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Improved Tolerance of Tomato Plants to High Temperature by Using Some Foliar Applications of Heat Stress Relievers

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ABSTRACT

Increasingly high temperatures are one of the challenges of climate change, which in turn negatively affects the production of horticultural crops. Additionally, heat stress severely reduces agricultural yield worldwide and is one of the main factors restricting plant development. Heat stress can be overcome by using some antioxidants, which have a role in stimulating growth and fruit setting. Two field experiments were carried out during the two successive late summer seasons of 2022 and 2023 in loamy clay soil to study the response of tomato plants cv. F_1 Hybrid K-186 for melatonin, 6-benzylaminopurine, anise oil, jasmonic acid, eugenol, potassium silicate, and control (only water tap) on vegetative growth, fruit set, yield, fruit characters, and some chemical components of tomato plants grown under high temperature conditions. Our results revealed that the treatments of melatonin, 6-benzylaminopurine and potassium silicate had significant increase in early and total yield of tomato plants as well as yield attributes at heat stress in the open field. Spraying of melatonin treatment led to an increase the total yield by 39.65% in the average of the two seasons. Accordingly, it can be recommended that applied melatonin or used 6-benzylaminopurine treatments to improve tomato yield productivity under heat stress conditions in the open field.

Keywords: Climate Changes- Heat stress- Growth and yield of tomato plants

INTRODUCTION

Climate changes in the world will affect the productivity of vegetable crops, especially tomato crops. Moreover, heat waves have increased in intensity, frequency, and duration globally (Perkins et al. 2015). It is important to find applied solutions to improve the tomato crop in Egypt. High temperatures impact several physiological and biochemical processes, ultimately lowering yield and quality (Peet et al.,1997 and Ibrahiem, 2011).

Tomato (*Solanum Lycopersicum* L.) is one of the most important vegetable crops in Egypt and is cultivated all-round the year for local fresh consumption, processing and exportation. It is an important source of several antioxidants due to its fruits containing vitamin C, vitamin E, carotenoids, lycopene, folate, tocopherol, and flavonoids such as quercetin, as well as mineral content such as potassium, magnesium, phosphorous, and calcium with great importance in human metabolic activities (Yeung and Laquatra ,1998 and Naranjo et al., 2016). Egypt is one of the major countries of tomato production and ranked as the fifth largest producing country in the world following China, India, Turkey, and the USA, according to FAO statistics (2022). According to the Egyptian Ministry of Agriculture in 2024, Egypt produced 6.3 million tons in all seasons, while the worldwide production of tomatoes was 186.6 million tons.

Tomato plants are exposed to unfavorable environmental conditions in the late summer, especially high temperatures and large variations in day and nighttime temperatures. These two factors lead to flower abscission and negatively impact fruit set%. Therefore, July and August have poor marketable tomato production. As a result, the tomato price is often expensive at this time (Ibrahiem, 2011). Utilizing biostimulants can enhance plant development by improving nutrient uptake efficiency and plant tolerance to abiotic stress, which in turn increases fruit set, yield, and quality characteristics (Poberezny et al., 2020). In this regard, it was discovered that melatonin (MET), sometimes referred to as N-acetyl-5-Methoxytryptamine, exogenous use by strengthening many defensive systems, MET therapy enhances plant growth and cold tolerance. Exogenous MET enhances plant tolerance to both heat and cold stress in two ways: either directly by scavenging ROS molecules or indirectly by enhancing the activities of antioxidant enzymes, photosynthetic efficacy, metabolite contents, and the expression of genes related to MET and stress-inducible genes in plants (Sharif et al., 2018 and Sun et al., 2021). Qi et al. (2018) discovered that foliar application of MET on tomato plants preserves pollen activity and lowers ROS accumulation by inducing antioxidant enzyme activities under heat stress. Mumithrakamatchi et al. (2024) on tomato found that MET application under heat stress significantly increased the number of fruits, fruit set percentage, fruit yield and quality of fruits through increased lycopene, carotenoid, and ascorbic acid content as well as titratable acidity compared with the stress control.

Notably, 6-Benzylaminopurine (BAP) is a first-generation synthetic cytokinin that elicits plant growth and development responses flowers to improve fruit quality and prevent plant respiratory kinase from working (Siddiqui et al., 2011). Suliman et al. (2024) mentioned that application of BAP on tomato genotypes *viz.*, Castlerock, Fayrouz F_1, and GS 12 F_1 plants enhanced the ability of tomato plants to withstand high temperatures and improved plant height, stem diameter, number of leaves, proline contents, and improved fruit quality as well as total yield under heat stress.

Treating plants with eugenol (Eug) and anise oil (AO) is an eco-friendly way to increase their tolerance to abiotic stressors. The possible role of eugenol in regulating plant physiology in response to environmental stresses is still little understood (Sun et al., 2017 and Zhao et al., 2022). Using eugenol and anise oil treatments on tomato plants under heat stress and antiviral caused a significant increase in salicylic acid and jasmonic acid and enhanced the tolerance of tomato plants to TYLCTHV infection compared to control (Tsai et al., 2019).

The natural plant jasmonic acid (JA) is found in all plant species and regulates a variety of physiological processes within plants such as fruit ripening, root growth, pollen formation, and seed germination (Zhang et al., 2011). When tomato plants are exposed to jasmonic acid, they undergo phytochemical alterations such as defensive proteins, polyphenol oxidases, and protease inhibitors in tissues of tomato plants (Koiwa et al. ,1998).

Furthermore, potassium silicate functions as an anti-transpirant, forming a double layer that lowers transpiration in plants, and an antioxidant on heat-stressed plants (Freitas et al., 2011). Silicon (Si) is considered the most abundant element in the Earth's crust. Although it is not considered an essential element in plant nutrition, it is very useful when plants are exposed to environmental stresses (Debona et al., 2017). Potassium silicate foliar spray on tomato had significant chlorophyll content and fruit characters as well as total yield under heat stress (Abou El-Nour and Badran, 2023). The goal of this research is to reduce the negative effects on tomato plants and improve growth, fruit set, yield, and quality characteristics under conditions of heat stress by applying some treatments in the open field to increase heat tolerance of tomato plants , which reflects on fruit setting and finally on yield and quality.

MATERIALS AND METHODS

Two field experiments were carried out during the two successive late summer seasons of 2022 and 2023 in clay soil at Kaha Vegetable Research Farm, Horticulture Research Institute, Agriculture Research Center, Qalubia Governorate Egypt, to study the effect of spraying with some eco-friendly treatments on the morphological and metabolic performance of tomato grown under high temperature in open field conditions.

1. Experimental design:

Seeds of tomato (*Solanum Lycopersicum* L.) F_1 Hybrid K-186 (produced by Green Seeds Company, Holland) were sown on 26th and 30th April of 2022 and 2023 seasons, respectively, in seedling trays (209 cells) filled with a mixture of peat moss and vermiculite (1:1 v/v) under unheated greenhouse conditions. The seedlings were transplanted on 2nd and 4th June in the 1st and 2nd seasons, respectively in a randomized complete block design with three replicates. The soil type of the experimental area was loamy clay. Each plot area was 10.5 m² (the plot consisted of three rows, each row was 1.0 m wide and 3.5 m long) with a spacing of 40 cm between plants. One row was left without planting as a guard between plots to avoid the interference of various treatments. Common cultural practices concerning tomato production, such as surface irrigation, fertilization, weed control and pest management were conducted whenever necessary according to the recommendation of the Egyptian Ministry of Agriculture and Land Reclamation. The meteorological data during the two late summer seasons of this work, obtained from the Central Laboratory for Agricultural Climate, Agricultural Research Center, Ministry of Agriculture and Land Reclamation, are shown in **Figs. (1 and 2).**

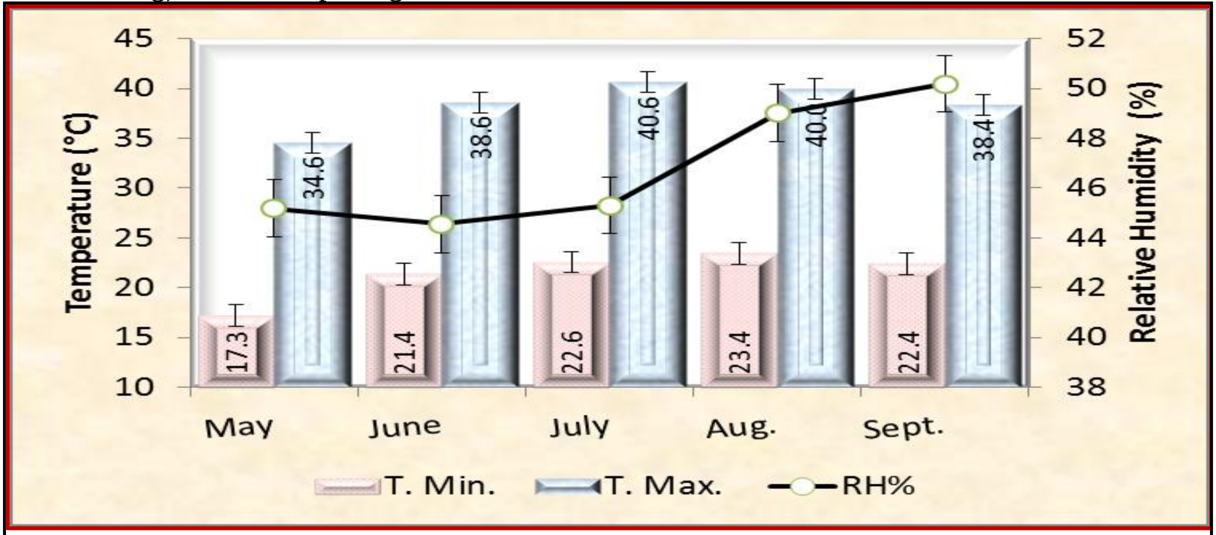

Fig.(1). Average of two the seasons day and night temperatures for the study months.

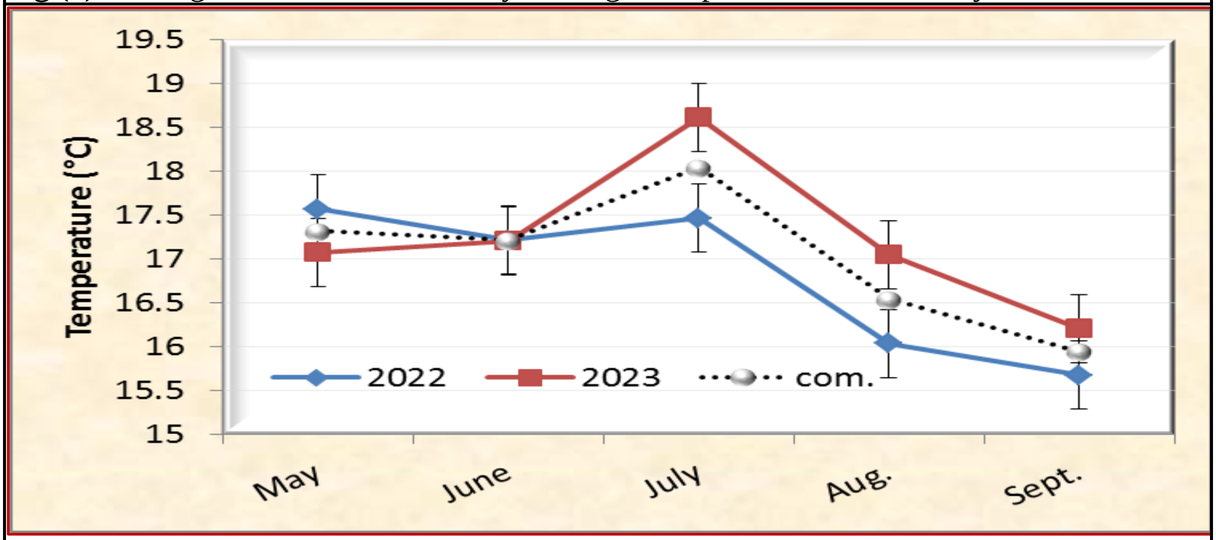

Fig.(2). Average monthly differences between day and night temperatures in both seasons.
com. (Average difference between day and night temperatures in the two seasons).

The experiment included the seven following treatments:

1- Melatonin (MET) at 100 ppm.
2- 6-Benzylaminopurine (BAP) at 800 ppm.
3- Anise oil (AO) at 0.5 %.
4- Jasmonic acid (JA) at 300 ppm.
5- Eugenol (Eug) at 100 ppm.
6- Potassium silicate (PS): (silica 25% + potassium 12%) at $2cm^3/l$.
7- Control (only water).

Tomato plants were sprayed four times during the growth period, where the first spray was conducted at the beginning of flowers initiation (28 days after transplanting) and repeated three times each 15-day intervals.

1. Data recorded:

Growth parameters: A random sample of five tomato plants was taken from each plot after 70 days of transplanting to estimate plant height, total number of branches per plant and both fresh and dry weight of both leaves and stems, as well as average stem diameter.

Flowering and fruit set: The number of days from transplanting to 50% flowering per plot and fruit set percentage average were taken for the first four clusters per plant. The fruit set data were recorded as an average of six plants from each plot.

$$\text{Fruit set \%} = \frac{\text{No. fruits / cluster}}{\text{Total no. flowers / cluster}} \times 100$$

Fruit yield and its characteristics: A sample of five fruits at the marketable stage was taken randomly for tomato fruits from the fourth picking to measure average of each fruit length, fruit diameter, and fruit weight as well as fruit firmness, which was measured using a pressure tester (pocket penetrometer). In addition, early yield was expressed as the weight of the first two pickings and total yield was expressed as the weight of fruits of all harvests.

Fruit chemical constitutes: A representative sample of 5 fruits from each experimental plot at the marketable ripe stage was taken from the fourth picking for determination of the following fruit contents (according to the methods of A.O.A.C. (1990) :

1. Ascorbic acid (vitamin C) content was determined using 2, 6 dichlorophenol indophenol dye.
2. Total soluble solids percentage (TSS %) was determined using a hand refractometer.
3. Titratable acidity percentage was determined using titration method with 0.1 N sodium hydroxide using phenolphthalein as an indicator.
4. Lycopene content was determined using cromatographic separation. Colour intensity was measured at 503 nm using a spectrophotometer.

Leaves chemical content:

1. The total leaf chlorophyll content (as SPAD unit) at the fourth upper leaves was recorded using a portable Minolta chlorophyll meter Model SPAD-501 (Spectrum Technologies, Inc., Aurora, IL, USA).
2. Total free amino acids was measured according to Yemm and Cocking (1955).
3. Proline content in leaves was determined calorimetrically using the ninhydrin reagent method according to Bates et al. (1973). The absorbance of the solution with toluene was determined at 520 nm, using a spectrophotometer (Model UV -120-20, Japan).
4. Total sugars concentration of tomato leaves expressed as glucose was determined spectro-colorimetricaly (at the wavelength of 490 nm) according to the method of Dubois et al. (1956).
5. Total phenols content was measured by folin-ciocalteau reagent method (Bray and Thrope, 1954).

Statistical Analysis: All data were subjected to statistical analysis according to Snedecor and Cochran (1982) using Statistix 8 program; the means were compared by L.S.D at the 0.05 level of probability in the two seasons.

RESULTS AND DISCUSSION

1. Vegetative growth parameters:

The data in **Table (1)** demonstrates the effects of application heat stress relievers on vegetative growth traits, *viz.*, plant height, total number of branches/plant, plant fresh weight, plant dry weight and stem diameter, during the late summer seasons of tomato plants under high temperature stress in the open field. The results showed that many significant increases in all vegetative growth traits were observed in both seasons compared to the control. Melatonin produced the highest plant height, plant dry weight, and stem diameter in both seasons **(Table 1)** and in average of both seasons, resulting in an increment percentage by 24.63%, 33.09% and 44.92% in descending order **(Fig. 3)** compared to control followed by potassium silicate for plant fresh weight and total number of branches/plant by 73.55% and 27.87% and BAP for plant height, No. of branches/plant, plant dry weight, stem diameter and plant fresh weight by 18.06%, 18.38%, 26.09%, 38.03% and 61.26%. On the opposite, both anise oil (AO) and eugenol (Eug) treatments exhibited the lowest significantly effects in reducing heat stress for all the vegetative traits under this study with non-significant differences between them in plant height, total number of branches/plant, plant dry weight, and plant fresh weight in both seasons. These results were similar; with those reported by Abou El-Nour and Badran (2023) and Mumithrakamatchi et al. (2024) and Suliman et al. (2024).

Enhancing the vegetative growth characteristics by melatonin and potassium silicate foliar applications were related to improving chlorophyll and non-enzymatic antioxidants **(Table 4).** Increasing the vegetative growth characteristics of plants subjected to high temperature stress could probably be attributed to the mechanism for application treatments mentioned in our study by its beneficial effects on the physiological mediated tolerance of heat stress. Aspects include maintaining nutrient balance, promoting photosynthetic rate, and improving plant tolerance to heat stress. Moreover, heat stress is a significant element that restricts plant development and leads to a significant decrease in agricultural productivity worldwide. Some researchers mentioned that high temperatures impact on several physiological and biochemical processes and molecular properties of the plants, and dealing with them finally causes yield reduction (Peet et al. 1997; Singh et al. 2017 and Khan et al. 2022).Therefore, the positive influences of exogenously applied melatonin increased the transcript accumulation of gibberellic acid and cytokinins work in concert to improve physiological indices, such as photochemical efficiency, chlorophyll content, and relative water content, increasing high temperature tolerance (Ma et al., 2018) as well as decreased sensitivity to abscisic acid (Arnao and Hernandez-Ruiz 2021).

Exogenous MET improves a plant's tolerance to heat stress in two ways: directly, by scavenging molecules of reactive oxygen species (ROS); or indirectly, by up regulating the expression of genes connected to stress-inducible pathways in plants, photosynthetic efficacy, metabolite content, and antioxidant enzyme activities (Sun et al., 2021 and Wang et al., 2022). Research has shown that BAP, a synthetic cytokinin, can enhance plant growth and development, particularly in tomato cultivars under heat stress (Mumithrakamatchi et al. 2024). Spraying BAP on tomato plants has been shown to increase plant height, stem diameters, leaf and branch numbers (Suliman et al., 2024).

Jasmonic acid (JA), a primary plant hormone, regulates plant defense mechanisms and induces various physiological as well as biochemical processes related to plant growth and development (Anderson et al., 2004 and Huang et al., 2023). JA application on tomato plants under heat stress conditions has shown significant increases in plant height, stem diameter, branch and leaf number, leaves dry weight/plant, shoots and dry weight /plant (Okasha et al., 2023). Additionally, foliar application of potassium silicate has been found to improve vegetative growth characteristics, chlorophyll, and non-enzymatic antioxidants mediated tolerance to heat stress. These benefits include maintaining nutrient balance, promoting photosynthetic rate, and improving plant tolerance to heat stress. In relation to potassium silicate spraying, boosting the vegetative growth characteristics **(Table 1)** through silicate foliar treatments was linked to a better tolerance of heat stress mediated by chlorophyll and non-enzymatic antioxidants **(Table 4)**. However, Keeping the balance of nutrients, increasing photosynthetic rate, and strengthening plant tolerance to heat stress are some of the factors. Accordingly, K boosts plant tissues' ability to store water, which may promote cell growth and development (Shanmugavelu, 1989). Our findings concurred with those of Hu et al. (2023), who found that tomato plant growth was enhanced by sailicon applied topically. When potassium silicate was applied foliar to potato plants, Saleh et al. (2024) observed a considerable increase in plant height, fresh and dry weight/plant, and chlorophyll content.

Table (1). Effects of foliar applications on some vegetative growth and some flowering characteristics of tomato plants during late summer seasons of 2022 and 2023.

Traits Treatments	Plant height (cm)	Total No. of branches/plant	Plant fresh weight (g)	Plant dry weight (g)	Stem diameter (cm)	Days to 50% flowering	Fruit setting (%)
			1st season				
Melatonin	77.63 a	16.63 a	866.73 a	182.69 a	2.24 a	31.04 c	80.30 a
6-Benzylamino Purine	73.00 bc	16.13 a	802.50 b	174.57 b	2.11 b	31.97 c	73.48 b
Anise oil	66.17 d	14.23 bc	593.33 d	146.96 d	1.95 c	31.44 c	71.85 b
Jasmonic acid	70.77 c	14.50 b	727.73 c	157.93 c	1.92 c	34.30 ab	73.63 b
Eugenol	66.58 d	14.37 bc	573.63 d	146.17 d	1.74 d	32.40 bc	64.74 c
Potassium silicate	75.50 ab	16.77 a	890.03 a	174.55 b	2.20 a	30.66 c	80.15 a
Control	61.93 e	13.03 c	507.40 e	134.20 e	1.55 e	36.30 a	56.13 c
L.S.D at 5%	**3.75**	**1.43**	**38.20**	**4.45**	**0.04**	**2.03**	**2.39**
			2nd season				
Melatonin	73.80 a	15.23 ab	760.17 a	173.23 a	2.18 a	30.42 d	76.33 a
6-Benzylamino Purine	70.44 b	14.33 bc	733.48 b	162.63 b	2.10 b	32.31 c	69.95 b
Anise oil	63.63 d	12.93 de	485.43 d	143.23 d	1.81 c	31.07 d	66.07 c
Jasmonic acid	67.03 c	13.97 c	656.84 c	153.83 c	1.85 c	33.82 b	69.33 b
Eugenol	64.90 cd	13.83 cd	492.73 d	143.13 d	1.66 d	30.36 d	62.90 b
Potassium silicate	72.07 ab	16.13 a	763.00 a	161.74 b	2.10 b	30.02 d	76.27 d
Control	59.57 e	12.70 e	445.07 e	133.23 e	1.50 e	37.42 a	54.80 a
L.S.D at 5%	**2.21**	**1.02**	**16.27**	**2.60**	**0.05**	**1.06**	**2.79**

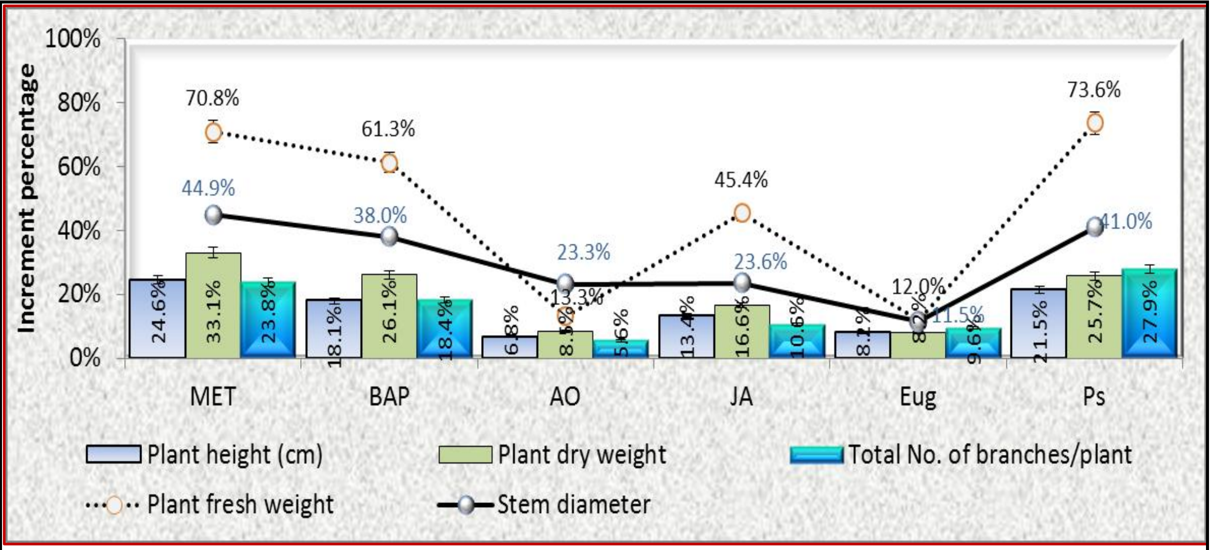

Fig. (3). Increment % of some vegetative growth traits of tomato plants as affected by eco-friendly foliar spray treatments over the control in average two seasons.

(MET) Melatonin, (BAP) 6-Benzylaminopurine, (AO) Anise oil, (JA) Jasmonic acid, (Eug) Eugenol and (PS) Potassium silicate

2. Flowering and fruit set.

Results of flowering characters are presented in **Table (1)** and **Fig. (4)**. Data revealed that the foliar application treatments significantly decreased number of days to 50 % flowering of tomato plants compared with the control in both seasons. The best treatments for decreasing the number of days to 50 % flowering of tomato plants recorded by potassium silicate (30.34) and melatonin (30.73 days) in average of both seasons with non-significant differences between them. The same table demonstrates that, in both seasons where heat stress was present in the open field, the applied treatments significantly increased the fruit set percentage average of the first four trusses per plant when compared to the control. The results showed that the best treatments for fruit setting (%) were spraying tomato plants with melatonin (78.32%) and potassium silicate (78.21%) in average throughout both seasons, resulting in an increment percentage by 41.2% and 41.01% in descending order **(Fig. 4)** compared to control with non- significant differences between them. BAP (71.72 %) and JA (71.48 %) were the next best treatments. However, because of the second season's high temperatures, the first season had the highest fruit setting percentage. According to Ripoll et al. (2014), heat stress in tomatoes disrupts the supply and transport pathways for carbohydrates, which has an adverse effect on the development and quality of the fruit. Tomato plants are subjected to heat stress, which lowers pollen viability and causes flower drop (Khattak et al., 2022). Tomato fruit setting is decreased by high temperatures (Ibrahiem, 2011 and Alsamir et al., 2017), which increase stigma exsertion. Our findings concurred with those of Suliman et al. (2024), who demonstrated that spraying tomato plants with BAP greatly increased the quantity of flowers/clusters, fruit/plant, and clusters/tomato plants. Moreover, **Table (4)** of the study shows that the administration of MET, BAP, and PS treatments considerably increased the formation of high amounts of proline. These effects may be the result of these compounds' ability to combat heat stress by stimulating proline, which improved fruit setting (%). Singh et al. (2017) discovered that under heat stress, tomato leaves with higher proline levels had better pollen viability.

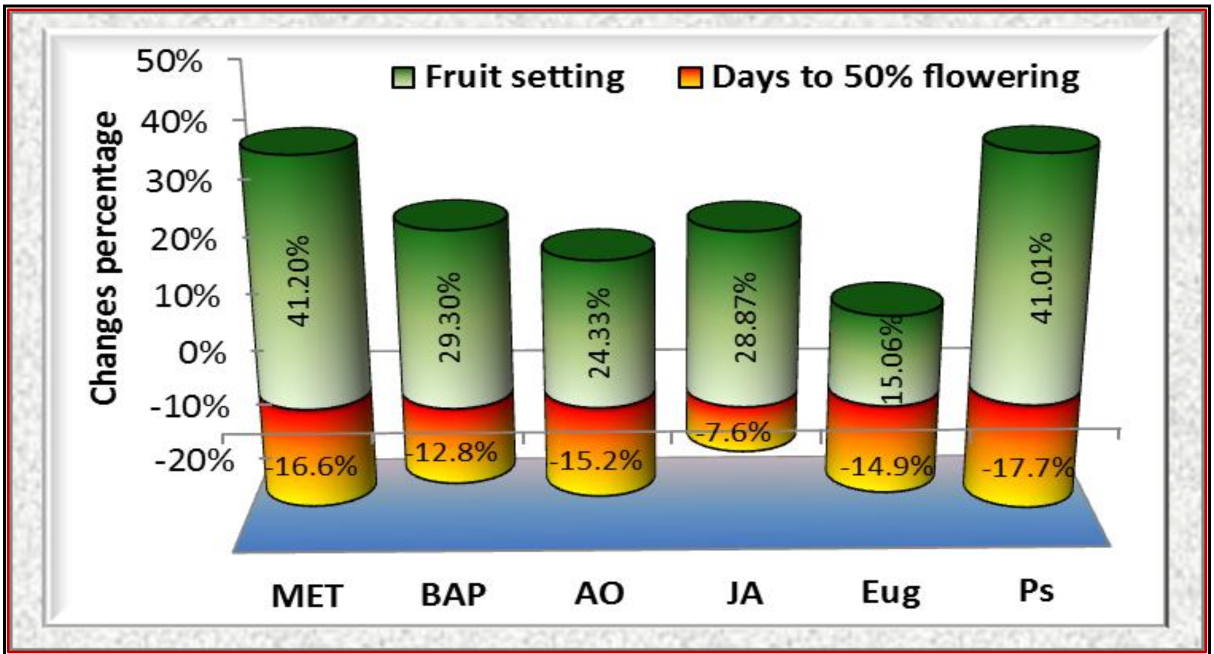

Fig. (4). Changes % of fruit sitting and flowering traits of tomato plants as affected by eco-friendly foliar spray treatments over the control in average two seasons.
(MET) Melatonin, (BAP) 6-Benzylaminopurine, (AO) Anise oil, (JA) Jasmonic acid, (Eug) Eugenol and (PS) Potassium silicate

3. Yield and its attributed traits:

Foliar spraying tomato plants with all eco-friendly treatments resulted in a significant improvement of fruit quality, early yield and total yield **(Table 2)** except of the application of eugenol on average fruit diameter (first season) and average fruit firmness (both seasons). In the current study, the melatonin treatment gave the highest significant value of average fruit weight (159.43 and 153.63g), average fruit length (6.93 and 6.79cm) and average fruit diameter (7.70 and7.53cm) in both seasons, resulting in an increment percentage by 30.1, 53.0 and 39.3%, respectively in average of both seasons **(Fig. 5).** However, the anise oil (2.4 and 2.39 kg/cm²) followed by jasmonic acid (2.29 & 2.26 kg/cm²) treatments were recorded highest significant value for average fruit firmness in both seasons and in average of both seasons, resulting in an increment percentage by 17.4 and 11.52%, respectively.

It is obvious from the data presented in **(Table 2)**, indicated that the effect of application heat stress relievers on tomato plants had significantly increased early and total tomato yield compared with the control in both seasons. However, the highest early tomato yield was achieved by potassium silicate followed by 6-Benzylaminopurin then melatonin as compared to the untreated control in both seasons and in average of both seasons, resulting in an increment percentage by 98.23, 88.65 and 71.28% in descending order **(Fig. 5).**

The early tomato yield in both seasons did not differ significantly across the other treatments, which include jasmonic acid, eugenol, and anise oil. As for total fruit yield, the highest values were obtained when tomato plants exogenous MET application followed by BAP when compared to the remaining treatments and control during the two late summer seasons of tomato plants under high temperature stress in the open field. Regarding the spraying of MET treatment led to an increase in production the total yield by 39.65% in the average of the two seasons **(Fig. 5).** However, exogenous eugenol treatment showed significantly lowest values of total yield in the average of the two seasons. The treatments of MET, BAP and PS had significant increase in early and total yield of tomato plants at heat stress in the open field as well as improvements in the average fruit weight, average fruit length and average fruit diameter. . Our results concurred with those of Breng (2024) and El-Sayed et al. (2024) regarding tomatoes. Plant development, growth, productivity, and qualities are all negatively impacted by late summer planting in open fields because it exposes plants to heat stress, which increases ROS species, reduces the amount of water in leaf cells, and slows down photosynthesis. Accordingly, numerous researchers discovered that when temperatures increased, pollen viability and fruit set (%) decreased (Peet et al. 1997, Ibrahiem, 2011 and Lee et al., 2022). Fruit setting is negatively impacted by temperatures below 12°C and above 32°C, according to Moor and Thomas (1952). A negative change in pollen grain viability and pollen tube growth, which twists and grows in a helical form, are the main causes of the decrease in fruit set under relatively high temperature stress (Pressman et al. 2002 and Sato et al., 2006). In our experiment, the amount of chlorophyll content in tomato plants may be decreased under heat stress and drop in the enzyme's activity required for chlorophyll synthesis, but exogenous MET, BAP and PS caused significant increase in early and total yield of tomato plants at heat stress in the open field as well as improvements in the fruit qualities (Khan et al., 2024).

Our findings coincided with those of Ibrahim et al. (2020), who reported that, when compared to the control, tomato plants treated with MET had the highest significant fruit output (37.4%) under water deficit conditions. Also, Mumithrakamatchi et al. (2024) discovered that under heat stress, foliar application of MET significantly increased fruit set %, overall fruit yield, and number of fruits. According to Suliman et al. (2024), BAP spraying greatly increased tomato yield and its components across all varieties under cultivation. Okasha et al. (2023) mentioned that applications of JA on tomato plants grown under high temperature conditions significantly increased in total fruit yield per plant. In addition, Wang et al. (2024) mentioned that exogenous Si treatment had significantly increased firmness and fruit weigh of tomato fruits compared to the control. Furthermore, a first-generation synthetic cytokinin (6-Benzylaminopurin) regulates the growth and development of tomato fruits and setting blossoms, lead to increase fruit quality and inhibit the respiratory kinase in plants (Siddiqui et al., 2011). Moreover, the most beneficial effects of foliar application of JA on fruiting and yield of tomato under heat stress conditions might be due to the stimulatory effect of the plant for many physiological and biochemical processes associated with plant growth and development, as well as stress tolerance (Ali and Baek, 2020). The positive influences of eugenol and anise oil under heat stress on yield and its components may be attributed to its priming agents, which elevate the salicylic acid and jasmonic acid content to mediate the thermotolerance and increase the resistance of tomato plants against TYLCTHV under heat stress conditions (Tsai et al., 2019).

Table (2). Effects of eco-friendly treatments on yield and its attributed traits of tomato plants during late summer seasons of 2022 and 2023.

Traits / Treatments	Fruit weight (g)	Fruit firmness (kg/cm²)	Fruit length (cm)	Fruit diameter (cm)	Early Yield (t/fed)	Total Yield (t/fed)
			1st season			
Melatonin	159.43 a	2.18 c	6.93 a	7.70 a	2.47 b	39.07 a
6-Benzylamino purine	142.90 c	2.11 cd	6.72 ab	7.64 ab	2.68 a	37.90 b
Anise oil	134.32 d	2.40 a	5.24 c	6.52 c	2.32 b	33.27 d
Jasmonic acid	137.44 d	2.29 b	6.65 b	7.13 b	2.40 b	36.67 c
Eugenol	142.80 c	2.07 d	5.35 c	5.94 d	2.44 b	34.13 d
Potassium silicate	153.07 b	2.18 c	6.76 ab	7.47 ab	2.85 a	36.77 c
Control	122.00 e	2.05 d	4.60 d	5.65 d	1.50 c	28.10 e
L.S.D at 5%	**4.83**	**0.08**	**0.27**	**0.54**	**0.18**	**1.06**
			2nd season			
Melatonin	153.63 a	2.16 cd	6.79 a	7.53 a	2.36 c	37.57 a
6-Benzylamino purine	139.07 c	2.12 de	6.37 b	7.37 a	2.64 b	36.20 b
Anise oil	127.57 e	2.39 a	5.00 d	6.30 c	2.27 d	32.00 c
Jasmonic acid	136.53 d	2.26 b	5.79 c	6.69 b	2.31 cd	35.37 b
Eugenol	139.97 c	2.07 ef	4.93 d	5.72 d	2.37 c	31.03 c
Potassium silicate	150.80 b	2.20 bc	6.14 bc	7.29 a	2.74 a	35.00 b
Control	118.70 f	2.03 f	4.37 e	5.28 e	1.32 e	26.78 d
L.S.D at 5%	**1.69**	**0.07**	**0.36**	**0.29**	**0.09**	**1.22**

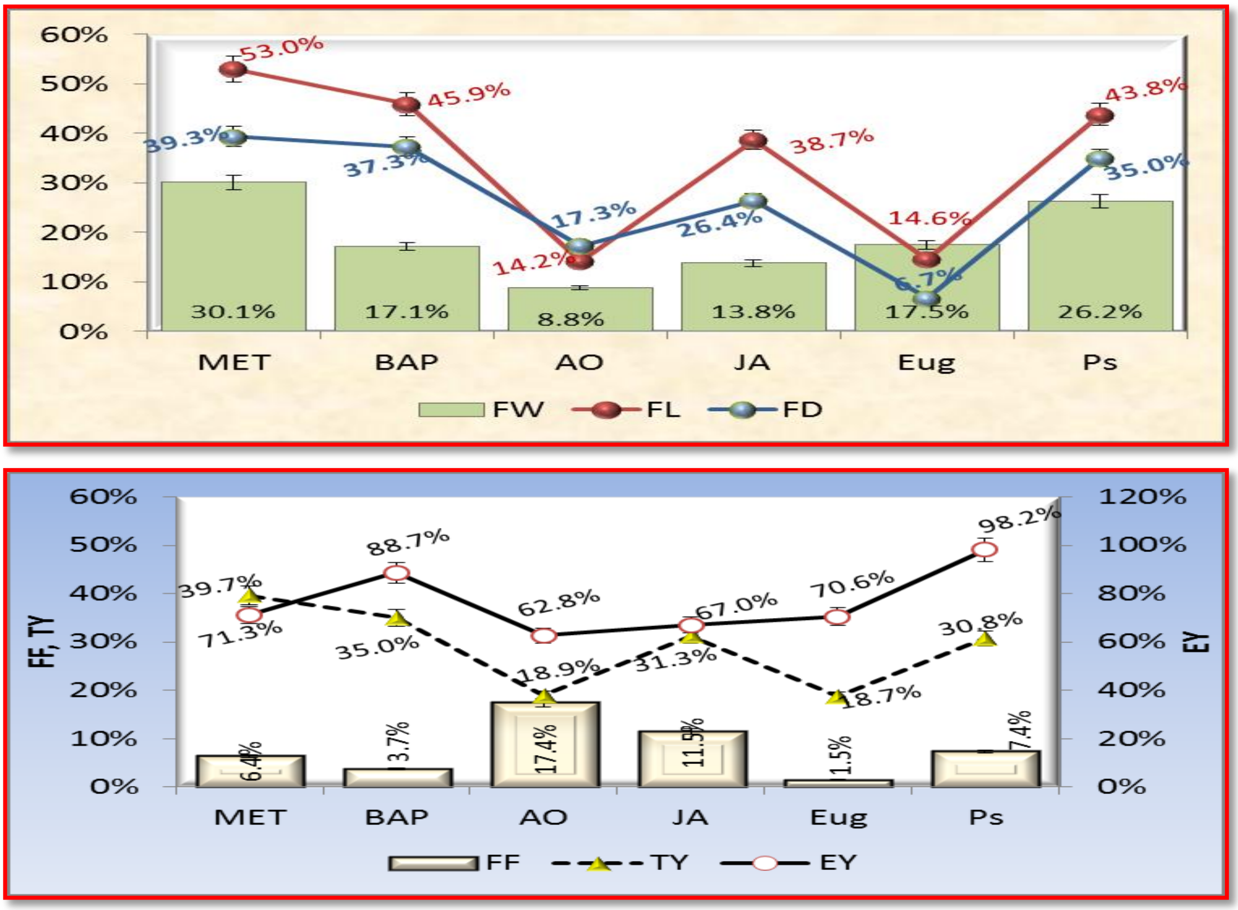

Fig. (5). Increment % of yield and its attributed traits of tomato plants as affected by eco-friendly foliar spray treatments over the control in average two seasons.

FW (fruit weight), FL(fruit length),FD(fruit diameter), FF(fruit firmness),TY(total yield), EY(early yield), (MET) Melatonin, (BAP) 6-Benzylaminopurine, (AO) Anise oil, (JA) Jasmonic acid, (Eug) Eugenol and (PS) Potassium silicate

4. Chemical properties (in fruits and leaves):

4.1. Fruits:

The results of chemical constituents of tomato fruits are presented in **(Table 3).** The results revealed that, all applied eco-friendly treatments showed significant increases in total soluble solids percentage (TSS%), titratable acidity percentage (TiTb%), ascorbic acid (ASA) and lycopene (Lcop) concentration in tomato fruits when compared with the control, except application anise oil (AO) on titratable acidity percentage and lycopene concentration in both seasons as well as ASA and TSS% in 1st and 2nd season, respectively. The best treatments for increasing the total soluble solids percentage and lycopene concentration of tomato fruits were recorded by PS followed by MET in average of both seasons. In the current study, the MET treatment gave the highest significant value of ascorbic acid in tomato fruits 24.36 and 25.13 mg/100g in 2022 and 2023 seasons, respectively. In this regard**,** tomato plant development under heat stress has a negative impact on the metabolic processes in tomato fruit, including vitamin C, carotenoids and lycopen content, which are decreased significantly when tomato plants are exposed to heat stress during fruit formation stages (Hernandez et al., 2015).

In this study, applied BAP, MET and PS were shown to enhance plant growth **(Table 1),** chlorophyll content, and non-antioxidant enzymes **(Table 4)** this reflected positively on the quality of tomato fruits under heat stress conditions. Our results were in agreement with results of Liu et al. (2016) and Ibrahim et al. (2020) showed that exogenous MET solution on tomato had significantly improved the contents of soluble solids, ascorbic acid, and lycopene content in fruit compared to the control. Mumithrakamatchi et al. (2024) on tomato showed that MET enhanced the quality of fruits through increased lycopene content, carotenoid content, titratable acidity, and ascorbic acid content, compared with the control under heat stress. Suliman et al. (2024) showed that spraying BAP on tomato plants had significantly improved total soluble solid and vitamin C content. In addition, JA is one of the plant hormones that control the quality of tomato fruits. Zhang et al. (2022) found that the application of JA had enhanced tomato fruit quality accumulation such as nutrition, glucose, fructose, soluble sugar, soluble protein, starch, total phenol, lycopene, and flavonoids. Stamatakis et al. (2003) found that potassium silicate had significantly increased the lycopene, β-carotene, and vitamin C content in tomato fruits. Wang et al. (2024) mentioned that exogenous Si treatment had significantly increased fruit soluble sugars, soluble solids, soluble proteins, lycopene and vitamin C content of tomato fruits compared to the control.

Table (3). Effects of foliar applications on some chemical constituents of tomato fruits during late summer seasons of 2022 and 2023.

Traits Treatments	Total soluble solids (%)	Ascorbic acid (mg/100 F.W)	Titratable acidity (%)	Lycopene (mg/100 F.W)
		1st season		
Melatonin	4.96 a	24.37 a	0.28 bc	7.00 ab
6-Benzylamino purine	4.66 b	24.23 a	0.33 a	6.78 b
Anise oil	3.94 e	23.34 bcd	0.24 d	5.23 d
Jasmonic acid	4.12 d	23.60 bc	0.27 c	5.86 c
Eugenol	4.44 c	23.05 cd	0.29 b	5.85 c
Potassium silicate	4.86 a	23.87 ab	0.27 c	7.28 a
Control	3.57 f	22.80 d	0.24 d	5.00 d
L.S.D at 5%	**0.12**	**0.61**	**0.01**	**0.29**
		2nd season		
Melatonin	4.51 b	25.13 a	0.29 b	6.51 a
6-Benzylamino purine	4.32 c	25.07 a	0.34 a	6.57 a
Anise oil	3.38 f	24.34 b	0.25 d	4.96 c
Jasmonic acid	4.08 e	24.44 b	0.27 c	5.57 b
Eugenol	4.22 d	24.24 b	0.27 c	5.54 b
Potassium silicate	4.76 a	25.08 a	0.29 b	6.54 a
Control	3.35 f	23.54 a	0.25 d	4.60 c
L.S.D at 5%	**0.05**	**0.54**	**0.01**	**0.43**

4.2. Leaves:

The results shown in **Table (4)** showed how all the treatments used in this study affected the fresh tissues of tomato leaves' total leaf chlorophyll (SPAD unit) and non-enzymatic antioxidant characteristics (total sugars, total amino acids, total phenols, and proline content). With the exception of exogenous anise oil's effects on total amino acids in both seasons and proline content in the first season, our study's findings demonstrated considerably induced production of high quantities of non-enzymatic antioxidants as compared to the control during the two seasons. During the two seasons of heat stress in the open field, exogenous MET had caused the most discernible increase in the level of total phenols, proline, and total amino acids as well as total sugars in the average two seasons. Throughout the two seasons of the current investigation, the content of total sugars in all treatments was considerably higher than the control. In the average two seasons, the exogenous MET and PS recorded the highest significant values of total sugars content (7.01 and 6.91 g/100g. d.w.). The current study's results showed that, except for anise oil, the concentration of all amino acids increased significantly in both seasons when compared to the control. In average two seasons, the greatest significant value of total amino acid level was obtained by the exogenous MET, followed by BAP (6.81 nd 5.89 g/100g. d.w.), respectively.

Regarding the content of proline in tomato leaves, the findings showed that, except for the exogenous anise oil in the first season, all administered treatments significantly outperformed the control in both seasons and average of both seasons **(Fig. 6).** In average both seasons, the greatest significant value of proline content was obtained by the exogenous MET, followed by BAP (26.18 and 24.71 mg/100g.d.w., respectively). Regarding the level of total phenols in tomato leaves, there were no noticeable differences between any of the treatments namely, anise oil, jasmonate acid, and eugenol in the second season; however, the exogenous MET, which was followed by PS, recorded the highest significant value of total phenols concentration (19.30 and

17.36 mg/100g.d.w.), respectively in average two seasons. In comparison to the control, all treatments showed a considerable increase in the total leaf chlorophyll content (SPAD unit) in the fresh tissues of tomato leaves throughout the two seasons. However, apart from the AO and Egu treatments, none of the treatments in the first season displayed significant changes in the amount of chlorophyll in the leaves.

Our findings concurred with those of Martinez et al. (2018), who discovered that exogenous MET enhances plant development while protecting the antioxidant defense systems and the photosynthesis I and II reactions. Exogenous MET considerably increased the amount of chlorophyll in tomato plants cultivated in an open field with deficit irrigation, according to Ibrahim et al. (2020).

According to Mumithrakamatchi et al. (2024) on tomato found that significantly increased total chlorophyll and proline content when MET was sprayed on the plants as well as Suliman et al. (2024), two genotypes of tomato under heat stress showed significantly higher levels of proline, total chlorophyll, and total phenolic content when BAP was sprayed on the plants.

Increasing the amount of proline in plants improves water absorption and translocation under stress by regulating the osmotic potential of the cells (Oraki et al., 2012). Brengi (2024) found that foliar application of melatonin on tomato plants resulted in considerably higher plant growth characteristics, chlorophyll, and proline contents. . Khan, et al.(2024) mentioned that exogenous MET on tomato had increased significantly proline contents, total soluble sugars, and fruit quality over control treatment, and heat-tolerant cultivars performed better as compared to heat-sensitive cultivars of tomato. Proline functions as an osmoprotectant and shields plant cells from oxidative injury by neutralizing ROS efficiently(Said et al.,2021). In addition, El-Sayed et al. (2022) found that foliar application of potassium silicate had significantly induced production of high concentrations of total free amino acids, total phenols, and carbohydrates in tomato plants grown under drought levels. Wang et al. (2024) application of Si treatment enhanced total amino acid content of tomato fruits compared to the control.

In addition, Anderson et al. (2004) states that one of the main hormones in plants that regulate their defensive systems is jasmonic acid (JA). Plant resistance to biotic and abiotic stress is regulated by jasmonates, which are defensive phytohormones crucial for controlling plant growth and development (Huang et al., 2023). By inhibiting the ROS-generating enzyme NADPH oxidase and enhancing the synthesis of amino acids and soluble carbohydrates, JA strengthens the antioxidant system and reduces the generation of ROS (Wang et al. 2020 and Ghorbel et al. 2021). Our findings agreed with those of Okasha et al. (2023), who demonstrated that jasmonic acid markedly increased the amount of chlorophyll in tomato plants cultivated in open fields under heat stress.

Table (4). Effects of foliar applications on some chemical ingredients in tomato leaves during late summer seasons of 2022 and 2023.

Traits Treatments	Total sugars (g/100 g. d. w.)	Total amino acids (g/100 g. d.w.)	Proline content (mg/100g.d.w.)	Total phenols content (mg/100g.d.w.)	Total chlorophyll content (SPAD)
			1st season		
Melatonin	7.12 a	6.45 a	25.75 a	19.23 a	67.03 a
6-Benzylamino purine	6.64 bc	5.59 b	24.25 abc	16.47 bc	68.43 a
Anise oil	6.29 c	3.63 d	18.48 d	14.89 de	61.90 b
Jasmonic acid	6.85 ab	4.76 c	23.31 bc	15.43 cd	66.00 a
Eugenol	6.80 ab	4.53 c	22.63 c	14.36 de	57.60 c
Potassium silicate	6.88 ab	5.44 b	24.59 ab	16.88 b	66.93 a
Control	5.10 d	3.45 d	17.46 d	13.81 e	51.37 d
L.S.D at 5%	**0.35**	**0.42**	**1.67**	**1.28**	**3.42**
			2nd season		
Melatonin	6.91 a	7.17 a	26.61 a	19.37 a	65.93 a
6-Benzylamino purine	6.53 b	6.18 b	25.16 b	17.67 b	64.33 a
Anise oil	5.85 d	3.27 e	17.39 d	14.57 c	57.93 b
Jasmonic acid	6.16 c	4.30 d	22.70 c	15.33 c	59.20 b
Eugenol	6.13 c	5.22 c	21.85 c	14.66 c	52.77 c
Potassium silicate	6.95 a	4.94 c	24.02 b	17.84 b	60.97 b
Control	4.87 e	3.03 e	15.32 e	14.23 c	49.03 d
L.S.D at 5%	**0.26**	**0.44**	**1.28**	**1.38**	**3.13**

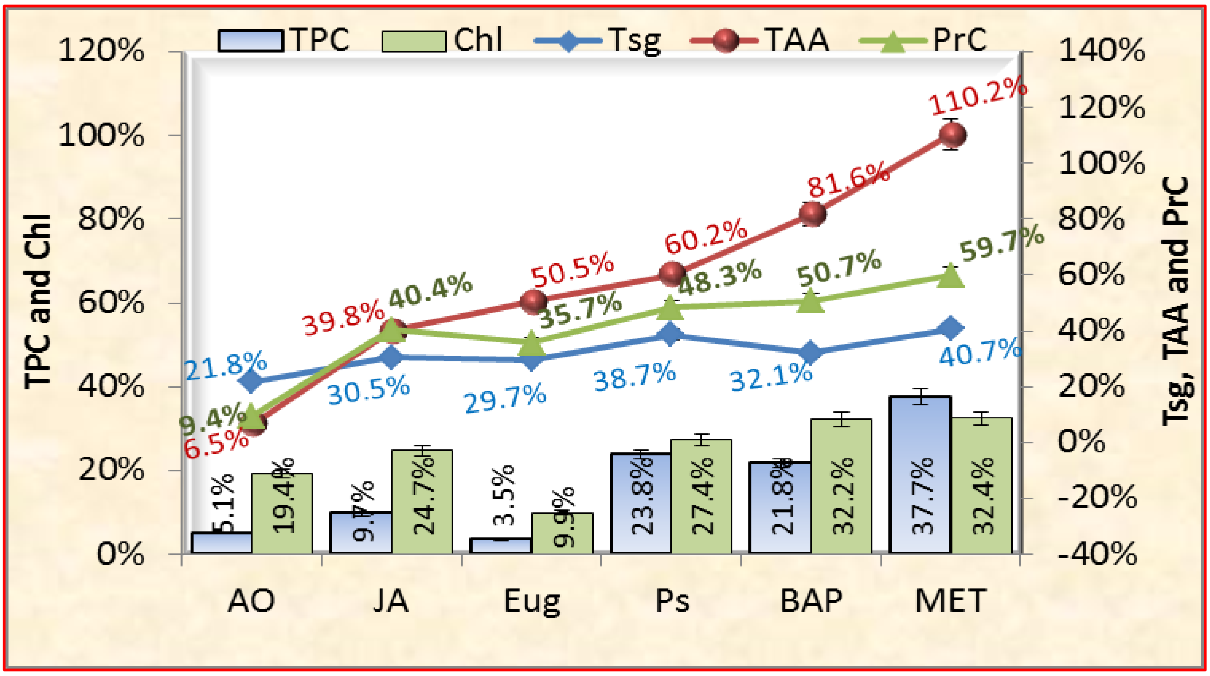

Fig. (6). Increment % of total leaf chlorophyll and non-enzymatic antioxidant characteristics of tomato plants as affected by eco-friendly foliar spray treatments over the control in average two seasons.

TPC(total phenols content), ChI (chlorophyll content),Tsg (total sugars),TAA(total amino acids), PrC (proline content). (MET) Melatonin, (BAP) 6-Benzylaminopurine, (AO) Anise oil, (JA) Jasmonic acid, (Eug) Eugenol and (PS) Potassium silicate.

Conclusion

Certain antioxidants can be applied as foliar spray to tomato plants grown in hot climates to help them cope with heat stress. Melatonin, 6-benzylaminopurine, and potassium silicate treatments significantly increased early and total tomato plant yields, as well as yield qualities under heat stress in the open field. These treatments are known to stimulate growth and fruit setting.

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الملخص العربى

تحسين تحمل نباتات الطماطم لدرجات الحرارة المرتفعة بالرش ببعض مضادات الاجهاد الحرارى

السيد البدوى إبراهيم وهدى إبراهيم أحمد إبراهيم

اقسام بحوث الخضر، معهد بحوث البساتين ، مركز البحوث الزراعية ، الجيزة ، مصر

ارتفاع درجات الحرارة بشكل متزايد هو أحد تحديات التغيرات المناخية، والذي يؤثر بدوره سلباً على إنتاج المحاصيل البستانية. بالإضافة إلى ذلك، فإن الإجهاد الحراري يقلل بشدة من الإنتاج الزراعي في جميع أنحاء العالم وهو أحد العوامل الرئيسية التي تحد من نمو النباتات. ويمكن التغلب على الإجهاد الحراري باستخدام بعض مضادات الأكسدة التي لها دور في تحفيز النمو وعقد الثمار. نفذت تجربتان حقليتان خلال موسمى النمو لعامى 2022 و2023 فى العروة الصيفية المتأخرة فى تربة طينية طميية. لدراسة تأثيراستجابة نباتات الطماطم صنف F_1 K-186 لبعض مركبات مضادات الأكسدة مثل الملاتونين، 6- بنزيل أمينوبيورين، زيت اليانسون، حمض الجاسمونيك، الايجينول، سليكات البوتاسيوم والكنترول على النمو الخضرى، عقد الثمار، المحصول، صفات الثمار وبعض المركبات الكميائية فى نباتات الطماطم النامية تحت ظروف الاجهاد الحرارى.

أظهرت نتائجنا أن معاملات الملاتونين، 6-بنزيل أمينوبيورين وسليكات البوتاسيوم أدت الى زيادة معنوية فى المحصول المبكر والكلى وأيضا مكونات المحصول تحت ظروف الإجهاد الحرارى فى الحقل المكشوف، وأدى الرش بمعاملة الميلاتونين إلى زيادة إنتاج المحصول الكلي بنسبة 39.65% في متوسط الموسمين.

وبناء علية يمكن التوصية باستخدام معاملة الميلاتونين أو معاملة 6- بنزيل أمينوبيورين لتحسين إنتاجية محصول الطماطم تحت ظروف الاجهاد الحرارى فى الحقل المكشوف.