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Mitigation of the Adverse Effects of Combined Salinity and Heat Stresses on Tomato Plants by Salt Repellent and Anti-stressor Applications

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HIGH TEMPERATURE and salinity are critical abiotic stresses that severely limit tomato production, especially in coastal farmlands of arid and semi-arid regions. The current study was conducted in the north River Nile Delta, close to the Mediterranean Sea coast, to evaluate the performance of tomato plants under combined heat and salinity stresses during the late summer season. Treatments included the application of salt repellent through the irrigation system and/or foliar spray with an anti-stressor. The effect of salt repellent and/or anti-stressor applications on plant growth, photosynthesis activity, antioxidant enzymes activity, flowering and fruit yield as well as fruit quality, was investigated in comparison to untreated plants. Salt repellent contained Ca, fulvic acid, legnosulphenic acid and organic acids; however, the foliar spray anti-stressor contained a solution of Mn and amino acids (lysine, proline, glutamic and glycine). The results showed a significant reduction by applying both salinity repellent and anti-stress in soil salts by about 26.5 and 13.2% in both seasons, respectively compared to the control treatment. Results showed that untreated plants were highly affected by heat and salinity, exhibiting reduced growth, photosynthetic activity, and yield. However, the studied anti-stressors improved plant growth, biomass, leaf area, photosynthesis, antioxidant enzymes activity, proline content, flowering attributes, and fruit yield and quality. Total fruit yield was increased by 25.2 –2 34.6% when the plant was treated by a salt repellent and by 10–24% with foliar spray by anti-stressor and by 14–22% with the combined treatment of salt repellent and anti-stressor application. These ratios were also achieved for water productivity and the extent of utilization of the cubic meter used for irrigation. These findings emphasize the role of anti-stressors in mitigating heat and salinity impacts on tomato, suggesting that further research should optimize formulations and application methods to improve crop adaptation under combined environmental conditions to support small farmers in the affected farmlands.

Keywords: Amino acids, Calcium, Manganese, Biochemical aspects, Fruit yield, Fruit quality.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated horticultural crops globally, valued for its nutritional, economic, and industrial significance (**Espinosa-Antón et al., 2025**). Tomatoes are grown worldwide in about 5412458 ha producing 192317973.01 tons with an average yield of 35.53 tons/ha (**FAOSTAT, 2025**). However, Egypt is the fifth-ranked producer with about 6.21 million tons from 155,874 ha total area with 39.85 tons /h as average yield. Environmental challenges, especially heat stress and salinization, which are becoming more severe due to climate change, have a significant impact on tomato production (**IPCC, 2021; FAO, 2022**). The stability and durability of tomato yield are in jeopardy due to rising global temperatures and increasing soil salinization, which present significant obstacles to food security in many areas. Additionally, rising sea levels are linked to global warming, which has an impact on the soil's ability to produce crops by increasing groundwater in the surrounding areas (**Rotzoll and Fletcher, 2012**). The South Mediterranean Sea region is considered a hot spot of climate change **(Alessandri et al., 2014)**. This region is characterized by high summer temperature, high solar radiation, and low relative humidity **(Sharaf-Eldin et al., 2024)**. Furthermore, the coastal area suffers from high sea level which reflects on high groundwater level and soil salinization problems. In Egypt, the northern River Nile Delta farms, which are close to the Mediterranean Sea, are the typical picture of this scenario. This area is well-known for its tomato cultivation. During the last decade, it was noticed that tomato production was severely affected by these conditions, in addition to the intense insect attack

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during the summer **(Sharaf-Eldin, 2015)**. Also, irrigation water quality was deteriorated as it became closer to the coast of the Mediterranean Sea **(Saffan et al. 2024)**.

Despite their moderate temperature requirements, tomato is thought to be a sensitive plant to heat stress **(Islam, 2011)**. Heat stress can occur beyond the ideal range of 25–30 °C **(Harel et al., 2014)**. Although tomato growth and development are affected by heat stress, the most sensitive stages are flowering and fruit set **(Bayoumi et al., 2025)**. Pollination failure is expected due to the low pollen viability and style elongation, as well as the flower cannot transfer to the fruit set stage and frequently results in dropping off **(Kafizadeh et al., 2008; Sharaf-Eldin et al., 2023)**. Tomato fruit set is optimal at 21–29 °C, but temperatures above 32–35 °C (day) or >24 °C (night) markedly reduce yield by 34–50% (**Sato et al., 2001**). Recent studies showed even greater losses of 52–85% under 35–38 °C with warm nights (>24 °C) (**Ayankojo and Morgan, 2020).** Moreover, the imbalance of hormones and enzyme activity negatively affects photosynthetic efficiency **(Zhou et al., 2016)**. Thus, these complex circumstances ultimately lead to the low yield and quality as reported by **Sharaf-Eldin (2015)** and **Sharaf-Eldin et al. (2023 & 2024)**.

Salinization has become an urgent issue facing agricultural production as the salt-affected area ranged of 20% of the total agriculture land to 33% of the irrigated land **(Shrivastava and Kumar, 2015)**. Soil or water salinization as a major abiotic stress restricts tomato development by causing osmotic stress, ionic toxicity (primarily due to Na^+ and $Cl^−$ ions), and nutritional imbalances (**Cuartero and Fernández-Muñoz, 1999; Munns and Tester, 2008**). The reduction in water uptake, photosynthesis, and disruption of the essential enzymatic activities for plant metabolism is a direct effect of high salinity level (**Zhu, 2001; Flowers, 2004**). When soil electrical conductivity exceeds 2.5 dS/m, tomato development and yield are anticipated to be reduced **(Shannon and Grieve, 1999).** Similarly, salinity stress progressively decreases tomato yield, with reductions of around 7–10% per unit increase in salinity above the threshold level (**Karaca et al.**, 2023). Under the late summer season in this region, the plant faces complicated stresses including salinity, heat, waterlogging, and insect attack. The harmful effect will be higher than suffering from one stress; to protect itself from the injury, it will require several adaptation strategies **(Rivero et al., 2014; Suzuki et al., 2014)**. These techniques include adjustment of physiological and biochemical processes as osmoses, hormone activity, enzymatic activity, and oxidoreductase **(Mittler, 2006).**

Some strategies were studied to ameliorate salinity stress, including the application of amino acids, calcium (Ca), and manganese (Mn). Amino acids especially proline and glutamic as foliar application have a role in improving osmoprotection and Reaction oxygen species (ROS) scavenging which was investigated by **Ashraf & Foolad (2007)** and **Hasanuzzaman et al. (2018).** Calcium is essential for lowering Na^+ toxicity, maintaining membrane integrity, and selectively ion absorption, therefore both soil and foliar calcium applications can improve K^+/Na^+ homeostasis and growth that have been observed in plants cultivated in high salinity environments (**Tavakkoli et al., 2011; Shahbaz et al., 2013).** Manganese application was reported as an effective treatment to reduce the negative effect of salinity on tomato by activating antioxidant enzyme activity and reducing oxidative **stress (Khan et al., 2013; Fahad et al., 2015). El-Henawy et al., (2024)** concluded that applying 75% of gypsum requirements as nano –gypsum is more efficient than using 100% conventional gypsum.

Even though the impact of climate change on food production has been extensively investigated over the past decade, more effort is still needed to modify agricultural techniques for the most severely impacted crops in certain climate change focal areas to accommodate varying farmer capacities. So, we are trying at the current study to investigate how climate change affects tomato production grown close to the Mediterranean Sea coast during the most difficult period of the year (late summer season) as the plants suffer from complex stressors. Moreover, we tried to suggest some strategies to mitigate the negative effect of combined stress (heat and salt) and consider their effect on tomato plant growth, flowering, biochemical parameters and fruit yield and quality.

Therefore, this study is attempting to ascertain how climate change impacts tomato production near the Mediterranean Sea coast at the most challenging time of year (late summer season), when the plants are subjected to numerous stresses. Additionally, this work was attempted to suggest some strategies to mitigate the negative effect of combined stress (heat and salt) for sustaining productivity, coping with future changes of climate, considering their effect on tomato morphological, physiological, biochemical, yield and fruit quality characteristics by using salt repellent through the irrigation system and/or foliar spray with an anti-stressor.

2. Materials and Methods

2.1. Plant materials and site location

A field experiment was conducted at private farm of El Burolos, Kafr El-Sheikh Governorate, Egypt (N 31° 35′ 15.1″, E 31° 02′ 39.1″ and elevation of about 1.0 m) during the late summer seasons of 2023 and 2024 as shown in Fig. 1. 023 F_1 tomato hybrid (Gaara Seeds Company Cairo, Egypt, exported from Sakata Vegetable Europe, Uchaud France https://sakata-vegetables.eu) was choice for planting due to its ability to fruit set under heat stress conditions which it is common during this period of the year. The seeds were sown in Styrofoam seedlings trays (209 cells) for 35 days in a nursery covered by insect-proof net-house. The common practices for irrigation, fertilization and pest control were followed. Tomato seedlings were transplanted in the open field on 10th July, 2023 and on 3rd July, 2024 and the end of seasons were 16th and 9th November in the same year, respectively.

Fig. 1. Experimental Location .

Table 1. Soil and irrigation water properties before experimenting.

Type	Season	EC (dS/m)	pH	Soluble cations (mmol L^{-1})				Soluble anions (mmol L^{-1})			
				Na^+	K^+	Ca^{++}	Mg^{++}	$CO_3^=$	HCO_3^-	Cl^-	$SO_4^=$
Soil	1	4.19	8.73	20.97	0.72	7.2	13.8	0.0	15.4	17.0	10.29
	2	4.54	8.32	21.72	0.78	10.0	14.0	0.0	`16.0	18.6	11.9
Water	1	1.62	7.26	8.75	0.30	2.8	4.6	0.0	4.4	8.3	3.45
	2	1.76	7.42	9.79	0.32	3.0	4.8	0.0	4.8	9.6	3.51

Experimental conditions

Tomato seedlings were transplanted in the open field and the area was divided into plots with 45 m^2 each. Every plot had three ridges (10 m in length and 1.5 m in width) and one more ridge was considered as interval between the plots. A drip irrigation system was set up with lateral of 16 mm diameter with GR emitters spaced at 40 cm. Fertilization, irrigation, pest control and other agricultural practices were followed the Egyptian Ministry of Agriculture and Land Reclamation's recommendations, 2022. Soil and irrigation water properties and climate conditions are shown in Table (1 & 2). Crop evapotranspiration was assessed using CROPWAT 8.0 (Food and Agriculture Organization/United Nations Model) using the procedure outlined in FAO No. 56 by **Allen et al. (1998)**. The prediction was made under the optimal conditions. The model determines crop water requirements (CWR) or actual crop evapotranspiration (ETc), actual effective precipitation, and irrigation requirements. ETc is determined as the product of reference evapotranspiration (ETo) and the representing crop coefficient (Kc) as shown in equation (1).

$$\mathrm{ETc} = \mathrm{ET_o} \times \mathrm{K_C} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The climate data in this program was modified according to the experimental area and was taken from NASA's Power program (https://power.larc.nasa.gov/). Baltim meteorological station average climatic data, analyzed using the Penman-Monteith methodology, formed the basis of the irrigation scheme. Climate, crop stage, and crop type are the three main factors that affect the crop coefficient. The crop coefficients (Kc) for various crops are reported in **Doorenbos and Pruitt (1977) and FAO (1986)**. In this study, crop coefficients of 0.45, 0.75, 1.15, and 0.80 were chosen for the initial [Kc_{ini}], crop development [Kc_{develp}], mid-season [$Kc_{md\text{-}s}$], and late-season or harvest stage [Kc_{hst}] growth periods of tomato, respectively. In used drip irrigation system daily reference evapotranspiration (ETo) and crop coefficient (Kc) readings were used to determine actual crop evapotranspiration (ETc) and (IWR) using the equation (2). The computed ETc was then used to estimate the daily irrigation water needs using the relationship presented by **Sharma et al., (2023)** as following:

$$\mathrm{IWR} = \mathrm{ET_C} \times \mathrm{W_P} \times \mathrm{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

Where:

IWR = Irrigation water requirement (liter plant^{-1} day^{-1}), ETc = actual crop evapotranspiration (mm day^{-1}, Wp= Wetting fraction (taken as 1 for most cases in close growing crops), A = Plant area, m^2 (i.e. spacing between rows, m x spacing between plants, m). Field efficiency was used as 85% for drip irrigation (**Irmak et al. 2011).** The IWR added during the two seasons was found to be 5803.06 m^3/ha for the 2023 season and 6026.19 m^3/ha for the 2024 season.

Table 2. The average meteorological data for the experimental area during the growing seasons.

Season	Month	Temperature, (°C)			Relative Humidity (%)	Wind Velocity (m/s)	Rainfall (mm/month)	ETo (mm/day)
		Max.	Min.	Average				
Summer, 2023	Jul.	37.57	23.57	30.57	64.38	3.35	0.00	7.24
	Aug.	36.27	24.55	30.41	64.02	3.41	0.00	6.94
	Sep.	37.01	24.51	30.76	62.93	3.73	0.06	6.67
	Oct.	33.14	21.99	27.57	62.13	2.84	1.28	4.92
	Nov.	31.69	15.32	23.51	63.51	3.46	9.52	4.31
Summer, 2024	Jul.	36.05	24.94	30.50	64.38	3.42	0.00	7.10
	Aug.	34.02	24.93	29.48	64.02	3.83	0.00	6.80
	Sep.	37.34	23.69	30.52	62.93	3.82	0.00	6.77
	Oct.	31.00	20.35	25.68	62.13	3.01	0.00	4.69
	Nov.	26.71	15.14	20.93	63.51	3.10	7.14	3.41

Water Productivity (WP)

WP was defined as the ratio between the actual crop yield and the total water use, in kg.m^{-3} **(Pereira, et al. 2012)** as follows: $WP=(Ya\ /\ TWU)$, where, "WP is the water productivity, kg.m^{-3}; Ya is the total yield, kg/ha; and TWU is the total water use, m^3/ha."

2.2. Treatments

As shown in Fig 2, four treatments were applied during the plant growth in the field as follow:

A. Control (common agricultural practices)

B. Anti-stressor (AS)

The plants were foliar sprayed with Safo Antistress ™ (MnO 10% + amino acids 35.5% including lysine, proline, glutamic, glycine) three times starting two weeks after transplanting with two weeks' intervals at the concentration of 2 g/l.

C. Salt repellent (SR)

Safo Sal (CaO 14% + N 8% + fulvic acid 5% + legnosulphenic acid 10% + organic acids 20%) was used as soil application. 2.4 litre per hectare of the product were injected through drip irrigation system three times starting two weeks after transplanting with two weeks' intervals.

D. A+B combination

The used products are purchased from Al Safwa Chemicals Company (3, Industry City, Balim, Kafr El-Sheikh, Egypt).

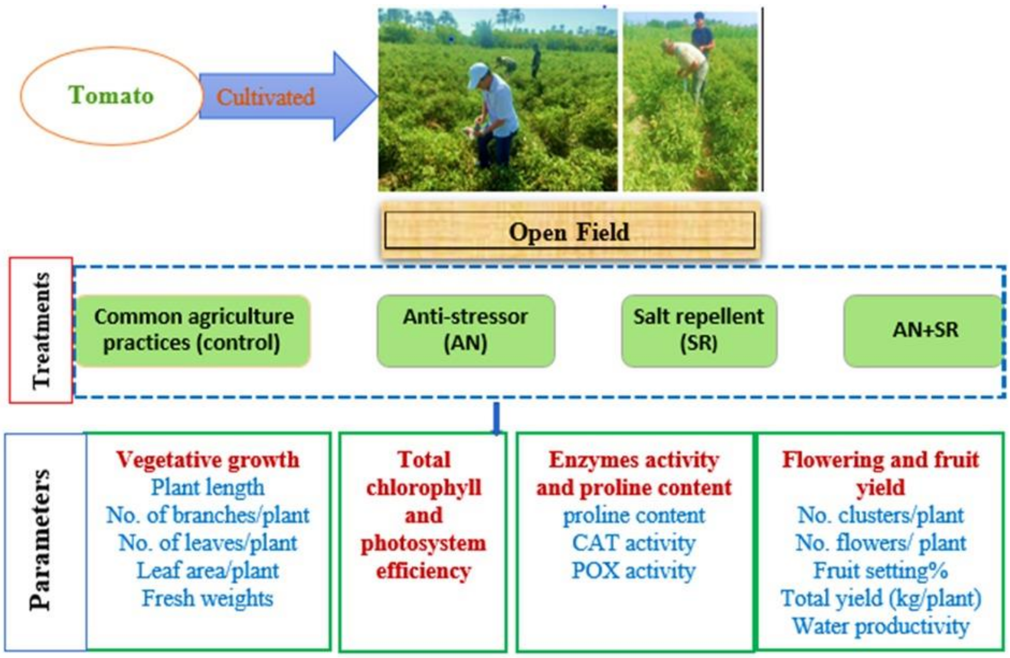

Fig. 2. General overview of the current experiment and studied parameters.

2.3. Data recorded in the experiment

Five random plants were selected form each plot to measure vegetative growth parameters at 60 and 75 days after transplanting (DAT). The parameters included plant length (cm), number of branches, number of leaves and plant parts (roots, leaves and stems) fresh and dry weights (g). Plant leaf area (dm^2) was measured in the first maximum expanded leaves from the plant tips via a portable leaf area meter (CI-202, Portable Laser, made in USA). Chlorophyll content was assayed by SPAD meter (Opti-Sciences, CCM-200 plus, USA). To determine the maximum efficiency of the photosystem (Fv/Fm) a portable Optic-Science OS-30p+ Fluorometer (Opti-Sciences, Inc., Hudson, New Hampshire, USA) was used at 90 DAT **(Maxwell and Johnson, 2000).**

At 75 DAT, some biochemical traits were assessed measured in Plant Physiology and Breeding of Horticultural Crops Lab., Horticulture Department, Faculty of Agriculture, Kafrelsheikh University, Egypt (Accredited according to ISO/17025). Proline content (mg. g^{-1} FW) was assayed according to the described method by **Bates et al. (1973)**. However, Catalase activity (CAT) was determined as Umg^{-1}FW min-1 **(Aebi, 1984)**. Peroxidase enzyme activity (POD) was evaluated as µg. g^{-1} FW min^{-1} by tracking the guaiacol oxidation-related shift at 470 nm absorbance as described by **Polle et al. (1994)**. The amount of H_2O_2 that was broken down by both enzymes was used to calculate the enzyme activity.

To determine fruit setting, the percentage of the number of successful fruit setting in relation to the total number of flowers was counted in five random plants from each plot at 75 DAT. The total fruit yield was concluded all harvested fruits from each plot and was attributed to ton/ ha (Three harvests of tomatoes). To evaluate fruit quality, fifty fruits were randomly chosen from each plot during the peak of harvesting time (middle harvest). The physical and chemical quality aspects of the fruits containing, fruit firmness (gcm^{-2}), total soluble solids (TSS %), titratable acidity (TA %), vitamin C, lycopene, β-carotene and nitrate content. Fruit firmness was assessed by a hand penetrometer **(Radusin et al., 2013)**. Total soluble solids (TSS %) was measured in fruit juice by a digital refractometer (model RFM 340 –T) according to **Ilić et al. (2015)**. To assay titratable acidity (TA %), automatic titration (model TTROLINEE®TL 5000/20M2 BASE UNIT, 20 ML TZ 3130) was used to measure citric acid % in fruit juice by titration with 0.1N sodium hydroxide **(Tigchelaar, 1986)**. However, to determine vitamin C (mg/100g fw), 2, 6-dichlorophenol indophenol was used in titration according the described method by **A. O. A. C. (1990).** Colour-meter method with spectrophotometer at 663, 645, 505 and 453 nm was used to determine lycopene and β-carotene contents (mg.g^{-1}fw), according to **Nagata and Yamashita (1992)**.

2.4. Experimental design and statistical analyses

The experiment was conducted in four replicates each one had 4 treatments. The treatments were randomly distributed in each block as randomized complete blocks design was used. The statistical analysis was followed by the recommendation of **(Snedecor and Cochran, 1989)** with one-way analysis of variance (ANOVA). After that, the treatment means were compared using Duncan's multiple range test **(Duncan, 1965)**. CoStat program software (Version 6.311) was used for statistical analyses.

3. Results

3.1. Soil salinity and soil pH

The results in Table (3) indicate that there are highly significant differences when adding a salt repellent, an anti-stressor, or a combination of both compared to the control treatment without any addition. The results indicate a decrease in total soil salinity when the salt repellent was added, followed by a decrease when the combination of salt repellent with the anti-stressor. However, soil salinity was not affected by the addition of the anti-stressors alone, and soil salinity increased under the control treatment at the end of the experiments in both seasons. Also, soluble Ca^{+2} was increased with adding salt repellent and the combined application of salt repellent and anti-stressor while, Mg^{+2} and Na^{+} were decreased. Soluble Cl^{-} showed the same trend as Na^{+}. Salt repellents improve soil structure and facilitate the removal of dissolved salts, which reduces overall soil salinity and increases the discharge of harmful ions such as sodium (Na^{+}). Salt repellents, which containing calcium (Ca^{2+}), can remove excess sodium (Na^{+}) from clay surfaces, preventing salinization. Displacing sodium from clay exchange sites leads to a decrease in dissolved sodium ions in the soil solution. Increasing the calcium (Ca^{2+}) content helps improve soil structure and improve its porosity and permeability by replacing sodium ions.

Table 3. Response of soil salinity and soil pH under combined stress conditions (heat and salt stress) in the late summer season for anti-stress treatments.

Season	treatments	EC, dS/m	pH	Soluble cations (mmol L^{-1})				Soluble anions (mmol L^{-1})			
				Na^{+}	K^{+}	Ca^{++}	Mg^{++}	$CO_3^{=}$	HCO_3^{-}	Cl^{-}	$SO_4^{=}$
1	Control	4.96a	7.7	23.97a	0.72	10.2a	16.8a	0.0	15.4a	25.0a	11.29
	AN	4.25b	8.3	21.14b	0.65	9.2b	12.8b	0.0	14.8b	19.6b	9.39
	SR	2.66d	8.32	16.22d	0.35	6.20d	4.0d	0.0	6.2d	11.5d	9.07
	AN + SR	3.35c	8.27	18.67c	0.50	8.8c	5.8c	0.0	7.8c	15.0c	10.97
	F. test	***	-	***	-	***	***	-	***	***	-
2	Control	5.24a	8.32	23.33a	0.88	13.0a	15.8a	0.0	16.2b	24.0b	12.81
	AN	5.00b	8.62	22.26b	0.77	12.4b	15.2b	0.0	18.8a	24.6a	7.23
	SR	2.95d	8.44	13.50d	0.46	8.8d	7.6d	0.0	14.0c	15.0c	7.76
	AN + SR	3.64c	8.34	18.67c	0.6	9.0c	8.2c	0.0	12.2d	14.0d	10.27
	F. test	***	-	***	-	***	***	-	***	***	-

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

3.2. Vegetative growth

Data in Table 4 indicate that the studied vegetative growth parameters including plant length, number of branches per plant, number of leaves per plant and plant leaf area of the tomato plant studied at 60 and 75 DAT significantly affected by the application of the studied treatments. Generally, the treated plants had higher growth than the untreated ones in both planting dates for both growing seasons, except in the case of plant length at 60 DAT in 2023and number of leaves at 75 DAT in 2023 where the differences were insignificant among the studied treatments. The application of salt repellent and the combined treatment between salt repellent and anti-stressor foliar spray had the best results.

Table 4. Response of plant growth of tomato grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments.

Treatments	Plant length (cm)		No. of branches/plant		No. of leaves/plant		Leaf area/plant (dm^2)	
	Days after transplanting (DAT)							
	60	75	60	75	60	75	60	75
	2023 season							
Control	105.0a	122.7b	8.7 b	14.7c	34.7c	65.0a	61.2d	117.2b
AN	107.3a	117.7b	10.0b	24.7a	44.0b	72.7a	72.1c	151.5a
SR	106.3a	129.3a	19.0a	24.3a	45.7b	70.0a	82.7b	157.0a
AN + SR	105.0a	132.3a	9.0b	16.7b	52.7a	72.3a	93.9a	156.3a
F. test	NS	**	***	***	**	Ns	**	***
	2024 season							
Control	95.0c	117.7b	8.7c	14.7c	33.0c	61.0b	65.4c	114.5c
AN	97.7bc	121.3b	9.3c	24.7a	41.3b	65.0ab	69.2b	133.5b
SR	108.3a	133.3a	16.0a	24.3a	46.3ab	66.7ab	84.3a	150.4a
AN + SR	104.0ab	131.7a	11.0b	16.7b	47.3a	71.0a	79.4a	151.4a
F. test	**	*	***	***	**	*	***	**

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

Fresh and dry weights partitioning for plant roots, leaves and stems at 75 DAT were significantly affected by anti-stress treatments (Table 5). The leaves obtained the highest portion of fresh and dry weights followed by stems then roots. Data indicate that all treatments produced higher biomass in comparison with the control in both growing seasons. However, the combined treatment of snit-stressor and salt repellent mostly had the highest value followed by salt repellent treatment. In the case of dry matter, foliar spray with anti-stressor produced the highest dry matter of the roots in both growing seasons while in the case of leaves dry matter, salt repellent was the best. Whereas the maximum stem dry matter was found in the combined treatment.

Table 5. Response of fresh and dry weights partitioning of tomato plant grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments.

Treatments	Fresh weights (g)			
	Roots	Leaves	Stems	Plant
	2023 season			
Control	95.3c	1127.0c	425.3d	1687.3c
AN	127.7a	1196.7b	465.0c	1746.7b
SR	107.7b	1258.0a	584.7b	1955.3a
AN + SR	117.0a	1180.0b	654.0a	1951.0a
F. test	***	***	***	***
	2024 season			
Control	93.3c	1043.3b	401.7d	1538.3c
AN	103.0b	1146.7a	424.0c	1673.7b
SR	105.7ab	1200.0a	585.7a	1891.3a
AN + SR	109.7a	1226.7a	534.7b	1871.0a
F. test	**	**	***	***
Treatments	**Dry weights (g)**			
	Roots	**Leaves**	**Stems**	**Plant**
	2023 season			
Control	7.4c	74.6c	28.6c	110.6b
AN	10.5a	84.2b	30.8b	125.5a
SR	7.5c	94.3a	31.5b	133.3a
AN + SR	8.9b	81.7bc	35.0a	125.5a
F. test	***	**	**	**
	2024 season			
Control	6.1c	68.6c	26.4a	101.1c
AN	9.0a	74.0b	26.9a	109.9b
SR	7.3bc	77.5a	29.9a	114.7a
AN + SR	8.4ab	73.3b	30.6a	112.3ab
F. test	*	**	**	***

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

3.3. Total chlorophyll and photosystem efficiency

The indices for photosynthesis efficiency were considered as chlorophyll content and photosystem measurements (Table 6). All studied treatments significantly improved photosynthesis indices compared with the untreated control in both growing seasons. Even though salt repellent provided darker leaves (SPAD), the combined treatment of foliar spray with anti-stressor and salt repellent was the most effective treatment for improving photosystem efficiency (Fv/Fm) under heat and salt stresses during both growing seasons.

Table 6. Response of chlorophyll content and photosystem efficiency of tomato plant grown under combined stress conditions (heat and salt stress) in the late summer season for anti-stress treatments.

Treatments	Chlorophyll content (SPAD)		Photosystem efficiency (Fv/Fm)
	Days after transplanting (DAT)		
	60	75	60
	2023 season		**2023season**
Control	28.4b	31.2c	0.711b
AN	31.5ab	28.6c	0.710b
SR	33.6a	36.7a	0.703b
AN + SR	30.9ab	29.8bc	0.749a
F. test	*	***	**
	2024 season		**2024 season**
Control	29.6b	30.1c	0.742bc
AN	31.4b	33.4b	0.734c
SR	35.1a	35.6a	0.752b
AN + SR	31.3b	33.4b	0.775a
F. test	*	***	**

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

3.4. Enzyme activity and proline content

Results presented in Fig. 3 illustrate that proline content, CAT activity, and POX activity were significantly affected by the application of studied anti-stress treatments under heat and salt stress conditions, except in the case of CAT which the significant difference was not detected in the first growing season. All studied treatments were higher than the untreated control. The injection of salt repellent throughout the irrigation system or when combined with anti-stressor foliar spray showed the most effective treatments for increasing proline content and enzyme activity of CAT and POX.

3.5. Flowering and fruit yield

The results in Table 7 indicate that all studied treatments significantly improved flowering characters and fruit yield compared to the control in both growing seasons. Whereas the differences were not statistically detectable in the case of the number of flower clusters per plant in both growing seasons and the number of flowers in the first season only. The highest registered values of flowers number, fruit set percentage, and fruit yield were obtained from the injection of salt repellent throughout the drip irrigation system. However, the untreated control had the lowest values. Fruit set percentage increased from 67.5 and 70.8 with the control to 77.1 and 78.6 with salt repellent treatment, in the first and second seasons respectively. However, the total fruit yield increased from 37.60 and 48.12 tons/ha with the control to 57.47 and 64.311 tons/ha with salt repellent treatment.

Also, the water productivity increased from 6.48 and 8.35 kg/m^3 with the control to 9.90 and 10.67 kg/m^3 with salt repellent treatment.

3.6. Fruit quality

Data in Table 8 show that average fruit weight, fruit firmness, and total soluble solids (TSS%) were significantly affected by the application of anti-stress treatments with the exception of TSS% in the second season only where the differences were insignificant. The individual treatment of salt repellent injection or in the combination with anti-stressor as foliar spray produced the highest average of fruit weight while the control had the lowest values. Regarding fruit firmness, the combined treatment obtained the highest values with insignificant differences from the control. However, the anti-stressor foliar spray recorded the lowest value.

According to the obtained data, the fruits from the treated plants with salt repellent throughout the irrigation system had the highest content of total soluble solids. However, when the plants were foliar sprayed with an anti-stressor either separately or with an injection of salt repellent, they dropped down reaching the lowest, while the untreated plants had intermediate values.

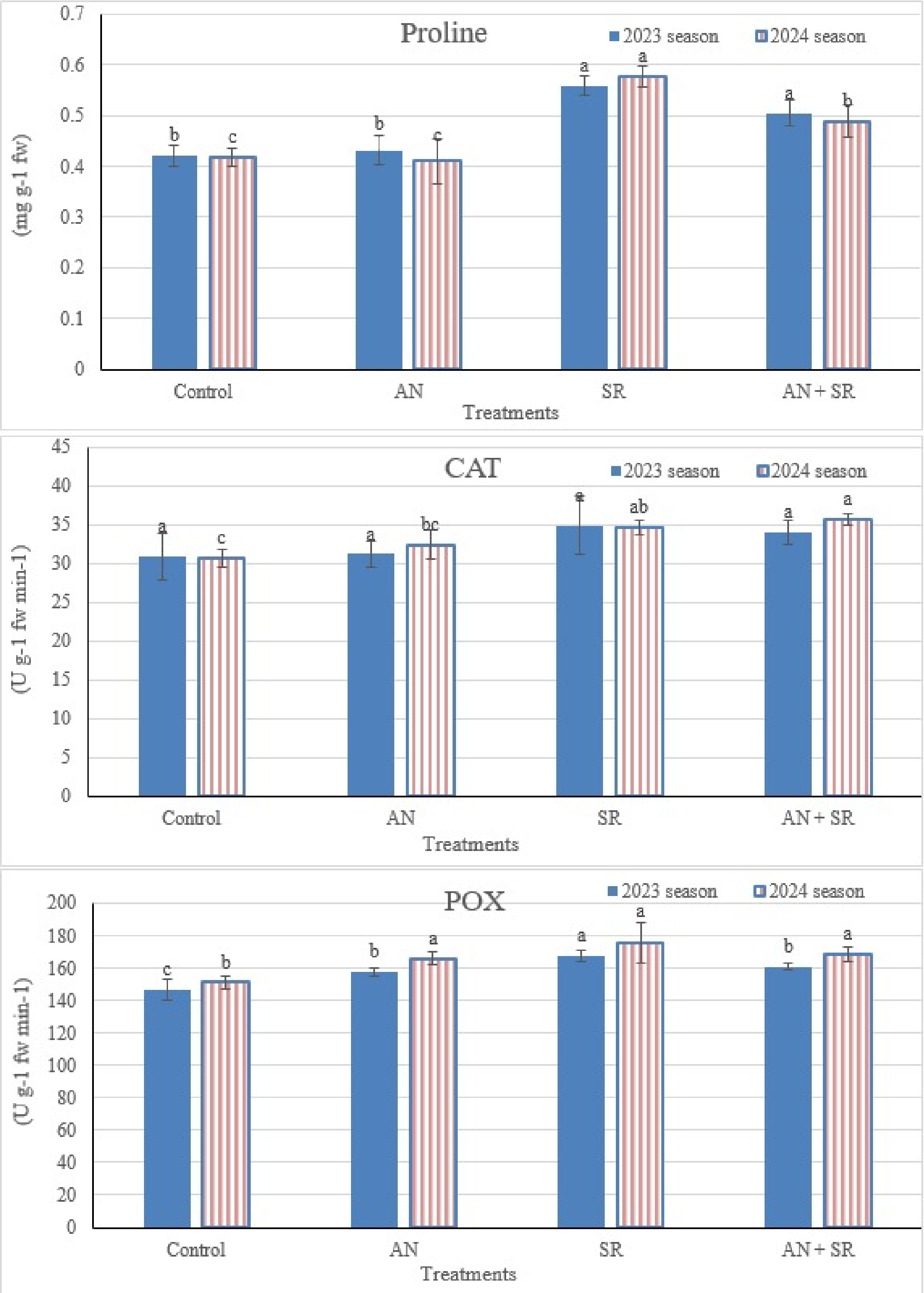

Fig. 3. Response of leaf content of proline, CAT, POX of tomato plant grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments. Different letters indicate significant differences among treatments at p < 0.05 according to Duncan's multiple rang test.

Table 7. Response of flowering attributes and fruit yield of tomato plant grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments.

Treatments	No. clusters/plant	No. flowers/ plant	Fruit setting%	Total yield (kg/plant)	Total yield (ton/ ha)	Water productivity (kg/m^3)
	2023season					
Control	16.7a	74.1a	67.5c	2.67c	37.60c	6.48c
AN	15.0a	72.3a	74.2ab	3.36b	49.72b	8.57b
SR	15.7a	75.6a	77.1a	3.88a	57.47a	9.90a
AN + SR	15.0a	72.2a	73.4b	3.27b	48.44b	8.35b
F. test	Ns	Ns	**	*	*	*
	2024season					
Control	17.3a	72.0b	70.8c	3.25c	48.12c	7.99c
AN	15.0a	80.5a	72.5b	3.60b	53.39b	8.86b
SR	17.0a	80.6a	78.6a	4.34a	64.31a	10.67a
AN + SR	15.7a	79.7a	72.3b	3.77b	55.78b	9.26b
F. test	Ns	*	***	***	***	***

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

Table 8. Response of some fruit quality attributes of tomato plant grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments.

Treatments	Fruit weight (g)	Firmness (g.cm^{-2})	TSS (%)
	2023 season		
Control	63.1c	773.3a	5.1b
AN	68.1b	520.0c	4.8bc
SR	75.8a	656.7b	5.7a
AN + SR	72.7a	830.0a	4.6c
F. test	**	***	**
	2024 season		
Control	62.0c	546.7a	5.3a
AN	64.2bc	498.3b	5.2a
SR	71.5a	560.0a	5.3a
AN + SR	68.7ab	553.3a	4.9a
F. test	**	**	NS

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at p < 0.05 according to Duncan's multiple range test.

According to the obtained data, Table 9 illustrates that all studied chemical quality attributes were significantly affected by the studied treatments except for vitamin C content which the differences were insignificant. These results were true in both growing seasons. It was noticed that the untreated plants (control) produced fruits with higher nitrate content and acidity compared with the treated plants. However, the application of salt repellent decreased the fruit content of nitrate. Whereas, when salt repellent treatment was combined with foliar spray with an anti-stressor fruit acidity was decreased. Salt repellent treatment obtained the highest fruit content of lycopene with insignificant differences from the untreated plant. However, anti-stressor foliar spray separately or in combination with salt repellent treatment lycopene content was significantly decreased. The data about the fruit content of β-carotene indicate that the individual treatments of anti-stressor or salt repellent increased its content in comparison to the control and the combined treatment, with insignificant differences within each group.

Table 9. Response of some chemical quality attributes of tomato plant grown under combined stress conditions (heat and salt stress) in late summer season for anti-stress treatments.

Treatments	Nitrate	Acidity (%)	Vitamin C (mg/100g fw)	Lycopene (mg/g fw)	β-carotene (mg/g fw)
			2023 season		
Control	62.7a	0.592a	20.6a	0.203a	0.026b
AN	58.3ab	0.558ab	22.9a	0.133b	0.039a
SR	43.3c	0.571ab	23.0a	0.225a	0.035a
AN + SR	57.0b	0.477b	23.2a	0.131b	0.026b
F. test	***	*	NS	***	**
			2024 season		
Control	75.0a	0.584a	21.9a	0.205a	0.025b
AN	56.7b	0.476b	22.3a	0.125b	0.038a
SR	41.7d	0.555a	21.6a	0.209a	0.039a
AN + SR	49.3c	0.470b	23.2a	0.136b	0.026b
F. test	***	*	NS	***	**

AN= Anti-stressor / SR= Salt repellent / AN + SR= Anti-stressor + Salt repellent
* and **indicate significant differences at p values < 0.05 and < 0.01, respectively according to F. test. Different letters in the same column indicate significant differences among each group of treatments at $p < 0.05$ according to Duncan's multiple range test.

4. Discussion

Undoubtedly, climate change has been recognized as a negative factor affecting the agriculture sector. During the current investigation, we selected a “hot spot” area for climate change. It is located in the north River Nile Delta, close to the Mediterranean Sea coast, which suffers from high sea level, causing water logging and soil salinization. This region is well-known for growing one of the most important vegetable crops, i.e., tomatoes. It has been noticed that tomato production in this area is failing during the late summer season as it faces complex stressors including water logging, salinity, high temperature, as well as biotic stresses. In order to ameliorate the negative effects of the combined stress (heat and salt), the current study suggested some applicable solutions for the farmers. Our results confirm that climate change affected tomato production during the late summer season as noticed in the control (untreated) plots which the limit plant growth (Tables 4, 5 & 6), yield (Table 8) and quality (Table 9) were present.

It was reported that when temperatures climbed beyond 35 ^{o}C as occurred in the experiment location, heat stress impacted chlorophyll and CO_2 fixation which in turn inhibited photosynthesis **(Sharma and Hall, 2005; Hasanuzzaman et al., 2013). According to Los et al. (1990)**, heat stress increased fluid leakage from plant cells and ROS production while negatively affecting membrane stability. Furthermore, **Dinar and Rudich (1985)** added that high temperature affected stomatal conductivity, photophosphorylation and electron transport in chloroplast. These findings are in harmony with the obtained results which the control plants had the lowest chlorophyll content and photosystem efficiency (Table 6). This reduction obviously appeared in low plant growth (Tables 4 & 5). The harm went beyond the stage of vegetative growth, surpassing both blooming and fruit set (Table 7). According to the results of **Sharaf-Eldin et al. (2023)**, pollination failed as a result of the decreased pollen viability and exserted stigma, resulting in poor fruit set, as seen in Table 5. In consequence, fruit yield and quality were affected (Tables 8 & 9).

As an extra stressor to heat stress, salinity is found in soil and irrigation water of the experiment site (Table 1, 3). Tomato plant grown under salinized soil conditions, its morphological, physiological, biochemical, yield and quality parameters negatively affected **(Bayoumi et al., 2025)**. The grown plant in salinized soil has difficulties absorbing water and nutrients due to the high concentrations of dissolved salts (mainly NaCl) in the root zone causing an osmotic stress **(Shrivastava and Kumar, 2015)**. High evaporation during hot weather, such as the late summer, causes salts to rise by capillary action and accumulate close to the root zone, particularly in areas with inadequate drainage **(Rengasamy, 2006)**. In order to regulate osmosis, the plant absorbs more Na^+ and Cl^-, which can lead to toxicity as seen in morphological changes including leaf necrosis, chlorosis, and dead tissues **(Roşca et al., 2023)**. Through stomatal closure and cell growth inhibition, the plant attempts to minimize damage and reduce water loss. Moreover, oxidative stress commonly happens during salt stress leading to accumulation of reactive oxygen species (ROS), **(Isayenkov and Maathuis, 2019)**. The negative effect of salt stress was appeared in the control plots without any application of anti-stressors. The morphological signs were appeared as low plant growth with little branches, short length, small leaf area, and low biomass (Tables 4 & 5).

Addition to morphological signs, biochemical indices were present reduction in chlorophyll, photosystem efficiency, proline and antioxidant enzymes (CAT and POX) were also noticed (Table 6 & Fig. 2). The negative effect prolonged to the flowering stage and fruit productivity (Table 6 & 7). The obtained results were in agreement with those obtained by **Zahra et al. (2020), Ludwiczak et al., 2021) and Bayoumi et al. (2025)**.

The combination of different kinds of stresses such as heat, salinity and biotic can multiple the deteriorate effect on the plant **(Pandey et al., 2015; Shalaby et al., 2021)**. The synergism impact of different stresses as presences in the current investigate may disturb hormonal and redox balance and increase susceptibility to pathogens attack with complicated signaling leading to detrimental impact of the plant **(Chojak-Koźniewska et al., 2018)**. Our results support these findings which the simulants of heat, salinity and biotic stresses significantly affected plant development, biochemical activity and fruit productivity.

The strategy of our study depended on injecting salt repellent throughout the drip irrigation system, and/or foliar spray of anti-stressor at various growth stages. Salt repellent included high concentrations of calcium, fulvic acid, and organic acids to ensure that calcium would replace sodium cations far from the root zone and enhance beneficial microbial activity in the soil. **Munns and Tester (2008)** reported that Ca^{++} alleviates salinity effect throughout by displacing Na^{+} on the exchange sites of the soil and improving soil structure. Moreover, calcium has a crucial role in plant stress tolerance as it binds the negative charge of phospholipids and lowers membrane leakage, leading to conserving membrane stability **(White and Broadley, 2003**). It also has an essential role on signal transduction pathways, antioxidant activity and ROS reduction in response to high temperature and salinity **(Reddy and Reddy, 2004; Yousuf et al., 2021)**. The favorable effect of calcium effect on plant growth, blooming and fruit set, and productivity well previously investigated as we confirm that as a part of our strategy to mitigate the combined stress (heat and salt) es (Tables 7, 8 & 9). We tried to get a synergism action of adding fulvic acid to calcium with using salt repellent. Under stressful situations, fulvic and organic acids have been reported to lower soil pH and EC, raise soil organic carbon and water retention, and promote root development, nutrient uptake, and total plant biomass **(Canellas and Olivares, 2014; Mosa et al., 2020)**.

Another approach we followed to mitigate combined stress (heat and salt) es is including foliar application of an anti-stressor that contains complex amino acids (lysine, proline, glutamic, and glycine) with Mn. Amino acids application as an anti-stressor is well-documented. The mode of action operates by stabilizing proteins, cell membranes, and subcellular structures, scavenges ROS, signaling route and balances osmotic pressure **(Ibrahim et al., 2020; Shi et al., 2020; Khan et al., 2022)**. Adding manganese to the amino acids may give more benefits for the plant as it noted in an extensive review by **Millaleo et al. (2010)**. According to their findings, manganese is an essential element of photosystem II (PSII) stability, ROS detoxification through Mn-SOD, and lignin generating as an enzymatic cofactor under stress exposure. The activity of antioxidant enzymes such as catalase (CAT), peroxidase (POD), and polyphenol oxidase (PPO) plays a central role in tomato tolerance to abiotic stresses, including salinity and heat. These enzymes, which are proteinaceous in nature and composed of amino acids, mitigate oxidative damage by scavenging reactive oxygen species (ROS). For instance, CAT rapidly decomposes hydrogen peroxide into water and oxygen, POD contributes to the detoxification of peroxides and strengthens cell walls, while PPO oxidizes phenolic compounds into quinones, enhancing plant defense responses. Their synthesis and activity depend on amino acid metabolism, highlighting the interconnection between primary metabolism and stress defense (Mittler, 2002; Gill & Tuteja, 2010).

In parallel, proline, a stress-related amino acid, accumulates in tomato tissues under salinity and heat stress. Proline acts as an Osmo protectant, stabilizing proteins, enzymes, and membranes, while also functioning as a molecular chaperone that preserves the activity of CAT, POD, and PPO under oxidative pressure. Moreover, proline directly scavenges ROS and contributes to redox balance, thereby complementing the enzymatic antioxidant system. Thus, the integration of amino acid-derived compounds like proline with antioxidant enzymes establishes a coordinated defense strategy that enhances tomato resilience to adverse environmental conditions (Szabados & Savouré, 2010; Ashraf & Foolad, 2007).

As an outcome, the current study offers straightforward and useful approaches to reduce combined stress (heat and salt) es for tomato production in a climate change spot area. The application of salt repellent and anti-stressor in the current study contributed to mitigate heat, salinity and biotic stress via improve tomato growth, biomass, photosystem activity, and antioxidant enzymes action which all led to enhance flowering and fruit set, as well as fruit productivity and quality.

5. Conclusions

A significant challenge brought on by climate change is the impact on agricultural productivity in the coastal arid and semi-arid zones, which has resulted in biotic and abiotic stressors. According to the current study, tomato production in the north River Nile Delta during the late summer season is significantly impacted by heat and salinity stresses, as a result of climate change. Applicable solutions could the farmers follow to reduce the harmful impact of late summer stressor including the injection of salt repellent throughout irrigation system

(CaO + fulvic acid + legnosulphenic acid + organic acids) and foliar spray with a solution of MnO + amino acids (lysine, proline, glutamic, and glycine). The studied treatments ameliorate abiotic stresses throughout improve plant growth, photosynthesis efficiency, anti-oxidant enzymes activity, flowering and fruit set attributes and finally reflected on higher fruit yield and quality. In the future, different types of salt repellents and anti-stress agents can be used, for tomato cultivation under high soil salinity with drip irrigation. In order to assist small farmers in the impacted farmlands, further effort is required to provide more practical strategies for dealing with climate change and adapting plants to multi-stresses.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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