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RESEARCH ARTICLE

Impact of titanium dioxide on growth, yield and biochemical parameters of three eggplant genotypes under heat stress conditions

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Abstract

The present research evaluated the effect of foliar application of titanium dioxide (TiO_2) on growth, yield and physiological parameters of three eggplant genotypes under various heat stress conditions. The experiments were conducted during the 2024 growing season. The treatments for stress conditions included in the horizontal factor, C0: open-field conditions or control, C1: green saran cover and C2: non-woven fabric cover. Three eggplant genotypes, viz. G1: Black Beauty variety, G2: Raheeb F1 hybrid and G3: Aswad F1 hybrid, in each treatment were subjected to three titanium concentrations, i.e. 0, 100 and 200 mg L^{-1}. Research findings revealed that the plants grown under condition (C2) showed the maximum average plant height, dry weight, fruit weight and total yield but minimum average leaf proline, leaf POD and leaf SOD as compared to control plants. The plants grown under control condition (C0) showed minimum average of plant height, dry weight, fruit weight and total yield. Maximum average of leaf proline, leaf POD and leaf SOD were noted in control plants. Of all the three genotypes, G1 exhibited an increase in the plant height, dry weight, total yield and leaf SOD. A significant improvement in plant height, dry weight, leaf antioxidants such as proline and activities of POD and SOD in leaves was noted in plants exposed to Ti concentration at 200 mg L^{-1}. While enhanced fruit weight and total yield were noted in plants exposed to Ti at 100 mg L^{-1}. Further study is required on Ti's long-term impacts and optimal doses across various environments.

Keywords: antioxidant enzymes; eggplant; growth; heat stress; productivity; proline; titanium dioxide

Introduction

Eggplant (*Solanum melongena* L.), also known as aubergine and brinjal, is a common and important vegetable crop belonging to the family Solanaceae. It is usually grown in spring and early summer and requires relatively high temperatures (warm weather) for its growth (1). Thus, it is cultivated in open fields during summer in Iraq. During winter, it is grown in greenhouses and plastic tunnels. Eggplants are nutritionally important because their fruits contain compounds important for human health. These include phenols and other phytochemicals. It is a dietary vegetable and is a good source of antioxidants, minerals, amino acids and multivitamins (A, B1, B6 and C) (2–5).

Factors such as genetic and environmental interactions determine the degree of growth, development of a plant species and its productivity. The genetic background of the cultivated species greatly influences the quantity and quality of the crop (6). The production and quality of eggplant can be increased by planting hybrids that respond to exogenous amendments (7).

Most higher plants have a critical temperature array that is harmful and falls between (55–39 °C) (8). High-temperature stress results in the production of Reactive Oxygen Species (ROS) that affect cell vitality by oxidizing lipids and damaging fatty membranes. These ROS also affect important macromolecules including nucleic acids and proteins, which ultimately cause cell death in plants (9,10). Therefore, shade nets are used in agriculture to protect plants from heat stress and other environmental hazards (11). A previous study indicated the effect of shading on the growth and yield of tomatoes and chili (12). Shading at rates of 50 % and 70 % mitigated the increase in leaf temperature in plants as compared to those grown in an open field. When plants are exposed to various abiotic stressors, a foliar application of beneficial elements can be given to induce tolerance, resistance or defensive responses that allow them to cope with stressors (13). Titanium (Ti) is a beneficial element that, when incorporated into agricultural practices, can significantly improve the resilience of plant species in environmental stress conditions. Titanium reduces the levels of free radicals, which are often responsible for oxidative damage within plant tissues (14). Titanium-treated plants have shown the presence of high levels of chlorophyll and carbohydrates, increased photosynthetic efficiency, enhanced tolerance to stress including heat stress, increased nutrient absorption and enzyme activity and improved crop yields and quality (15-17).

This study assessed the growth and yield of three eggplant genotypes under conditions of heat stress and examined the impact of foliar application of titanium in reducing heat stress and increasing plant tolerance. In addition, we identified the type of environment most favorable for crop growth and productivity.

Materials and Methods

The field experiment was conducted at the research station of the University of Kufa during the growing season of 2024. Three genotypes of eggplant seeds were taken and planted in standard trays supplied with sterile agricultural medium containing peat moss and perlite blended in a ratio of 2:1, respectively. The seedlings were transplanted to open fields and greenhouses at the stage when 4-6 true leaves are formed. Random soil samples were taken from a depth of 0-30 cm from different areas for physical and chemical analysis before planting the seedlings (Table 1). Primary operations of plowing, harrowing and the addition of decomposed organic manure were performed. Subsequently, the land was divided into three blocks, each containing 27 experimental units, resulting in a total of 81 experimental units in the form of furrows. Each furrow was 4 m in length and 1 m in width, with 0.7 m apart from the other furrow, resulting in a total area of 5.60 m^2 for the experimental unit. Sixteen plants were distributed in two lines alternately within each furrow, with 0.5 m between two plants. A drip irrigation system was installed and crop management, irrigation and control operations were conducted as needed.

Field layout and studied factors

A strip-split plot system based on the Randomised Complete Block Design (RCBD) was adopted with three replicates, including three factors. Factor I included three different conditions C0: open-field conditions as a control, C1: plastic house supplied with a green saran cover 65 % shading (to prevent heat stress) and C2: 1.5 m high tunneling supplied with a non-woven fabric cover (to prevent heat stress). The latter cover was imported by SUN MORNING CO., LTD. The fabric cover weighed approximately 19 g m^{-2} and was characterized by its resistance to external weather conditions and high temperatures. An electronic thermometer was installed inside each area to record the daily temperature (Table 2). Factor 2 was assigned to subplots, including three eggplant genotypes viz. G1: Black Beauty variety, G2: Raheeb F_1 hybrid and G3: Aswad F_1 hybrid. Black Beauty eggplant is of US origin, Raheeb F_1 hybrid is produced by Gmbh Agi-aaten German origin and Aswad F_1 hybrid is produced by Agi Huizer Zaden and is of Thai origin. The third factor was two titanium concentrations i.e. 100 and 200 mg L^{-1} given in the form of foliar application of titanium oxide (IV) in the sub-subplots. The plants without any application of titanium were referred to as control (0 mg L^{-1}). The first spray was performed 60 days after seedling emergence, while the second spray was performed at the beginning of flowering. A 15-day interval was kept between the second and third applications (18). At the end of the experiment, yield parameters were recorded.

Parameters measured

Vegetative parameters

All parameters were measured by taking an average of five plants from each experimental unit, including plant height (cm), number of branches per plant (branch $plant^{-1}$), total plant leaves (leaf $plant^{-1}$) and shoot dry weight (g $plant^{-1}$). Vegetative parts were measured at the end of the growing season. The plants were removed after the fruiting stage. The roots were separated and dried in an electric oven at 75 °C for 48 hr until they were completely dried. Subsequently, shoot dry weight (g $plant^{-1}$) was also estimated (19).

Fruit yield and related parameters

The number of fruits (fruit $plant^{-1}$), fruit weight (g), fruit length (cm), fruit diameter (cm) and total yield per area unit (tonnes ha^{-1}) were measured.

Leaf and fruit chemical parameters

The total chlorophyll content of the leaves (mg 100 g^{-1} F.W.) was estimated following the acetone extraction method given by Goodwin (20), while the free proline content of the leaves (µg g^{-1} F.W.) was estimated using previous studies (21,22). The activity of the antioxidant enzyme i.e. superoxide dismutase (SOD) in the leaves (unit mg $protein^{-1}$) was estimated using the nitroblue tetrazolium (NBT) reduction and riboflavin (23). Peroxidase (POD) in the leaves (unit mg $protein^{-1}$) activity was estimated according to caramelization and maillard reaction (24). The nitrogen content (%) of the leaf was estimated using a previously described method (25) and potassium (%) was determined using a previously described method (26) with a flame photometer.

Data analysis

The data was analyzed for variance using a three-way ANOVA. A comparison of the means of treatment was done using the Least Significant Difference (LSD) test at a probability level of 0.05 using Statistix 10 (27).

Table 1. Physical and chemical characteristics of the field soil measured prior to cultivation

pH	EC $dS.m^{-1}$	O. M. %	N $mg\ kg^{-1}$	P $mg\ kg^{-1}$	K $mg\ kg^{-1}$	Clay $g\ kg^{-1}$	Silt $g\ kg^{-1}$	Sand $g\ kg^{-1}$	Soil texture
6.90	3.50	0.70	4.10	2.19	41.10	125	140	735	Sandy soil

Table 2. Relative temperature and humidity for three different conditions for the months of June to September

Month	Average of max. temp. (°C)	Average of min. temp. (°C)	Average Humidity (%)
June			
Open field C0	45.40	29.05	25.07
Saran cover C1	42.23	28.67	28.30
Fabric cover C2	42.40	24.30	33.75
July			
Open field C0	50.10	26.27	19.88
Saran cover C1	48.81	26.71	20.37
Fabric cover C2	49.68	24.04	32.75
August			
Open field C0	49.96	24.00	25.83
Saran cover C1	48.31	26.85	20.33
Fabric cover C2	48.16	21.31	45.50
September			
Open field C0	49.50	21.41	25.50
Saran cover C1	48.10	24.80	23.20
Fabric cover C2	48.70	20.10	45.00

Results and Discussion

Vegetative parameters

The results in Table 3 showed that the plants grown under non-woven fabric (C2) had a significant effect on plant height, branch number and dry weight of total shoot (117.37 cm, 5.71 branch plant^{-1} and 202.72 g plant^{-1}, respectively), in contrast to those growing in open field condition (C0), which gave the lowest values for plant height (75.94 cm), as well as saran cover (C1), which gave the lowest branch number (4.50 branch plant^{-1}) and the lowest dry weight of the shoot (159.38 g plant^{-1}). The number of leaves was highest in the open field (C0) (168.72 leaf plant^{-1}) and lowest in the greenhouse (C1), which gave the lowest number of leaves (131.08 leaf plant^{-1}). However, heat stress did not significantly affect the total chlorophyll content of the leaves.

Among the eggplant genotypes Black Beauty genotype (G1) showed an increase in plant height, number of branches, number of leaves and dry weight of total shoot (110.78 cm, 6.20 branch plant^{-1}, 161.35 leaf plant^{-1} and 245.59 g plant^{-1}, respectively), in comparison with the G2 hybrid, which gave the lowest values for plant height (86.77 cm), dry weight of total shoot (137.40.1 g plant^{-1}). This did not differ from the G3 hybrid, whereas the G3 recorded a decrease in the number of branches (4.65 branches plant^{-1}), number of leaves (140.69 leaves plant^{-1}). However, the genotypes did not show any significant effect on the total chlorophyll content of the leaves.

Titanium dioxide spraying (TiO_2) at concentration of 200 mg L^{-1} had a substantial effect on plant growth and recorded highest values for the number of branches, number of leaves, dry weight of total shoot and total chlorophyll content of the leaves (5.63 branch plant^{-1}, 164.31 leaf plant^{-1}, 192.26 g plant^{-1} and 100.23 mg 100 g^{-1} F.W., respectively). Conversely, the control plants showed the lowest values for the number of branches (4.54 branch plant^{-1}), number of leaves (129.77 leaves plant^{-1}), shoot dry weight (158.33 g plant^{-1}) and total chlorophyll content in the leaves (69.73 mg 100 g^{-1} F.W.).

The binary interaction between the genotypes and titanium dioxide concentrations yielded a considerable effect on some of the traits. The interaction between Black Beauty (G1) along with treatment of titanium oxide at the rate of 200 mg L^{-1} induced a positive effect on plant growth as measured in terms of plant height and number of branches (118.23 cm and 7.06 branch plant^{-1}, respectively). In contrast, the interaction between G3 under conditions of no foliar spray recorded the lowest values of plant height (83.38 cm) and branch plant^{-1} (4.02). Interaction between G3 along with foliar application of titanium oxide at the

Table 3. The effect of heat stress, titanium exposure on the growth of different eggplant genotypes represented by the main and bi-interaction effects

Treatments			Plant height (cm)	Branches plant^{-1}	Leaves plant^{-1}	Dry weight (g plant^{-1})	Total chlorophyll (mg 100 g^{-1} F.W.)
		C0	75.94	5.40	168.72	164.22	88.22
Stress Conditions		C1	91.18	4.50	131.08	159.38	93.40
		C2	117.37	5.71	146.71	202.72	82.12
$LSD_{0.05}$			**7.12**	**0.90**	**18.93**	**31.77**	**N.S.**
		G1	110.78	6.20	161.35	245.59	87.29
Eggplant Genotypes		G2	86.77	4.77	144.48	137.40	86.63
		G3	86.95	4.65	140.69	143.33	89.82
$LSD_{0.05}$			**5.82**	**0.91**	**16.73**	**40.38**	**N.S.**
		0	92.33	4.54	129.77	158.33	69.73
Titanium Concentrations		100	94.76	5.45	152.42	175.74	93.77
		200	97.41	5.63	164.31	192.26	100.23
$LSD_{0.05}$			**N.S.**	**0.32**	**13.49**	**20.14**	**6.13**
		G1	86.17	6.59	166.67	208.58	89.18
	C0	G2	72.21	4.55	184.70	150.56	87.60
		G3	69.44	5.06	154.78	133.52	87.89
Stress Conditions		G1	110.35	4.89	154.60	230.88	95.11
X	C1	G2	81.42	4.26	110.76	123.22	91.12
Eggplant Genotypes		G3	81.78	4.37	127.89	124.05	93.95
		G1	135.82	7.11	162.78	297.31	77.57
	C2	G2	106.67	5.51	137.97	138.43	81.17
		G3	109.62	4.52	139.39	172.42	87.62
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**
		0	74.39	4.74	150.89	147.73	65.77
	C0	100	73.00	5.47	175.55	162.24	97.58
		200	80.44	6.00	179.71	182.69	101.32
Stress Conditions		0	89.29	3.70	109.85	131.85	77.28
X	C1	100	91.47	5.03	137.06	167.32	97.95
Titanium Concentrations		200	92.78	4.78	146.34	178.98	104.95
		0	113.31	5.18	128.58	195.40	66.13
	C2	100	119.80	5.85	144.67	197.65	85.80
		200	119.00	6.11	166.89	215.11	94.42
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**
		0	110.01	5.43	141.20	215.92	70.52
	G1	100	104.11	6.10	168.37	247.86	92.92
		200	118.23	7.06	174.47	273.00	98.42
Eggplant Genotypes		0	83.61	4.17	124.80	134.27	73.59
X	G2	100	89.20	5.27	136.48	134.83	92.87
Titanium Concentrations		200	87.49	4.88	172.15	143.10	93.42
		0	83.38	4.02	123.31	124.79	65.08
	G3	100	90.96	4.98	152.42	144.52	95.53
		200	86.50	4.95	146.32	160.68	108.85
$LSD_{0.05}$			**8.28**	**0.55**	**N.S.**	**N.S.**	**10.62**

Non-significant values based on ANOVA Results are denoted via N.S.

rate of 200 mg L^{-1} showed high chlorophyll values in leaves (108.85 mg 100 g^{-1} F.W.) as compared to the treatment where G3 has not been subjected to any titanium treatment, which gave the lowest total chlorophyll content in the leaves (65.08 mg 100 g^{-1} F.W.). The triple effect of the experimental factors did not have any significant effect on the parameters listed in Table 4.

Yield and related parameters

The results in Table 5 show that the non-woven fabric cover (C2) had a substantial effect on the productivity parameters such as fruit weight and total yield (200.44 g $fruit^{-1}$ and 50.63 t ha^{-1}, respectively), noted a significant increase. The results did not differ significantly from the treatment where saran cover (C1) was used. In comparison, the open field treatments (C0) recorded the lowest fruit weight (146.05 g $fruit^{-1}$) and the lowest total yield (36.18 t ha^{-1}). The treatment under the Saran cover (C1) was considerably superior in terms of the number of fruits (32.69 fruit $plant^{-1}$) compared to the non-woven fabric cover (C2). Heat stress environments had no significant influence on the length or diameter of eggplant fruits.

The genotype experiments showed that the Black Beauty (G1) variety exhibited an increase in the number and diameter of the fruits (33.09 fruit $plant^{-1}$ and 8.39 cm, respectively). The hybrid Aswad F1 (G3) produced the lowest number of fruits (27.13 fruit $plant^{-1}$) and the smallest diameter of the fruit (6.09 cm), but weight and length of the fruit (177.66 g $fruit^{-1}$ and 14.42 cm, respectively) increased. The Black Beauty (G1) variety exhibited the minimum weight (161.27 g $fruit^{-1}$) and length of the fruit (9.22 cm). No significant differences were observed among the eggplant genotypes in terms of total yield.

Foliar application of TiO_2 had significant effects on eggplant plants. The concentration of 200 mg L^{-1} increased the fruit yield as fruit number, fruit length and fruit diameter (32.60 fruit $plant^{-1}$, 13.50 cm and 7.32 cm) noted a significant increase. However, the control plants had the lowest values for fruit number (26.76 fruit $plant^{-1}$), fruit length (11.29 cm) and fruit diameter (6.50 cm). Application of TiO_2 at a concentration of 100 mg L^{-1} gave the highest productivity (47.29 t ha^{-1}) as compared to the control (unsprayed plants) that showed the lowest productivity values (38.67 t ha^{-1}). Furthermore, the weight of the fruits did not report a significant change at 0.05 level.

The binary interaction between the environmental factors and genotypes showed a significant impact on some of the traits studied (Table 6). Consequently, the interaction [saran cover (C1) x Black Beauty (G1)] appeared to have a greater number of fruits (39.54 fruit $plant^{-1}$) compared to the interaction [non-woven fabric cover (C2) x Aswad F1 (G3)], which gave the fewest number of fruits (25.45 fruit $plant^{-1}$). In addition, the interaction (C2) x (G3) showed better performance for the fruit weight (217.86 g $fruit^{-1}$) in comparison with the interaction (C0) x (G1), which gave the minimum fruit weight (136.05 g $fruit^{-1}$). Also, the interaction [(C2) x Raheeb F1 (G2)] provided the maximum total productivity of (54.34 t ha^{-1}). On the contrary, the interaction of (C0) and (G3) recorded the lowest total productivity of (32.67 t ha^{-1}). The triple interaction of the factors did not have a significant effect on these traits.

Leaf and fruit chemical parameters

The different growing environments reflect a substantial effect in reducing heat stress. The saran cover (C1) did not show any significant difference from the non-woven fabric cover (C2). In both conditions, proline levels showed a low concentration of the leaf proline content in comparison to the open-field condition (C0) where the leaf proline content was high (96.20 µg g^{-1} F.W.). Moreover, C2 treatment was superior showing high POD and SOD activities (7.03 unit mg^{-1} protein and 29.20 unit mg^{-1}

Table 4. The effect of heat stress, titanium concentrations on the growth of three genotypes of eggplant represented by the triple interaction effects

Stress conditions x Eggplant genotypes x Titanium concentrations			Plant height (cm)	Branches $plant^{-1}$	Leaves $plant^{-1}$	Dry weight (g $plant^{-1}$)	Total chlorophyll (mg 100 g^{-1} F.W.)
	G1	0	88.50	5.68	134.11	185.00	64.63
	G1	100	75.50	6.55	182.11	201.68	101.91
	G1	200	94.52	7.55	183.79	239.07	101.00
	G2	0	67.50	4.11	171.77	144.98	68.22
C0	G2	100	72.00	4.89	173.11	140.03	93.88
	G2	200	77.14	4.66	209.22	166.66	100.69
	G3	0	67.17	4.44	146.78	113.21	64.47
	G3	100	71.50	4.96	171.44	145.02	96.94
	G3	200	69.67	5.78	146.14	142.33	102.26
	G1	0	105.21	4.22	139.17	167.56	85.14
	G1	100	106.67	4.77	157.00	256.67	91.85
	G1	200	119.17	5.66	167.63	268.42	108.35
	G2	0	82.50	3.44	90.05	116.05	79.00
C1	G2	100	82.75	5.00	110.67	113.51	97.29
	G2	200	79.00	4.33	131.55	140.09	97.07
	G3	0	80.17	3.44	100.33	111.94	67.70
	G3	100	85.00	5.32	143.50	131.77	104.72
	G3	200	80.17	4.33	139.83	128.43	109.44
	G1	0	136.31	6.39	150.33	295.20	61.78
	G1	100	130.17	6.98	166.00	285.23	84.99
	G1	200	140.99	7.95	172.00	311.51	85.92
	G2	0	100.84	4.98	112.59	141.80	73.55
C2	G2	100	112.85	5.93	125.67	150.94	87.46
	G2	200	106.33	5.63	175.67	122.55	82.50
	G3	0	102.79	4.18	122.83	149.21	63.07
	G3	100	116.39	4.65	142.33	156.77	84.94
	G3	200	109.67	4.74	153.00	211.27	114.85
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**

Non-significant values based on ANOVA Results are denoted via N.S.

Table 5. The effect of titanium on the yield parameters of three eggplant genotypes under heat stress conditions represented by the main and bi-interaction effects

Treatments			Fruit No. plant^{-1}	Fruit weight (g)	Fruit length (cm)	Fruit diameter (cm)	Total yield (t ha^{-1})
Stress Conditions		C0	28.72	146.05	11.39	6.54	36.18
		C1	32.69	157.86	12.27	7.04	45.44
		C2	28.62	200.44	13.80	7.58	50.63
$LSD_{0.05}$			**3.85**	**19.16**	**N.S.**	**N.S.**	**5.39**
Eggplant Genotypes		G1	33.09	161.27	9.22	8.39	46.55
		G2	29.82	165.42	13.82	6.68	43.53
		G3	27.13	177.66	14.42	6.09	42.17
$LSD_{0.05}$			**3.45**	**6.64**	**0.85**	**1.15**	**N.S.**
Titanium Concentrations		0	26.76	166.15	11.29	6.54	38.67
		100	30.67	175.63	12.67	7.30	47.29
		200	32.60	162.57	13.50	7.32	46.28
$LSD_{0.05}$			**2.97**	**N.S.**	**0.59**	**0.49**	**4.03**
Stress Conditions X Eggplant Genotypes	C0	G1	33.93	136.05	8.59	8.17	41.12
		G2	26.29	154.52	13.18	6.06	34.76
		G3	25.94	147.59	12.39	5.39	32.67
	C1	G1	39.54	143.05	9.00	8.42	50.57
		G2	28.53	162.98	13.26	6.54	41.49
		G3	29.99	167.53	14.56	6.17	44.24
	C2	G1	25.79	204.71	10.06	8.58	47.94
		G2	34.64	178.74	15.03	7.43	54.34
		G3	25.45	217.86	16.31	6.72	49.60
$LSD_{0.05}$			**5.04**	**19.28**	**N.S.**	**N.S.**	**7.99**
Stress Conditions X Titanium Concentrations	C0	0	24.00	157.42	10.22	6.11	32.27
		100	28.88	145.51	11.83	6.83	36.59
		200	33.27	135.24	12.11	6.67	39.69
	C1	0	31.36	149.26	10.76	6.46	41.17
		100	33.88	165.57	12.79	7.63	48.74
		200	32.82	158.75	13.27	7.05	46.40
	C2	0	24.92	191.78	12.89	7.06	42.57
		100	29.27	215.81	13.39	7.44	56.55
		200	31.69	193.72	15.13	8.24	52.75
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**
Eggplant Genotypes X Titanium Concentrations	G1	0	29.97	153.40	8.53	7.71	39.56
		100	34.79	166.53	8.72	9.07	50.57
		200	34.50	163.89	10.40	8.39	49.51
	G2	0	26.58	173.22	12.32	6.41	40.79
		100	30.58	172.90	14.55	6.44	47.06
		200	32.28	150.13	14.60	7.17	42.74
	G3	0	23.73	171.84	13.02	5.50	35.66
		100	26.65	187.45	14.74	6.39	44.25
		200	31.01	173.69	15.50	6.39	46.59
$LSD_{0.05}$			**N.S.**	**N.S.**	**1.02**	**N.S.**	**N.S.**

Non-significant values based on ANOVA Results are denoted via N.S.

Table 6. The effect of titanium on the yield parameters of three eggplant genotypes under heat stress conditions represented by the triple interaction

Stress conditions X Eggplant genotypes X Titanium concentrations			Fruit No. plant^{-1}	Fruit weight (g)	Fruit length (cm)	Fruit diameter (cm)	Total yield (t ha^{-1})
	G1	0	32.25	136.69	7.67	7.67	38.83
	G1	100	32.50	142.29	8.83	8.67	41.30
	G1	200	37.03	129.18	9.26	8.17	43.24
	G2	0	21.17	177.83	12.17	5.50	33.30
C0	G2	100	29.75	142.26	13.48	6.00	35.95
	G2	200	27.95	143.48	13.90	6.67	35.03
	G3	0	18.59	157.73	10.83	5.17	24.67
	G3	100	24.39	151.96	13.17	5.83	32.53
	G3	200	34.84	133.06	13.17	5.17	40.80
	G1	0	37.35	131.83	8.58	7.64	44.19
	G1	100	42.80	139.36	8.33	9.55	53.45
	G1	200	38.48	157.97	10.08	8.08	54.07
	G2	0	27.68	165.54	11.46	6.40	40.59
C1	G2	100	30.25	168.15	14.33	6.67	45.89
	G2	200	27.65	155.27	14.00	6.56	38.00
	G3	0	29.07	150.41	12.23	5.33	38.72
	G3	100	28.59	189.19	15.72	6.67	46.87
	G3	200	32.33	163.00	15.72	6.50	47.14
	G1	0	20.30	191.68	9.33	7.83	35.65
	G1	100	29.08	217.94	9.00	9.00	56.96
	G1	200	27.97	204.51	11.86	8.92	51.22
	G2	0	30.91	176.28	13.33	7.33	48.48
C2	G2	100	31.75	208.30	15.83	6.67	59.34
	G2	200	41.25	151.64	15.92	8.29	55.20
	G3	0	23.54	207.37	16.00	6.00	43.60
	G3	100	26.96	221.20	15.33	6.67	53.36
	G3	200	25.85	225.01	17.61	7.50	51.84
	$LSD_{0.05}$		**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**

Non-significant values based on ANOVA Results are denoted via N.S.

protein, respectively), while the treatment C0 showed an increase in activities of the enzyme POD and SOD (17.23 unit mg^{-1} protein and 61.61 unit mg^{-1} protein). The treatments under the C2 condition had a significant effect on potassium content in the leaves. The levels of potassium in open field condition C0 and the saran cover condition (C1) were found to be 3.17 % and 2.86 % respectively. Heat stress environments had no significant effect on the leaf nitrogen rate.

The results for genotype treatments showed that the Black Beauty (G1) variety was significantly superior, showing the highest SOD activity (55.35 unit mg^{-1} protein) as compared to the Raheeb F1 (G2) hybrid, which gave the lowest activity (33.37 unit mg^{-1} protein) (Table 7). Eggplant genotypes did not show a significant difference at 0.05 level for the leaf traits such as proline, POD, nitrogen and potassium.

Spraying of titanium oxide (TiO_2) had a substantial effect on the eggplant plants, where the concentration of 200 mg L^{-1} provided the highest values of proline, POD and SOD in the leaves (82.04 µg g^{-1} F.W., 12.92 unit mg^{-1} protein and 58.42 unit mg^{-1} protein, respectively). On the other hand, the control plants (without TiO_2 treatment) recorded the lowest values of proline, POD and SOD (51.48 µg g^{-1} F.W., 8.44 unit mg^{-1} protein and 31.14 unit mg^{-1} protein, respectively). Titanium treatment at the concentration of 100 mg L^{-1} yielded the maximum rate of nitrogen in leaves (3.63 %) as compared with the control. TiO_2 application had no substantial impact on the leaf potassium rate. In addition, the triple interaction had no significant effect on the leaf parameters (Table 8).

The quality of crop yields tends to improve in protected agricultural systems compared to open field systems. High vegetation indices are noted in C1 and C2 cover conditions. A positive response has been noted after shading on various parameters related to crop yield. The coverings played a substantial role in lowering the heat stress temperatures. Plants exposed to heat stress, i.e. open field conditions, showed a decrease in plant growth and production. A rise in temperature by 1 °C induced a reduction of crop production by approximately 17 % during the growing season (28). This can be ascribed to high -temperature stress-induced decrease in the amount of active protein due to its breakdown or loss of its natural form. Besides this, other events such as a change in the nature of nucleic acids, alteration in membrane permeability due to accumulation of certain toxic substances, high rate of transpiration, dehydration reduced the overall growth and decreased flower formation. In addition, the leaves show a decrease in photosynthesis efficiency, evident through a reduction of carbohydrates along with a rise in the rate of respiration (29). High heat stress also disrupts enzymes and inhibits many metabolic pathways. This results from the accumulation of free radicals (ROS and RNS) such as $O_2^{\bullet -}$, OH•, H_2O_2, ROO• and NO•, leading to oxidative stress (30,31). These free radicals act as signal molecules, which stimulate the antioxidant defense mechanism of plants. Both enzymatic antioxidants such as SOD, CAT, APX, GR, GPX, dehydroascorbate reductase (DHAR) and non-enzymatic antioxidants such as ascorbates, glutathione, thiol and phenols increase in this case (10). This is what leads to the rise of antioxidants in the open field (C0) conditions as compared to

Table 7. The effect of titanium on leaf biochemical parameters of three eggplant genotypes under heat stress conditions represented by the main and bi-interaction effects

Treatments			Leaf proline (µg g^{-1} F.W)	POD activity (unit mg^{-1} protein)	SOD activity (unit mg^{-1} protein)	Leaf N (%)	Leaf K (%)
Stress Conditions		C0	96.20	17.23	61.61	3.37	3.14
		C1	51.10	8.78	41.91	3.42	2.86
		C2	52.13	7.03	29.20	3.53	3.14
$LSD_{0.05}$			**30.99**	**1.60**	**10.66**	**N.S.**	**0.23**
Eggplant Genotypes		G1	76.18	9.61	55.35	3.47	3.11
		G2	69.73	12.44	33.37	3.42	3.01
		G3	53.53	10.99	44.00	3.44	3.06
$LSD_{0.05}$			**N.S.**	**N.S.**	**6.61**	**N.S.**	**N.S.**
Titanium Concentrations	0		51.48	8.44	31.14	3.08	2.98
	100		65.92	11.68	43.15	3.63	3.15
	200		82.04	12.92	58.42	3.62	3.05
$LSD_{0.05}$			**13.13**	**1.96**	**8.28**	**0.16**	**N.S.**
Stress Conditions X Eggplant Genotypes	C0	G1	112.59	12.64	74.17	3.59	3.31
		G2	109.96	20.94	45.76	3.36	2.96
		G3	66.05	18.11	64.91	3.17	3.14
	C1	G1	55.61	8.44	55.20	3.31	2.79
		G2	51.94	8.51	35.68	3.46	2.95
		G3	45.77	9.39	34.86	3.51	2.85
	C2	G1	60.34	7.73	36.68	3.51	3.22
		G2	47.28	7.87	18.68	3.43	3.11
		G3	48.77	5.48	32.23	3.63	3.19
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**0.31**	**N.S.**
Stress Conditions X Titanium Concentrations	C0	0	69.57	13.75	46.55	2.96	3.12
		100	102.02	19.06	56.06	3.66	3.26
		200	117.01	18.87	82.23	3.50	3.03
	C1	0	45.62	6.04	27.80	3.08	2.74
		100	51.10	8.54	45.12	3.52	2.94
		200	56.59	11.76	52.81	3.67	2.91
	C2	0	39.24	5.52	19.08	3.19	3.07
		100	44.62	7.44	28.28	3.71	3.25
		200	72.53	8.11	40.23	3.68	3.20
$LSD_{0.05}$			**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**
Eggplant Genotypes X Titanium Concentrations	G1	0	60.82	6.45	42.77	3.05	3.19
		100	80.55	12.67	53.40	3.72	3.27
		200	87.17	9.70	69.87	3.63	2.87
	G2	0	48.31	10.82	23.47	3.10	2.74
		100	71.69	10.71	33.02	3.57	3.16
		200	89.18	15.79	43.62	3.58	3.12
	G3	0	45.31	8.05	27.19	3.08	3.01
		100	45.50	11.66	43.04	3.60	3.03
		200	69.77	13.26	61.77	3.63	3.14
$LSD_{0.05}$			**N.S.**	**3.39**	**N.S.**	**N.S.**	**0.30**

Non-significant values based on ANOVA Results are denoted via N.S.

Table 8. The effect of titanium on leaf biochemical parameters of three eggplant genotypes under heat stress conditions represented by the triple interaction

Stress conditions X Eggplant genotypes X Titanium concentrations			Leaf proline (µg g^{-1} F.W.)	POD activity (unit mg^{-1} protein)	SOD activity (unit mg^{-1} protein)	Leaf N (%)	Leaf K (%)
	G1	0	81.50	7.05	65.88	3.24	3.43
	G1	100	125.78	18.15	70.47	3.83	3.50
	G1	200	130.50	12.72	86.15	3.70	2.99
	G2	0	83.15	20.13	32.78	3.09	2.84
C0	G2	100	119.40	20.70	42.17	3.51	3.11
	G2	200	127.34	21.99	62.32	3.49	2.94
	G3	0	44.07	14.08	40.98	2.56	3.10
	G3	100	60.89	18.33	55.53	3.64	3.18
	G3	200	93.18	21.91	98.22	3.32	3.16
	G1	0	55.05	5.33	41.42	2.78	2.84
	G1	100	60.93	9.89	57.70	3.67	3.01
	G1	200	50.84	10.11	66.49	3.47	2.53
	G2	0	37.04	7.30	21.06	3.15	2.53
C1	G2	100	51.65	4.48	38.42	3.55	3.18
	G2	200	67.12	13.75	47.55	3.68	3.13
	G3	0	44.78	5.50	20.93	3.33	2.86
	G3	100	40.73	11.26	39.25	3.35	2.63
	G3	200	51.80	11.43	44.39	3.85	3.07
	G1	0	45.90	6.96	21.01	3.14	3.29
	G1	100	54.95	9.97	32.03	3.67	3.30
	G1	200	80.17	6.26	56.99	3.73	3.09
	G2	0	24.74	5.04	16.56	3.07	2.85
C2	G2	100	44.01	6.94	18.46	3.65	3.18
	G2	200	73.08	11.61	21.00	3.58	3.30
	G3	0	47.08	4.57	19.66	3.35	3.08
	G3	100	34.89	5.41	34.33	3.83	3.29
	G3	200	64.32	6.45	42.71	3.72	3.20
	$LSD_{0.05}$		**N.S.**	**N.S.**	**N.S.**	**N.S.**	**N.S.**

Non-significant values based on ANOVA Results are denoted via N.S.

saran cover (C1) and non-woven fabric cover (C2). Nevertheless, treatments under C2 conditions can provide an ideal environment for mitigating the deleterious effects of heat stress as well as boosting crop growth and productivity. These results are consistent with previous studies on tomatoes (12) and studies on sweet peppers and eggplant (32).

The results from this study showed that genotypic makeup has an obvious influence on some of the vegetative growth, yield and chemical parameters. The marked variation in several traits is due to the nature of the genetic background and the way plants interact with the environmental conditions. Also, it is due to the suitability of genotypes for the prevalent experimental conditions or may be due to the physiological differences in the assimilation of the primary compounds formed by biological processes. Consequently, this has been reflected in plant production capacity and the gene expression of the studied hybrids (33). The reason for the superiority of Beauty Black is the nature of the genetic profile of the variety and its influence by environmental conditions (34). These results are consistent with previous studies (35).

Results indicate that titanium concentrations significantly influenced the vegetative growth, yield and biochemical parameters of eggplant. This may be due to the fact that TiO_2 improves crop performance by enhancing chlorophyll content and photosynthesis as well as stimulating some enzymes, increasing the enzyme activity of lipoxygenase and nitrate reductase (36,37). Besides this, the role of titanium in enhancing the activity of antioxidant enzymes such as peroxidase, catalase, absorption of water and nutrients, acceleration in growth, improvement in plant resistance to stress conditions and improvements in the activity of enzymes such as nitrogenase, nitrate reductase (38,39) is well known. It also acts as the Redox Catalyzer in electron transport from photosystem II to photosystem I (40,41). The total chlorophyll content and number of leaves increased and this reflected a positive effect on other vegetable traits as well as yield components. These results are consistent with the studies conducted on pepper (42) and tomato plants (43). This has contributed positively to the increase in growth of eggplant. These current results are consistent with earlier findings which that showed the role of TiO_2 in the improvement of nutrient absorption (17,44).

Conclusion

The response of the three eggplant genotypes to titanium application under heat stress conditions was evaluated. The results demonstrated a positive response in genotypes on exposure to 200 mg L^{-1} of titanium oxide given as foliar application. The highest effect on the vegetative growth was noted in Black Beauty (G1) as evident through parameters such as vegetative, productive and biochemical characteristics. The non-woven fabric cover (C2) was found to be the best option in terms of providing protection from heat stress damage and enhancing overall crop growth.

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Authors' contributions

QMH conducted the field experiment and collected field measurements. ASA supervised the entire research and contributed to analysing the data. QMH wrote, reviewed and edited this manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors have no conflict of interest to declare.

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References

1. Khalil MAI. Vegetable physiology. 1st ed. The Knowledge Facility in Alexandria, Arab Republic of Egypt; 2013
2. Kandoliya UK, Bajaniya VK, Bhadja NK, Bodar NP, Golakiya BA. Antioxidant and nutritional components of eggplant (*Solanum melongena* L.) fruit grown in Saurastra region. Int J Curr Microbiol Appl Sci. 2015;4(2):806-13.
3. Okmen B, Sigva HO, Mutlu S, Doganlar S, Yemenicioglu A, Frary A. Total antioxidant activity and total phenolic contents in different Turkish eggplant (*Solanum melongena* L.) cultivars. Int J Food Prop. 2009;12(3):616-24. https://doi.org/10.1080/10942910801992942
4. Gramazio P, Prohens J, Plazas M, Andújar I, Herraiz FJ, Castillo E, et al. Location of chlorogenic acid biosynthesis pathway and polyphenol oxidase genes in a new interspecific anchored linkage map of eggplant. BMC Plant Biol. 2014;14(1):1-5. https://doi.org/10.1186/s12870-014-0350-z
5. Gurbuz N, Uluisik S, Frary A, Frary A, Doganlar S. Health benefits and bioactive compounds of eggplant. Food Chem. 2018;268:602-10. https://doi.org/10.1016/j.foodchem.2018.06.093
6. Atul Kumar AK, Dahiya MS, Bhutani RD. Performance of brinjal genotypes in different environments of spring-summer season. Haryana J Hort Sci. 2000;29(1/2):82-3.
7. Athafa QJ. Effect of ascorbic acid foliar application and chelated iron on growth and yield of two eggplant hybrids (*Solanum melongena* L.). Diyala Agric Sci J. 2018;10(1):73-80.
8. Rao SM, Raghavendra R, Reddy SJ. Physiology and molecular biology of stress tolerance in plants. Netherlands: Springer; 2006
9. Kumar V, Sharma M, Khare T, Wani SH. Impact of nanoparticles on oxidative stress and responsive antioxidative defense in plants. In: Nanomaterials in plants, algae and microorganisms. Academic Press; 2018. p. 393-406 https://doi.org/10.1016/B978-0-12-811487-2.00017-7
10. Thakur S, Asthir B, Kaur G, Kalia A, Sharma A. Zinc oxide and titanium dioxide nanoparticles influence heat stress tolerance mediated by antioxidant defense system in wheat. Cereal Res Commun. 2022;50:385-96. https://doi.org/10.1007/s42976-021-00190-w
11. Shahak Y, Gussakovsky EE, Gal E, Ganelevin R. ColorNets: Crop protection and light-quality manipulation in one technology. Acta Hortic. 2004;(659):143-51. https://doi.org/10.17660/ActaHortic.2004.659.17
12. Masabni J, Sun G, Niu G, Del Valle P. Shade effect on growth and productivity of tomato and chili pepper. Hort Technol. 2016;26 (3):344-50. https://doi.org/10.21273/HORTTECH.26.3.344
13. Gómez-Merino FC, Trejo-Téllez LI. The role of beneficial elements in triggering adaptive responses to environmental stressors and improving plant performance. In: Vats S, editor. Biotic and abiotic stress tolerance in plants. Singapore: Springer; 2018. p. 137-72 https://doi.org/10.1007/978-981-10-9029-5_6
14. Bacilieri FS, Pereira de Vasconcelos AC, Quintao Lana RM, Mageste JG, Torres JL. Titanium (Ti) in plant nutrition-A review. Aust J Crop Sci. 2017;11(4):382-6. https://doi.org/10.21475/ajcs.17.11.04.pne202
15. Kleiber T. Effect of titanium application on lettuce growth under Mn stress. J Elem. 2017;22(1):329-37.
16. Lyu S, Wei X, Chen J, Wang C, Wang X, Pan D. Titanium as a beneficial element for crop production. Front Plant Sci. 2017;8:597. https://doi.org/10.3389/fpls.2017.00597
17. Haghighi M, Daneshmand B. Beneficial effect of titanium on plant growth, photosynthesis and nutrient trait of tomato cv. Foria. Iran Agric Res. 2018;37(1):83-8.
18. Al-Bayati AS, Turk HAM, Al-Tufaili AKH, Aboohanah MA, Mohan RK, Qader HM. Characterization of green onion with NPK fertilization and foliar application of hornwort extract. Sabrao J Breed Genet. 2023;55(6):2140-8. https://doi.org/10.54910/sabrao2023.55.6.25
19. Hocking PJ, Randall PJ, Demarco D, Bamforth I. Assessment of the nitrogen status of field-grown canola (*Brassica napus* L.) by plant analysis. Aust J Exp Agric. 1997;37(1):83-92. https://doi.org/10.1071/EA95068
20. Goodwin TW. Chemistry and biochemistry of plant pigment. 2nd ed. Academic Press; 1976. p. 373
21. Bates LS, Waldren RP, Teare ID. Rapid determination of free proline for water stress studies. Plant Sci. 1973;39:205-07. https://doi.org/10.1007/BF00018060
22. Salman AD. Growth variables and quantitative and qualitative yield of cherry tomato plants Agrosol and Enraizal sprayed under exposed cultivation conditions and plastic house. Masters [thesis]. Baghdad University; 2014
23. Beyer WF Jr, Fridovich I. Assaying for superoxide dismutase activity: some large consequences of minor changes in conditions. Anal Biochem. 1987;161 (2):559-66. https://doi.org/10.1016/0003-2697(87)90489-1
24. Pitotti A, Elizalde BE, Anese M. Effect of caramelization and Maillard reaction products on peroxidase activity. J Food Biochem. 1994;18 (6):445-57. https://doi.org/10.1111/j.1745-4514.1994.tb00515.x
25. Jackson ML. Soil chemical analysis. Englewood Cliffs (NJ): Prentice Hall; 1958
26. Page AL, Miller RH, Keeney DR. Methods of soil analysis. Part 2: chemical and microbiological properties. Madison (WI): American Society of Agronomy and Soil Science Society of America; 1982. p. 539-79 https://doi.org/10.2134/agronmonogr9.2.2ed
27. Analytical Software. Statistix 10: user's manual. Tallahassee (FL); 2013
28. Lobell DB, Asner GP. Climate and management contributions to recent trends in U.S. agricultural yields. Science. 2003;299 (5609):1032. https://doi.org/10.1126/science.1078475
29. Efeoglu B, Terzioglu S. Photosynthetic responses of two wheat varieties to high temperature. Eurasia J Biosci. 2009;3:97-106. https://doi.org/10.5053/ejobios.2009.3.0.13
30. Asada K. Production and scavenging of reactive oxygen species in chloroplasts and their functions. Plant Physiol. 2006;141:391-6. https://doi.org/10.1104/pp.106.082040
31. Hasanuzzaman M, Nahar K, Alam MM, Roychowdhury R, Fujita M. Physiological, biochemical and molecular mechanisms of heat stress tolerance in plants. Int J Mol Sci. 2013;14(5):9643-84. https://doi.org/10.3390/ijms14059643
32. Aied KY, Zaidan GJ, Abdulrahman HB. Using plastic house shading

in the summer improves eggplant and sweet pepper yield. Pesqui Agropecu Trop. 2023;53:e74478. https://doi.org/10.1590/1983-40632023v5374478

33. Burhan AK, Al-Taey DK. Effect of potassium humate, humic acid and compost of rice wastes in the growth and yield of two cultivars of dill under salt stress conditions. Adv Nat Appl Sci. 2018;12(11):1-6.
34. Mukhtar FA. Gardening and plant breeding. Baghdad: Ministry of Higher Education and Scientific Research; 1988. p. 232
35. Al-Zubaidi AHA. Effect of foliar sprays (basfoliar kelp and fylloton) on growth of varieties *Solanum melongena* L. and yield. Babylon Univ J Pure Appl Sci. 2018;26(1):276-89.
36. Sarmiento C, Daood H, Pais I, Biacs PA. Effect of titanium ascorbate on the lipoxygenase pathway of tomato and red pepper seedlings. J Plant Nutr. 1995;18(6):1291-9. https://doi.org/10.1080/01904169509364980
37. Hrubý M, Cigler P, Kuzel S. Contribution to understanding the mechanism of titanium action in plant. J Plant Nutr. 2002;25(3):577-98. https://doi.org/10.1081/PLN-120003383
38. Alcaraz CF, Sánchez MF, Giménez JL. Ascorbato de titanio, fertilizante foliar. Agric Rev Agropecu. 1991;708:636-8.
39. Navarro E, Baun A, Behra R, Hartmann NB, Filser J, Miao A, et al. Environmental behaviour and ecotoxicity of engineered nanoparticles to algae, plants and fungi. Ecotoxicology. 2008;17:372-86. https://doi.org/10.1007/s10646-008-0214-0
40. Carvajal M, Martínez-Sánchez F, Alcaraz CF. Effect of Ti (IV) on some indicators of physiological activity in *Capsicum annuum* L. J Hortic Sci. 1994;69(3):427-32. https://doi.org/10.1080/14620316.1994.11516471
41. Choi HG, Moon BY, Bekhzod K, Park KS, Kwon JK, Lee JH, et al. Effects of foliar fertilization containing titanium dioxide on growth, yield and quality of strawberries during cultivation. Hortic Environ Biotechnol. 2015;56:575-81. https://doi.org/10.1007/s13580-015-0023-3
42. Lopez-Moreno JL, Giménez JL, Moreno A, Fuentes JL, Alcaraz CF. Plant biomass and fruit yield induction by Ti (IV) in P-stressed pepper crops. Fert Res. 1995;43:131-36. https://doi.org/10.1007/BF00747692
43. Kleiber T, Markiewicz B. Application of "Tytanit" in greenhouse tomato growing. Acta Sci Pol Hortorum Cultus. 2013;12(3):117-26.
44. Burke DJ, Pietrasiak N, Situ SF, Abenojar EC, Porche M, Kraj P, et al. Iron oxide and titanium dioxide nanoparticles affect plant performance and root-associated microbes. Int J Mol Sci. 2015;16(10):23630-50. https://doi.org/10.3390/ijms161023630

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