. 2011; 103:351-370.

Hegazy, H., Hassan, N., Abdel-Haliem, M., and Naguib, D. (2015). Biochemical response of rice plant to biotic and abiotic stress under silica ions and nanoparticles application. Egypt J Bot 55, 79-1030375.

Ibrahim A (2013) Applications in irrigation and fertilization. Part II, Nutrients requirements for field and horticulture crops, Ain Shams Univ., Cairo, Egypt, Ch.13, pp 507–508. (Textbook in Arabic). ISBN: 978-977-90-0328-3.

Jackson ML (1973). Soil Chemical Analysis. Prentic-Hall of India-Private, New Delhi, pp: 144-197.

Khalifa, R.M. (2019) Response of faba bean to alternate irrigation and cut-off irrigation combined with mineral phosphorus levels and biofertilizer at North Nile Delta soils. Egypt. J. Soil Sci. 59 (2), 175-191.

Kader, A. A., J. M. Lyons and L. L. Morris (1974) Postharvest responses of vegetables to preharvest field temperature. HortScience, 9(6):523-527.

Loudari, A., Latique, S., Mayane, A., Colinet, G., and Oukarroum, A. (2023). Polyphosphate fertilizer impacts the enzymatic and non-enzymatic antioxidant capacity of wheat plants grown under salinity. Scientific Reports 13, 11212

Mahoney J (1991) Field pea. In: New crops: agronomy and potential of alternative crop species (Melbourne, Australia: Inkata Press; 53–62.

Mohamed S. , Farouk E. , Hasnaa E. , Yousry B. , Adel H. E. , Salah E. and Reda M.(2024). Modifying Low Tunnels to Mitigate Heat Stress on Cucumber Grown on Salt-Affected Soil under Late Summer Season Conditions Egypt. J. Soil Sci. Vol. 64, No. 4, pp: 1457 – 1477 DOI: 10.21608/EJSS.2024.307241.1823.

Moretti CL, Mattos LM, Calbo AG, Sargent SA (2010) Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: a review. Food Research International, 43(7): 1824-1832.

Motsa MM, Slabbert MM, Van Averbeke W, Morey L (2015) Effect of light and temperature on seed germination of selected African leafy vegetables. South African Journal of Botany, 99: 29-35.

Munns R, Gilliham M (2015) Salinity tolerance of crops - What is the cost? New Phytol. 2015, 208, 668–673

Nikolić N, Ghirardelli A, Schiavon M, Masin R (2023) Effects of the salinity-temperature interaction on seed germination and early seedling development: a comparative study of crop and weed species. *Plant Biology*, Vol. 23 (446): 1-14.https://bmcplantbiol.biomedcentral.com/articles/10.1186/s12870-023-04465-8

Oktay, M, Küfreviolu I, Kocaçalişkan I, Şaklrolu H (1995) Polyphenoloxidase from Amasya apple. Journal of Food Science, 60(3), 494-496.

Peters W, Beck E, Piepenbrock M, Lenz B, Schmitt JM (1997) Cytokinin as a negative effector of phosphoenolpyruvate carboxylase induction in Mesembryanthemum crystallinum. Journal of plant physiology, 151(3), 362-367.

Riham M.N. Faiyad; Eman H. Abd El-Azeiz; Enas E. yousif (2023). Effect of Sulfur, Boron, Zinc and Iron on Canola under Salt Affected Soils. Egypt. J. Soil Sci. Vol. 63, No. 4, pp: 475-487 (2023)

Ruth G. Alscher and Alan R. Wellburn (1994) Plant Responses to the Gaseous Environment Molecular, metabolic and physiological aspects. Springer Science+Business Media Dordrecht.DOI 10.1007/978-94-011-1294-9

http://www.sciencepub.net/nature

Sanders D (2019) Lettuce Horticulture Information Leaflets. NC State Extension Publications.

https://content.ces.ncsu.edu/lettuce https://content.ces.ncsu.edu/

SAS Institute Inc. (2011). SAS/STAT® 9.3 User's Guide. SAS Inst. Inc.,Cary, NC, USA. 536 p.

Shalaby, T.A., Abd-Alkarim, E., El-Aidy, F., Hamed, E., Sharaf-Eldin, M., Taha, N., El-Ramady, H., Bayoumi, Y. and Reis, A. (2021). Nano-selenium, silicon and H2O2 boost growth and productivity of cucumber under combined salinity and heat stress. Ecotoxicology and Environmental Safety, 212, 111962. https://doi.org/10.1016/j.ecoenv.2021.111962

Sharaf-Eldin M.A., Yaseen Z.M., Elmetwalli A.H., Elsayed S., Scholz M., Al-Khafaji Z., and Omar G.F. (2023). Modifying walk-in tunnels through solar energy, fogging, and evaporative cooling to mitigate heat stress on tomato. Horticulturae, 9(1), 77. https://doi.org/10.3390/horticulturae9010077

Shin YK, Bhandari SR, J. Su Jo, JW. Song, MC Cho, EY. Yang and JG. Lee (2020) Response to Salt Stress in Lettuce: Changes in Chlorophyll Fluorescence Parameters, Phytochemical Contents, and Antioxidant Activities. *Agronomy* 2020, 10(11),1627. https://doi.org/10.3390/agronomy10111627

Song J, Huang H, Hao Y, Song Y, Zhang Y, Su W, Liu H (2020) Nutritional quality, mineral and antioxidant content in lettuce affected by interaction of light intensity and nutrient solution concentration. Sci Rep. 2020; 10: 2796. Doi: 10.1038/s41598-020-59574-3

Tolinggi W, A. Murtisari, Y. Saleh and A. Fadhly(2018) Economic feasibility analysis of agribusiness sub terminal in integrated agricultural program area. The Journal of Perspectives on Financing and Regional Development, DOI: https://doi.org/10.22437/ppd.v5i3.4501

Troll W, Lindsley J. (1955) A photometric method for the determination of proline. Journal of biological chemistry, 215(2), 655-660.

Tuteja, M. and Dubey, G. (2012) A Research Study on Importance of Testing and Quality Assurance in Software Development Life Cycle (SDLC) Models. International Journal of Soft Computing, 2, 251

Wahid A, Gelani S, Ashraf M, Foolad M (2007) Heat tolerance in plants: an overview. *Environ. Exp. Bot.* 61, 199–223. Doi: 10.1016/j.envexpbot.2007.05.011

Walkley A (1947) A Critical Examination of a Rapid Method for Determining Organic Carbon in Soils – Effect of Variations in Digestion Conditions and of Inorganic Soil Constituents. Soil Science, 63(4): 251-264

https://openknowledge.fao.org/server/api/core/bitstreams/e498d73e-1711-4d18-9183-aa8476387e2c/content

Wang QL, Chen JH, He NY, Guo FQ (2018) Metabolic reprogramming in chloroplasts under heat stress in plants. Int. J. Mol. Sci. 2018, 19, 849.

Waraich E, Ahmad R, Halim A, Aziz T (2012) Alleviation of temperature stress by nutrient management in crop plants: a review. *J. Soil Sci. Plant Nutr.* 12, 221–244. Doi: 10.4067/S0718-95162012000200003

Walinga, I., Van Der Lee, J. J., Houba, V. J., Van Vark, W., & Novozamsky, I. (2013) Plant analysis manual. Springer Science & Business Media.

Xu C, Mou B (2015) Evaluation of Lettuce Genotypes for Salinity Tolerance. HORTSCIENCE 50(10):1441–1446. 2015.

Younis TY, Shaimaa H Abd-Elrahman and Mohamed AA Abdrabbo (2021). Equilibrium Content between Nitrogen and Phosphorus for Lettuce (Lactuca sativa L.) Grown in A Clay Soil. Egypt. J. Soil Sci. Vol.61, No. 2, pp. 275-285 (2021)