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Interspecific Hybrid Rootstocks Improve Productivity of Tomato Grown under High-temperature Stress

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***Abstract.* Grafting can be a useful technology to improve productivity of vegetable crops, including tomato, particularly under the serious challenges of climate change for agricultural systems. This study aimed to evaluate the impact of some local tomato interspecific hybrid rootstocks along with Maxifort on the vegetative growth, productivity, and fruit quality of tomato under field production conditions. Heat-tolerant tomato hybrid 023 F_1 was used as a scion over the two late summer seasons of 2021 and 2022. Grafting 023 F_1 onto Maxifort or KFS-16 rootstocks resulted in the maximum plant growth. Similarly, Maxifort and KFS-16 rootstocks significantly increased the fruit setting percentage from 22.2% to 23.5% and 17.8% to 24.6%, total fruit yield from 33.5% to 53.7% and 29.6% to 51.6%, and marketable yields from 34.1% to 56.0% and 27.3% to 56.7%, respectively, during both seasons compared with nongrafted plants. These two rootstocks enhanced nutrient (nitrogen, phosphorus, potassium) uptake compared with nongrafted planted. However, grafting with the interspecific hybrid rootstocks (KFS-8 and KWS-9) significantly decreased the content of catalase, peroxidase, and proline, which might be associated with lower plant vigor and yield in these rootstocks. All rootstocks had an impact on fruit chemical composition; however, generally, Maxifort and KFS-16 had greater contents of vitamin C, β-carotene, and total antioxidants than nongrafted plants. KFS-16 had also greater lycopene content than nongrafted plants. These results demonstrate the potential use of Maxifort and local rootstock KFS-16 to boost the growth and yield of tomato plants under high-temperature stress in the late summer season.**

Tomato (*Solanum lycopersicum* L.) is one of the most important and widely distributed vegetable crops grown worldwide. The total world cultivated area of tomato is approximately 5 million ha, with an average yield of 36.98 tons·ha^{-1}, and the total production was 189 million tons in 2021 (FAOSTAT 2023). China is the largest tomato producer, whereas Egypt occupies the fifth rank in terms of tomato production, with approximately 6.24 million tons annually produced from the total cultivated area (150,109 ha), with an average yield of 41.6 tons·ha^{-1} in 2021 (FAOSTAT 2023). Tomato is beneficial to human health because it contains different antioxidants (e.g., carotenoids especially lycopene, β-carotene, ascorbic acid, vitamin A, and phenolic compounds, particularly flavonoids) as well as several minerals such as calcium, potassium, and phosphorus (Bjarandottir 2023), which might help prevent diseases such as cancer, cardiovascular risk, osteoporosis cellular aging, and chronic diseases (Ali et al. 2020).

Tomato needs relatively warm weather during all growing stages and is able to grow well between 15 and 32 °C, depending on the cultivar. The most appropriate temperatures for flowering and fruit set ranged between 23 and 28 °C (day) and 17 and 22 °C (night), respectively, according to Ayankojo and Morgan (2020) and Alsamir et al. (2021). Tomato is grown in Egypt over the year during five main seasons. The best season for tomato cultivation is the summer season, which is from February to May. During the late summer season (May–September), tomato production faces both biotic stress (mainly *Tuta absoulta*, tomato yellow curl virus) and abiotic stress (mainly heat stress) that significantly decrease production and fruit quality during this season. At high temperatures (>35 °C), the anther and pollen development and pollen viability reduced, which directly influenced the fruit set percentage, the number of fruits, and fruit size and weight, and it delayed the development of normal fruit colors (Mesa et al. 2022; Raja et al. 2019). The reproductive stage of tomatoes is more sensitive to heat stress than the vegetative seedling phase (Alsamir et al. 2021; Dasgan et al. 2021). At the seedling stage, heat stress can reduce the photosynthesis rate in plants (Moore et al. 2021; Zahra et al. 2023). There are many strategies to manage heat stress, including growing tolerant tomato cultivars (Osei-Bonsu et al. 2022; Shubha et al. 2021), using chemical fertilizers and antistress compounds (Guo et al. 2022; Tonhati et al. 2020), shadow net (Ahmed 2019), and different protective cultivation methods, or by grafting onto different rootstocks (Shehata et al. 2022).

Grafting is a technical process through which two plants are combined (one of which is called the rootstock and the other is the scion) and produce a new plant, namely, a grafted plant. Vegetable grafting is mainly applied for both solanaceous and cucurbitaceous crops, including tomato, pepper, eggplant, watermelon, cucumber, and melon (Bayoumi et al. 2022). Currently, there is a huge grafted tomato business in numerous countries in Latin America, Europe, and Asia (Ray et al. 2023). However, grafting in Egypt is widely used mainly for watermelon and cucumber. Grafting for tomato is still limited because of the lack of local rootstocks and high prices of foreign rootstock seeds. Grafting tomato might expand in the near future with increasing problems of soil-borne diseases, salinity, heat stress, and water scarcity in many regions in Egypt.

Grafting might improve growth, fruit yield (Zhang et al. 2021), fruit quality traits (Zhou et al. 2022), resistances against soil-borne diseases (Manickam et al. 2021; Shalaby et al. 2022), foliar diseases like tomato mosaic virus (Akhtar et al. 2019; Spanò et al. 2020), tolerance to abiotic stresses such as salinity (Sanwal et al. 2022; Zeist et al. 2023), drought (El-Mogy et al. 2022; Kazemi et al. 2021), and waterlogging, or hot and wet seasons (Evy and Rima 2020; Ray et al. 2023), and high temperatures (Lee et al. 2023). Rootstocks are usually designated to improve the tolerance of tomato scions to abiotic stress such as heat stress (Lee et al. 2023), which is achieved through translocation between rootstocks and scions of hormones, proteins, and nucleic acids, which can function as signaling molecules that alter the gene expression of scion genotypes (Balfagón et al. 2021; Shalaby et al. 2022). Furthermore, grafted plants usually increase the uptake of water and minerals compared with self-rooted plants as a result of the vigorous root system used as the rootstock (Fullana-Pericàs et al. 2020; Leonardi and Giuffrida 2006). According to Gisbert-Mullor et al. (2023), grafted pepper plants were more thermo-tolerant than nongrafted plants and exhibited higher antioxidant

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enzymes activity and lower hydrogen peroxide (H_2O_2) concentrations. Higher enzyme activities and proline accumulation levels and lower lipid peroxidation levels have been found in grafted tobacco plants compared with nongrafted plants (Liu et al. 2014). Moreover, greater chlorophyll fluorescence and lower electrolyte leakage have been reported for cucumber plants grafted onto different rootstocks under high-temperature stress conditions in greenhouses.

Interspecific hybrids have been used for grafting tomato to increase yield (Djidonou et al. 2017), drought tolerance (Nilsen et al. 2014), soil-borne disease resistance (Vanlay et al. 2022), or tolerance to salinity (Zeist et al. 2023). In contrast, interspecific hybrids have not been tested for grafting tomato under heat stress in open field conditions. This study aimed to evaluate the impact of different local interspecific hybrid tomato rootstocks along with Maxifort for grafting tomato to improve fruit yield and quality under high-temperature stress during the late summer season under open field conditions.

Materials and Methods

Plant materials and treatments. Two field trials were conducted in the late summer season from May to September in 2021 and 2022. These included eight treatments: six tomato rootstocks (five local rootstocks plus Maxifort) along with self-grafted and nongrafted control plants (Fig. 1). The tomato 023 F_1 hybrid was used as the scion for all rootstocks. This hybrid is commonly cultivated by growers in Egypt during the late summer season under high-temperature conditions because of its tolerance to high temperatures and tomato yellow leaf curl virus disease. Maxifort rootstock seeds were obtained from DeRuiter Seeds Company (France; https://www.vegetables.bayer.com), and the rest of the rootstocks seeds were developed by Dr. Mohamed Rakha as local rootstocks. Seeds of the 023 F_1 hybrid were obtained from the Gaara Seeds Company (Cairo, Egypt), which were exported from Sakata Vegetable Europe (Uchaud, France; https://sakata-vegetables.eu). Six tomato rootstocks were selected for grafting with the 023 F_1 scion. All details about tomato rootstock species are presented in Table 1.

Grafting process. The grafting process was performed at the Grafting House nursery in Badr City in Al-Beheira governorate. Seeds of all rootstocks were sown 1 week before the scion in seedlings in Styrofoam trays (104 cells) for 35 d until uniformity of the seedlings (length and diameter) occurred. The trays were filled with common substrate comprising a mixture of coco peat and vermiculite (1:1, volume/volume). The splice grafting method was performed, whereby the rootstock was cut at a 45-degree angle from under the cotyledons, whereas the scion was cut from above the cotyledons using a sharp blade as described by Lee et al. (2010) and Maurya et al. (2019). The grafting union between the scion and rootstock was held together using silicon clips (diameter, 2.5 mm; height, 1.5 cm). Grafted seedlings were planted in other seedlings trays that were filled with the fertilized peatmoss and placed in healing chambers for 7 to10 d at 24 to 27 °C with relative humidity of 90% to 95% using shading net and ~70% to 80% external radiation. Grafted seedlings were moved to a plastic greenhouse with partial shading (65%) to avoid excessive heat during the daylight for 7 d. Successful grafted seedlings were transferred into the plastic greenhouse nursery for further acclimatization for 5 d at temperatures of 25 to 27 °C with air humidity of 60% to 65%. Grafted and nongrafted seedlings were irrigated daily and fertilized weekly until they were transferred into the open field of the experimental location 21 d after grafting.

Experimental site and growth conditions. Grafted and nongrafted tomato seedlings were transplanted on 11 May and 7 Jun in 2021 and 2022 during both seasons, respectively, at Baltiem district, Kafr El-Sheikh Governorate, Egypt (31°6′22.752″N, 30°56′31.11″E), which comprise the highest summer temperatures in Egypt. Soil texture was clay. The pH values were 7.90 and 7.70, and electrical conductivity (EC) values were 2.15 and 3.21 $dS \cdot m^{-1}$ during both seasons, respectively. Salinity of irrigation water had average EC values of 1.9 and 2.2 $dS \cdot m^{-1}$ during both seasons, respectively. The grafted seedlings and control were transplanted in the experimental plots with an area of 24 m^2 (length, 12 m; width, 2 m). According to the recommendations of the Ministry of Agriculture and Land Reclamation (EMALR 2019), plants were watered and fertilized twice per week using a drip irrigation system. The regular practices such as cultivation, irrigation, and pest control were applied whenever necessary, as usually performed by the local growers. Weekly average maximum and minimum air temperatures and relative humidity percentages recorded 15 cm above the plants during the growing period in both seasons are shown in Fig. 2.

Data recorded. Five plants for each treatment were selected to measure vegetative growth traits at 65 d after transplanting (DAT) and included plant height (cm), number of lateral branches, fresh and dry weights per plant (g), and leaf area per plant (dm^2) using a portable leaf area meter model (LI-3050A).

At 65 DAT, physiological and biochemical traits were measured. The total chlorophyll content (mg/plant) was measured using a spectrophotometer and N, N-dimethylformamide was measured (663 nm and 645 nm, respectively) as described by Moran (1982). Nutrient [nitrogen (N), phosphorus (P), and potassium (K)] uptake in plants (g/plant) was determined as follows: dry weight of the plant (g) × the nutrient (N, P, and K) concentration of the plant (%) $\times 10^{-2}$, as reported by Godebo et al. (2021). Proline was extracted with sulphosalicylic acid. The red chromophore was created when the extracted proline reacted with ninhydrin acid. At 520 nm, the absorbance was measured as described by Bates et al. (1973). Catalase and peroxidase enzymes are often measured using assays based on the reduction in hydrogen peroxide absorbance at $\lambda = 240$ nm and 470 nm, respectively, as described by Aebi (1984) and Polle et al. (1994), respectively.

Five plants were selected from each plot at 55 DAT, and five clusters from each plant were randomly selected and labeled to estimate the fruit setting percentage according to the following equation:

$$\text{Fruit setting \%} = \frac{\text{Number of successful fruit setting}}{\text{Total number of flowers}} \times 100$$

Early yield (first two pickings) and total yield (all four pickings) were recorded as the weight of fruits (kg/plant and ton/ha). The total yield was classified as the marketable yield and unmarketable yield (ton/ha). The unmarketable yield includes all fruits with blossom-end rot, sunscald, and cracks, in addition to malformed and diseased infected fruits, which were calculated as the weight and number of fruits in each treatment.

Five fruits were randomly selected from each treatment of the second picking during both seasons to measure some chemical quality parameters of fruits, including total

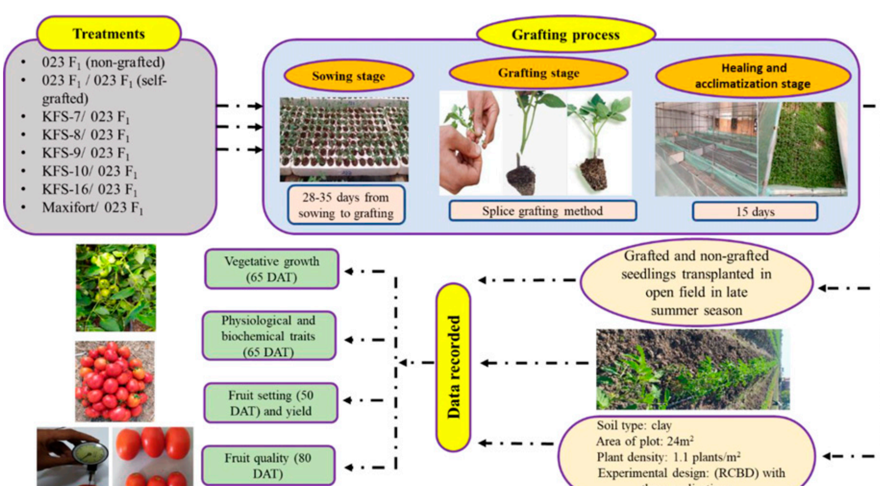

Fig. 1. An overview of plant materials and methods used during the present study.

Table 1. Details of different tomato rootstock species used in the experiment during the 2021 and 2022 seasons.

Rootstock name	Rootstock species	Importance of plant species for tomato breeding and grafting	References
KFS-7; KFS-8	*S. lycopersicum* × *S. galapagense*	Salt-tolerant; insect- and virus-resistant	Rakha et al. (2017); Pailles et al. (2020)
KFS-9	*S. lycopersicum* × *S. habrochaites*	Cold- and frost-tolerant; resistant to viruses, soil-borne diseases, and insects	Liu et al. (2012)
KFS-10; KFS-16	*S. lycopersicum* × *S. pimpinellifolium*	Color and fruit quality; resistant to insects, nematodes, and diseases; drought- and salt-tolerant	Foolad (2013); Rakha et al. (2017)

Seeds of Maxifort were obtained from DeRuiter Seeds Company. The other tomato rootstock seeds were developed by Dr. Mohamed Rakha.
KFS = Kafrelsheikh.

soluble solids (TSS%), using a digital refractometer (model RFM 340-T) at 20 °C. Titratable acidity was measured by automatic titration (model TTROLINEE® TL 5000/20M2 BASE UNIT; 20 ML TZ 3130) as the citric acid percent by titration with 0.1 N sodium hydroxide up to pH 8.1, as described by Tigchelaar (1986). Vitamin C (mg/100 g fresh weight) was measured by titration with 2,6- dichlorophenol Indophenol blue in tomato fruits according to the Association of Official Analytical Chemists (1990). Lycopene and β-carotene contents of fruits were measured using a spectrophotometer at 663 nm, 645 nm, 505 nm, and 453 nm, according to Nagata and Yamashita (1992). Total phenols (mg GAE/g fresh weight) were analyzed using the folin ciocalteau reagent, as described by Singleton and Rossi (1965). The total antioxidant capacity (μmol TE/10 g fresh weight) was determined using the DPPH assay, as described by Binsan et al. (2008). These chemical analyses were conducted for the tomato fruits harvested during the second picking in the second season.

Experimental design and statistical analysis. Treatments were randomly distributed using a randomized complete block design with three replications. All data (vegetative growth, physiological and biochemical traits, fruit yield and fruit quality) were statistically determined using a one-way analysis of variance (ANOVA), in accordance with Snedecor and Cochran (1989). Duncan's multiple range test (Duncan 1965) was used to compare the means of the treatments. All statistical analyses were conducted using the "CoStat program" software package (version 6.311).

Results

Vegetative growth traits. Vegetative growth traits, including plant height, number of branches, leaf area, and fresh and dry weights of tomato plants, were significantly affected by grafting onto different rootstocks at 65 DAT during both seasons (Table 2, Fig. 3). Tomato grafted onto Maxifort and KFS-16 rootstocks had the tallest plants, the most branches, and the largest leaf area per plant. In contrast, tomato grafted onto KFS-7 and KFS-8 rootstocks had the shortest plants during both seasons. Self-grafted plants and both KFS-7 and KFS-9 rootstocks displayed the least branches per plant during both seasons. Nongrafted plants and KFS-7 displayed the smallest leaf area per plant during the 2021 season, whereas KFS-9 had the smallest leaf area per plant during the 2022 season. KFS-16, KFS-10, and Maxifort rootstocks had the heaviest fresh and dry weights of tomato plants. However, self-grafted plants had the lowest fresh and dry weights (Fig. 3).

Physiological and chemical traits. The total chlorophyll and nutrient (N, P, K) uptake of grafted and nongrafted tomato plants were significantly influenced by grafting during both seasons (Table 3). Maxifort, KFS-16, and KFS-10 rootstocks provided significantly higher total chlorophyll and nutrient (N, P, K) uptake values compared with those of

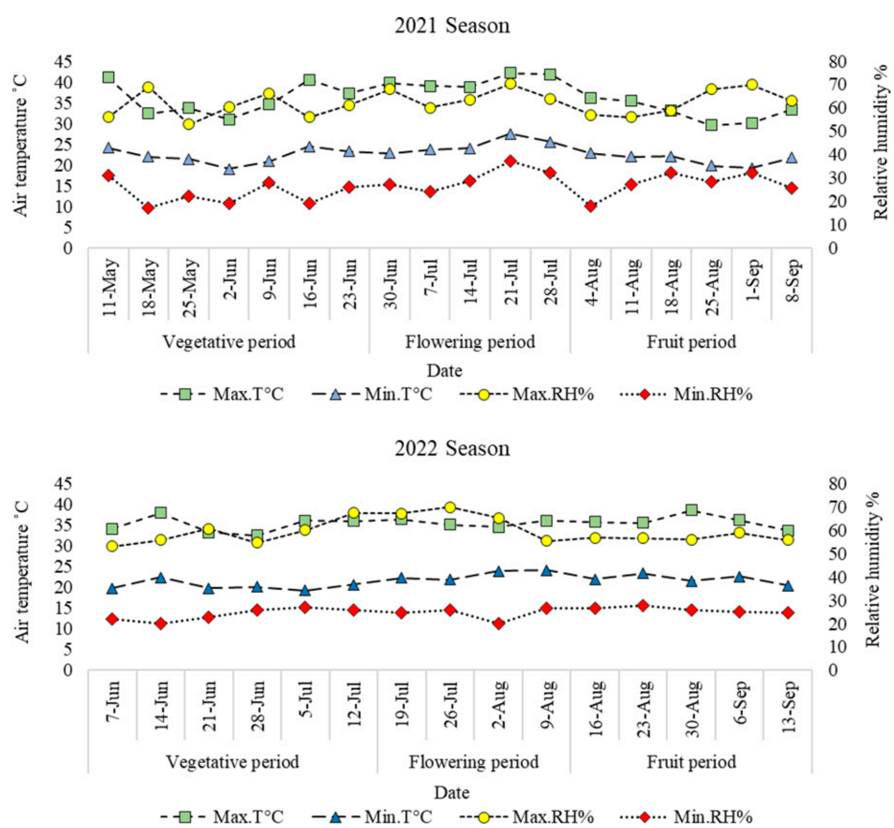

Fig. 2. Weekly average of maximum and minimum air temperatures (T°C) and relative humidity (RH%) during the growing seasons of 2021 and 2022.

Table 2. Means of vegetative growth traits of grafted and nongrafted tomato plants at 65 d after transplanting during the 2021 and 2022 seasons.

Rootstocks	Plant ht (cm)	No. of branches/plant	Leaf area/plant (dm^2)	Plant ht (cm)	No. of branches/plant	Leaf area/plant (dm^2)
	2021 season			2022 season		
Nongrafting	108.2 ± 2.80 ab	11.1 ± 1.86 bc	25.10 ± 2.20 c	123.4 ± 1.31 b	14.2 ± 0.40 bc	49.24 ± 2.89 bc
Self-grafting	105.3 ± 1.60 abc	10.2 ± 1.99 c	29.74 ± 2.41 abc	121.7 ± 1.14 bc	14.1 ± 0.64 bc	47.17 ± 6.64 bc
KFS-7	96.6 ± 14.6 bc	13.4 ± 2.45 ab	24.32 ± 3.63 c	121.3 ± 3.33 bc	14.0 ± 1.22 c	50.14 ± 4.36 b
KFS-8	94.9 ± 10.4 c	11.7 ± 0.30 bc	27.46 ± 2.05 bc	117.4 ± 0.72 d	15.3 ± 0.31 ab	47.13 ± 1.83 bc
KFS-9	105.4 ± 5.0 abc	11.5 ± 1.50 bc	28.46 ± 9.06 bc	119.0 ± 1.78 cd	13.5 ± 0.64 c	42.62 ± 1.85 c
KFS-10	106.1 ± 11.2 abc	13.3 ± 2.50 ab	30.13 ± 3.07 abc	121.9 b ± 0.83 b	15.3 ± 0.51 ab	50.62 ± 8.07 b
KFS-16	114.0 ± 13.2 a	15.9 ± 2.19 a	35.40 ± 6.22 a	123.7 ± 3.18 b	15.7 ± 0.76 a	57.34 ± 2.05 a
Maxifort	109.8 ± 6.8 a	16.1 ± 2.91 a	32.78 ± 1.95 ab	126.3 ± 2.08 a	16.6 ± 0.20 a	61.13 ± 37 a
F test	*	**	*	**	**	**

Significant differences at $*P < 0.05$ and $**P < 0.01$, respectively, according to the F test. Means followed by the same letter in the same column are not significantly different at the 0.05 level according to Duncan's multiple range test. Plant ht = plant height.

nongrafted plants during both seasons. Other rootstocks and controls had the lowest total chlorophyll and nutrient (N, P, K) uptake values during both seasons.

Tomato grafted onto different rootstocks and controls had highly significant differences in terms of proline content and antioxidant activities (catalase and peroxidase) during both seasons (Fig. 4). Tomato grafted onto KFS-7, KFS-10, and KFS-16 rootstocks as well as nongrafted plants had the highest proline content and catalase and peroxidase activities. In contrast, plants grafted onto the KFS-8 rootstock followed by the KFS-9 rootstock had the lowest values.

Fruit yield. Fruit setting, early and total yields, and marketable and unmarketable yields were significantly influenced by grafting during both seasons (Table 4). Plants grafted onto most rootstocks had a significantly improved fruit setting value compared with nongrafted and self-grafted plants during both seasons. Tomato grafted onto KFS-16 and Maxifort had the highest fruit setting values (80.6% and 81.9%) and (79.9% and 84.9%) during the 2021 and 2022 seasons, respectively. However, nongrafted plants had the lowest percentages during the two seasons, with 64.7% and 69.5%, respectively.

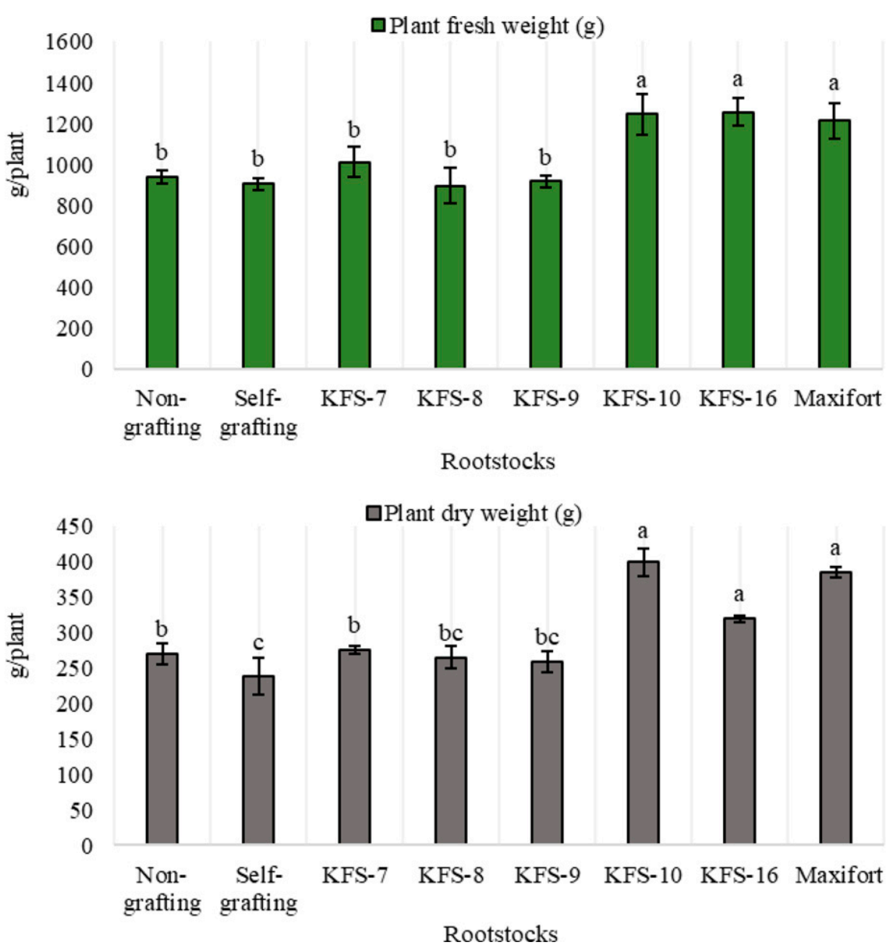

Fig. 3. Fresh and dry weights of tomato plants as affected by grafting onto different rootstocks during the 2022 season. Different letters indicate significant differences among treatments at $P < 0.05$ according to Duncan's multiple range test.

For early yield, there were no significant differences among grafting treatments for fruit weight as kg/plant and ton/ha during the first season; however, the differences were significant during the second season. During the 2022 season, plants grafted onto KFS-16 and Maxifort rootstocks had the heaviest fruit weights as kg/plant and ton/ha, whereas KFS-9 and nongrafting or self-grafting treatments had the lowest values.

Regarding the total yield and marketable yield, the fruit weights as kg/plant and ton/ha were significantly affected by grafting onto different rootstocks during the two seasons (Table 4). The total yield was significantly increased by grafting onto Maxifort and KFS-16 rootstocks, with 53.7% and 51.6% during both seasons compared with nongrafted plants, respectively. There were significant differences in the unmarketable yield during the two seasons. Tomato plants grafted onto Maxifort and KFS-16 produced the highest values for marketable yield (ton/ha), with increases reaching 58.4% and 56.7% compared with nongrafted plants, respectively. Conversely, the lowest marketable yield was obtained from nongrafting, self-grafting, and KFS-9 treatments.

Fruit quality traits. The TSS, titratable acidity, and vitamin C contents of tomato fruits were highly significantly influenced by grafting onto different rootstocks during both seasons (Table 5). Plants grafted onto KFS-9 rootstock during the first season as well as KFS-9 and KFS-8 rootstocks during the second season had the maximum recorded TSS percentages. However, the minimum values of TSS were obtained from grafting onto KFS-10 during the first season and onto KFS-7, KFS-10, KFS-16, Maxifort, and nongrafting during the second season. Grafting onto KFS-16 had the highest fruit acidity percentage, followed by KFS-9 and KFS-7 rootstocks, whereas grafting onto Maxifort and KFS-9 provided the lowest values. Concerning the vitamin C content in fruits, grafting onto KFS-8 rootstock resulted in the highest values, followed by nonsignificant differences by grafting onto KFS-7 and KFS-16 rootstocks, during the first season; however, the lowest values were obtained by using KFS-10 rootstock and self-grafting. However, grafting onto Maxifort provided the highest vitamin C content; the lowest content

Table 3. Total chlorophyll content and nitrogen, phosphorus, and potassium uptake in tomato plants as affected by grafting onto different rootstocks during the 2021 and 2022 seasons.

Rootstocks	Total chlorophyll (mg/plant)	N (gm/plant)	P (gm/plant)	K (gm/plant)
		2021 season		
Nongrafting	187 ± 5.61 c	12.6 ± 0.78 bc	1.45 ± 0.23 b	8.7 ± 0.72 b
Self-grafting	222 ± 19.60 bc	10.4 ± 0.82 c	1.30 ± 0.14 bc	8.2 ± 1.72 b
KFS-7	180 ± 25.43 c	13.6 ± 0.24 b	1.22 ± 0.12 c	8.4 ± 0.83 b
KFS-8	218 ± 18.85 bc	11.2 ± 2.28 bc	1.34 ± 0.08 bc	7.5 ± 0.24 b
KFS-9	190 ± 10.35 c	13.0 ± 1.48 b	1.42 ± 0.03 bc	7.77 ± 0.27 b
KFS-10	243 ± 18.37 ab	18.7 ± 1.18 a	2.30 ± 0.12 a	13.5 ± 1.49 a
KFS-16	274 ± 49.55 a	20.5 ± 1.34 a	2.16 ± 0.11 a	13.3 ± 1.03 a
Maxifort	238 ± 16.06 ab	18.8 ± 0.35 a	2.19 ± 0.11 a	13.0 ± 0.56 a
F test	**	**	**	**
		2022 season		
Nongrafting	197 ± 3.03 bc	12.8 ± 1.02 d	1.30 ± 0.04 c	12.8 ± 0.62 c
Self-grafting	198 ± 19.51 bc	11.9 ± 1.34 cd	1.22 ± 0.03 c	11.9 ± 0.55 c
KFS-7	234 ± 32.22 a	14.1 ± 0.62 c	1.36 ± 0.07 c	11.8 ± 1.03 c
KFS-8	239 ± 19.96 a	12.7 ± 0.40 d	1.34 ± 0.13 c	12.1 ± 0.94 c
KFS-9	176 ± 5.24 c	13.0 ± 0.63 cd	1.27 ± 0.09 c	12.7 ± 0.88 c
KFS-10	225 ± 38.86 ab	23.3 ± 0.36 a	2.31 ± 0.20 a	21.1 ± 1.28 a
KFS-16	257 ± 13.32 a	21.9 ± 0.94 b	2.28 ± 0.10 a	18.7 ± 0.77 b
Maxifort	249 ± 16.42 a	21.0 ± 0.50 b	1.93 ± 0.22 b	21.6 ± 1.57 a
F test	**	**	**	**

Significant differences at *$P < 0.01$ according to the F test. Means followed by the same letter in same column are not significantly different at the 0.05 level according to Duncan's multiple range test.
K = potassium; N = nitrogen; P = phosphorus.

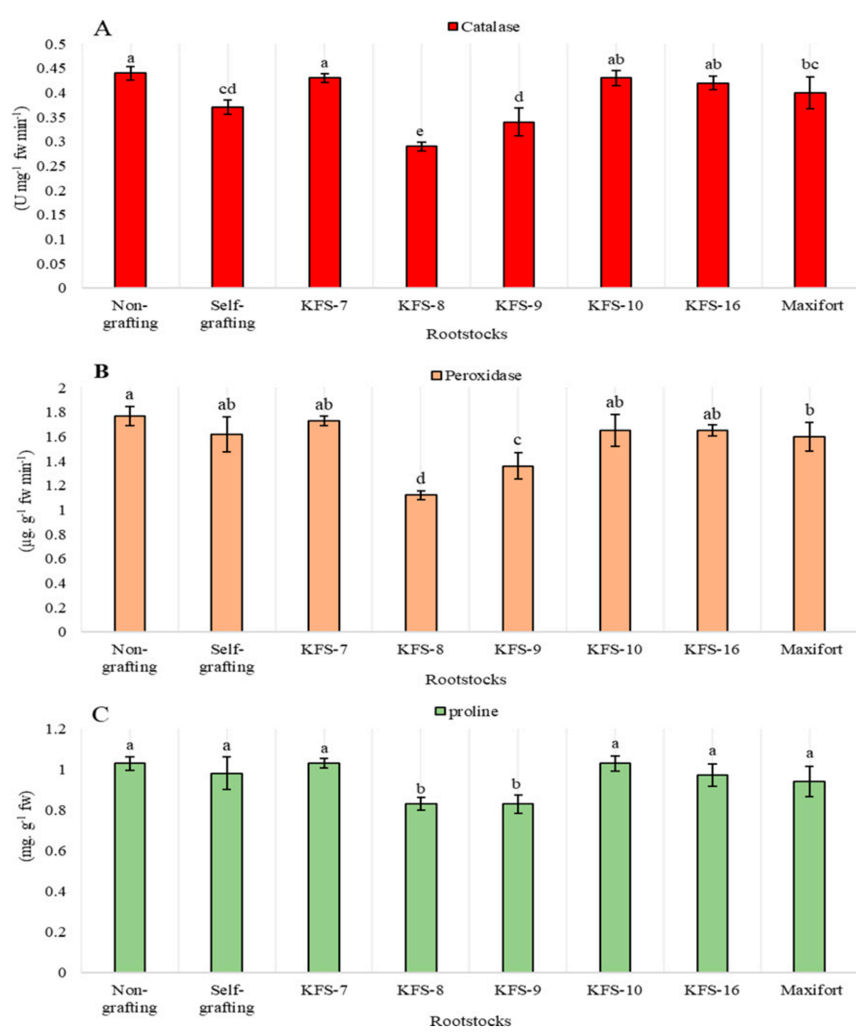

Fig. 4. Catalase (**A**) and peroxidase (**B**) activities and proline content (**C**) in tomato leaves as affected by grafting onto different rootstocks during the 2022 season. Different letters indicate significant differences among treatments at $P < 0.05$ according to Duncan's multiple range test.

was obtained by grafting onto KFS-8 during the 2022 season.

There were highly significant differences in lycopene, β-carotene, and total antioxidants among grafting treatments because of grafting tomato onto different rootstocks; however, the differences in total phenols were nonsignificant (Fig. 5). Grafting significantly improved both β-carotene and total antioxidants compared with nongrafting. Maxifort KFS-9 and KFS-16 rootstocks resulted in the maximum β-carotene content. KFS-8 had the highest total antioxidant content. In contrast, nongrafting treatment had the lowest values for both β-carotene and total antioxidants. Regarding fruit lycopene content, grafting onto both KFS-16 and KFS-9 rootstocks produced the highest values, whereas the lowest values were achieved with Maxifort, KFS-8, and KFS-7 rootstocks. No significant differences were observed between grafted and nongrafted plants in terms of phenol contents.

Discussion

Tomatoes are grown during different seasons throughout the year in Egypt (EMALR 2019). The main challenges associated with growing tomato during the late summer period are high temperatures and virus infections. Tomato yields can decrease dramatically by up to 80% when temperatures increase above 35 °C (Rieu et al. 2017). Heat-tolerant cultivars can continue flower production and fruit setting despite high temperatures; however, the available cultivars are not sufficient to meet farmers' demands. During the present study, grafting heat-tolerant tomato hybrid 023 F_1 onto Maxifort and KFS-16 rootstocks significantly improved fruit yield, with 53%, compared with nongrafted plants under the high temperatures of field production conditions.

Grafting onto Maxifort and KFS-16, followed by KFS-10, rootstocks significantly enhanced vegetative growth traits, including the number of branches, leaf area, and fresh and dry weights compared with nongrafted plants. These vegetative growth traits were positively correlated with the absorption of nutrients (N, P, K) and chlorophyll contents (Supplemental Table 1). These results are in agreement with those of previous studies of grafting cucumber and tomato (Bayoumi et al. 2021; Ilić et al. 2022), indicating better physiological and nutritional statuses of grafted plants. This might be associated with the stronger root system of grafted plants, which allows greater water and nutrient uptake compared with nongrafted plants under stress. Numerous studies reported that grafting on a compatible rootstock under abiotic stress improved plant vigor that resulted from increased absorption and translocation of nutrients (Gisbert-Mullor et al. 2023; Sayed et al. 2022). Furthermore, stressed plants might have others strategies for improving plant tolerance to heat stress, including the strength of their growth and spread of the root system (Peng et al. 2020), strength of adhesion between the rootstock and scion (Rasool et al. 2020), and physiological and

Table 4. Fruit setting percentage, early and total yields, and marketable and unmarketable yields of tomato plants as affected by grafting onto different rootstocks during 2021 and 2022 seasons.

Rootstocks	Fruit setting %	Early yield (kg/plant)	Early yield (ton/ha)	Total yield (kg/plant)	Total yield (ton/ha)	Marketable yield (ton/ha)	Unmarketable yield (ton/ha)
				2021 season			
Nongrafting	64.7 ± 3.4 d	2.4 ± 0.21 a	26.55 ± 2.31 a	5.83 ± 0.27 cd	64.76 ± 3.04 cd	63.07 ± 2.56 cd	1.69 ± 0.74 a
Self-grafting	69.6 ± 1.3 cd	2.5 ± 0.20 a	27.76 ± 2.22 a	5.57 ± 0.69 d	62.00 ± 7.68 cd	58.06 ± 3.63 d	3.95 ± 4.08 a
KFS-7	70.0 ± 1.8 cd	2.17 ± 0.40 a	24.00 ± 4.42 a	5.60 ± 0.48 cd	62.32 ± 5.31 cd	59.88 ± 5.72 d	2.45 ± 0.79 a
KFS-8	70.8 ± 3.1 cd	2.2 ± 0.07 a	24.48 ± 0.76 a	6.63 ± 0.14 b	73.68 ± 1.54 b	70.41 ± 1.83 b	2.26 ± 1.39 a
KFS-9	73.9 ± 4.3 abc	1.87 ± 0.66 a	20.77 ± 7.36 a	5.50 ± 0.28 d	61.30 ± 3.14 d	58.93 ± 3.02 d	2.37 ± 1.26 a
KFS-10	73.4 ± 3.5 bc	2.6 ± 1.53 a	19.19 ± 12.80 a	6.37 ± 0.27 bc	70.73 ± 2.30 bc	68.94 ± 2.04 bc	1.8 ± 0.45 a
KFS-16	80.6 ± 2.1 a	2.37 ± 0.43 a	26.11 ± 4.73 a	7.57 ± 0.83 a	83.91 ± 9.18 a	80.49 ± 7.55 a	3.41 ± 1.78 a
Maxifort	79.9 ± 6.1 ab	2.13 ± 0.47 a	23.80 ± 5.23 a	7.77 ± 0.56 a	86.42 ± 6.25 a	84.55 ± 4.93 a	1.87 ± 1.32 a
F test	**	NS	NS	**	**	**	NS
				2022 season			
Nongrafting	69.5 ± 1.6 b	2.03 ± 0.33 c	22.59 ± 3.61 c	5.10 ± 0.66 d	56.74 ± 7.28 c	53.37 ± 7.13 c	3.37 ± 0.16 a
Self-grafting	69.9 ± 4.3 b	2.35 ± 0.30 c	26.08 ± 3.28 c	5.53 ± 0.31 cd	61.16 ± 3.45 c	56.16 ± 5.10 c	5.00 ± 1.69 a
KFS-7	72.3 ± 5.6 b	2.50 ± 0.37 bc	27.71 ± 4.07 bc	6.13 ± 0.59 bcd	68.16 ± 6.53 bc	65.48 ± 7.31 bc	2.68 ± 0.83 a
KFS-8	74.5 ± 5.1 b	2.52 ± 0.26 abc	28.03 ± 2.89 abc	6.97 ± 0.19 ab	77.24 ± 2.14 ab	74.43 ± 1.82 ab	2.81 ± 0.33 a
KFS-9	68.4 ± 5.4 b	1.98 ± 0.01 c	21.98 ± 0.16 c	5.27 ± 0.05 d	58.61 ± 0.51 c	55.69 ± 0.32 c	2.92 ± 0.20 a
KFS-10	82.0 ± 3.8 a	2.67 ± 0.76 abc	29.68 ± 8.46 abc	6.80 ± 1.45 abc	75.61 ± 16.09 ab	71.91 ± 15.87 ab	3.71 ± 0.63 a
KFS-16	81.9 ± 2.4 a	3.23 ± 0.08 a	35.87 ± 0.85 a	7.80 ± 0.21 a	86.00 ± 2.38 a	83.64 ± 2.54 a	3.35 ± 1.05 a
Maxifort	84.9 ± 1.7 a	3.21 ± 0.18 ab	35.65 ± 1.95 a	7.87 ± 0.61 a	87.22 ± 6.80 a	83.09 ± 7.43 a	4.13 ± 1.88 a
F test	**	**	**	**	**	**	NS

Significant differences at $^{**}P < 0.01$ according to the F test. Means followed by the same letter in the same column are not significantly different at the 0.05 level according to Duncan's multiple range test.
NS = nonsignificant.

biochemical responses as chlorophyll fluorescence (Fv/Fm), electrolyte leakage, MDA content, antioxidant enzyme activities (superoxide dismutase, ascorbate peroxidase, glutathione reductase, and peroxidase), and total soluble protein contents, as well as some hormones such as abscisic acid, phasic acid, salicylic acid, indoleacetic acid, jasmonic acid, jasmonic acid-isoleucine and 12-oxo-phytodienoic acid (Balfagón et al. 2022; Lee et al. 2023). These factors might be controlled by a hormonal signal from the rootstock to the scion (Walubengo et al. 2022; Zhou et al. 2022).

The chlorophyll content of tomato leaves increased by grafting onto different rootstocks under heat stress. Similarly, a previous study showed that tomato grafted onto Maxifort increased the chlorophyll content compared with nongrafted and others rootstocks under different stress conditions (Lee et al. 2023). Grafting could protect chlorophyll from reactive oxygen species under abiotic stress, which causes a disruption in the fine chloroplast structure and pigment–protein complex or chlorophyll stability, resulting in the oxidation of chlorophyll (Elsheery et al. 2020). Antioxidant enzymes (i.e., catalase, peroxidase, and superoxide dismutase) and nonenzymatic antioxidants (i.e., proline, ascorbic acid, or glutathione) are among the most general defense mechanisms of plants against different stresses. Other approaches for improving plant tolerance to stress include genetic engineering, cultivating stress-tolerant/resistant cultivars, exogenous application of soil amendments, mineral nutrients, microbes, osmolytes, and appropriate agricultural practices such as grafting. Our results indicated that grafting onto KFS-8 and KFS-9 rootstocks had lower values of catalase and peroxidase activities and proline content, which might be the reason for reduced vegetative growth traits and fruit yield with these rootstocks. However, there were no significant increases in enzyme activities and proline contents in plants grafted onto vigorous rootstocks Maxifort and KFS-16 compared with nongrafted plants. Tomato scion 023 F_1 is the most favorable heat-tolerant commercial hybrid in Egypt and might produce enzyme activities and proline contents comparable to those of Maxifort and KFS-16 treatments under heat stress conditions. The obtained results are in agreement with those of recent studies that indicated that certain tomato rootstocks led to improved antioxidant responses under abiotic stress (Zhang et al. 2019). Moreover, Lee et al. (2023) found that the proline content and leaf ascorbate peroxidase, root superoxide dismutase, and catalase increased in heat-tolerant tomato 'Celebrity' grafted onto Maxifort compared with heat-sensitive 'Arkansas Traveler' under heat stress (38/30 °C day/night) for 14 d.

Heat stress can stimulate flower abscission, which reduces the fruit set percentage and limits the fruit yield (Cammarano et al. 2022). High temperatures may also affect the development and maturity of the fruit as well

Table 5. Total soluble solids (TSS), titratable acidity, and vitamin C contents of tomato fruits as affected by grafting onto different rootstocks during the 2021 and 2022 seasons

Rootstocks	TSS (%) 2021	TSS (%) 2022	Acidity (%) 2021	Acidity (%) 2022	Vitamin C (mg/100 g fw) 2021	Vitamin C (mg/100 g fw) 2022
Nongrafting	5.80 ± 0.175 bc	5.10 ± 0.183 c	0.65 ± 0.044 cd	0.59 ± 0.007 d	30.10 ± 0.813 cd	30.90 ± 1.311 c
Self-grafting	5.30 ± 0.040 d	5.60 ± 0.150 b	0.65 ± 0.032 cd	0.67 ± 0.003 c	28.10 ± 3.149 de	31.00 ± 1.260 c
KFS-7	5.40 ± 0.210 d	5.30 ± 0.213 c	0.72 ± 0.161 abc	0.71 ± 0.030 b	35.30 ± 1.219 ab	34.80 ± 3.105 b
KFS-8	5.60 ± 0.095 cd	5.90 ± 0.028 a	0.62 ± 0.022 d	0.74 ± 0.005 a	38.20 ± 1.625 a	26.90 ± 0.690 d
KFS-9	6.60 ± 0.295 a	5.90 ± 0.018 a	0.73 ± 0.008 ab	0.57 ± 0.024 d	25.20 ± 4.063 ef	35.40 ± 2.423 b
KFS-10	4.80 ± 0.333 e	5.20 ± 0.061 c	0.67 ± 0.092 bcd	0.65 ± 0.039 c	22.80 ± 1.625 f	33.50 ± 2.305 bc
KFS-16	6.00 ± 0.030 b	5.30 ± 0.177 c	0.76 ± 0.008 a	0.72 ± 0.017 ab	35.20 ± 2.045 ab	35.10 ± 1.815 b
Maxifort	5.40 ± 0.188 d	5.20 ± 0.048 c	0.59 ± 0.020 d	0.58 ± 0.017 d	33.70 ± 1.219 bc	39.10 ± 0.930 a
F test	**	**	**	**	**	**

Significant differences at $^{**}P < 0.01$ according to the F test. Means followed by the same letter in the same column are not significantly different at the 0.05 level according to Duncan's multiple range test.
fw = fresh weight.

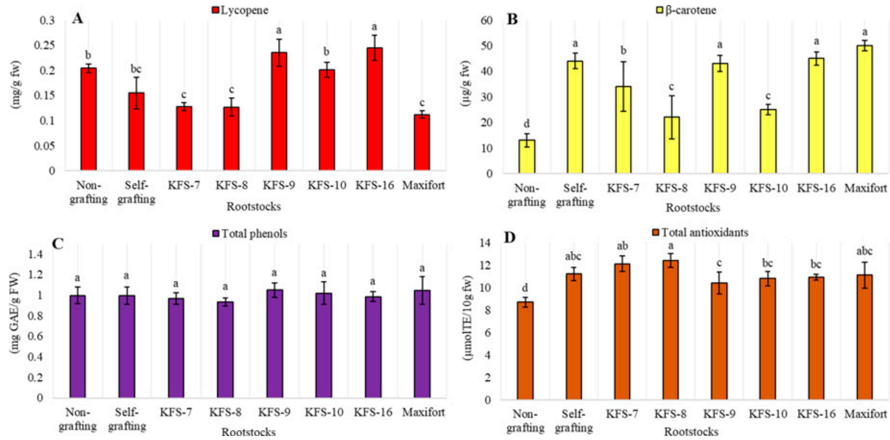

Fig. 5. Lycopene (**A**), β-carotene (**B**), and total phenol (**C**) contents and total antioxidant (**D**) capacity of tomato fruits as affected by grafting onto different rootstocks during the 2022 season. Different letters indicate significant differences among treatments at $P < 0.05$ according to Duncan's multiple rang test.

as consequently reduce the fruit color quality. During this study, the average temperature during the flowering period was 38 to 40 °C during the two seasons. Tomato grafted onto Maxifort and KFS-16 significantly enhanced the fruit setting rate and total and marketable yields compared with nongrafted plants. Similarly, numerous studies have reported improved fruit setting (Gisbert-Mullor et al. 2023; Latifah et al. 2023), average fruit weight (Jenkins et al. 2022; Mizumura et al. 2021), and early and marketable yields of different vegetable crops (Ilić et al. 2022; Sayed et al. 2022). Other possible factors that led to such positive results of grafting on fruit yield may include disease resistance and maintaining vigorous growth until the final harvest stages (Manickam et al. 2021). Maxifort and KFS-16 rootstocks provided more vigorous vegetative growth that might be related to a stronger root system with higher water and nutrient uptake rates, thus increasing the fruit setting and yield in both rootstocks.

Although there was no superior rootstock for all fruit quality traits, Maxifort and KFS-16 achieved satisfactory results in terms of vitamin C, TSS, total phenols, and total antioxidants. Previous studies have shown inconsistent results regarding the effect of grafting on fruit quality traits of tomato. No significant effects of grafting on tomato fruit quality such as TSS, titratable acidity, and vitamin C compared with the nongrafted plants were observed (Jenkins et al. 2022; Walubengo et al. 2022). Conversely, grafting improved the fruit quality of tomato, including firmness, TSS, vitamin C, and pH, in other studies (Mahmoud 2020; Oztekin and Tuzel 2017). Furthermore, slight increases of β-carotene, total phenols, and total antioxidants were found among the grafted plants when compared with nongrafted tomato plants (Manickam et al. 2021; Pugalendhi et al. 2021). The antioxidant capacity and phenolic content of heirloom tomatoes were enhanced when grafted onto wild-type rootstock (Greathouse et al. 2021). Hence, the effect of grafting on the quality of fruits depends mostly on the type of rootstock. In the present study, vigorous rootstocks Maxifort and KFS-16 improved some fruit quality traits of tomato scion 023 F_1. Maxifort is a result of hybridization between *S. lycopersicum* × *S. habrochaites*, whereas KFS-16 is a cross between *S. lycopersicum* × *S. pimpinellifolium*. Previous studies showed that *S. habrochaites* and *S. pimpinellifolium* contained higher amounts of β-carotene and lycopene, respectively, compared with cultivated tomato (Duduit et al. 2022; Efremov et al. 2020; Kilambi et al. 2017), whereas *S. pimpinellifolium* has an exceptionally high fruit lycopene content (300–390 µg/g fresh weight), which is nearly six-times higher than the lycopene content of commercial cultivars grown in Northern India (Foolad 2013). This genetic information might explain the higher content of β-carotene in tomato grafted onto Maxifort and similarly high content of lycopene in tomato grafted onto KFS-16.

Conclusion

None of the available heat-tolerant tomato cultivars in Egypt provide satisfactory productivity for farmers under heat stress conditions during the late summer season. In the present study, grafting the heat-tolerant cultivar (023 F_1) onto either of two vigorous interspecific hybrid rootstocks (Maxifort and KFS-16) improved productivity and some fruit quality traits under heat stress during the late summer season. This was associated with improvements in vegetative growth traits, nutrient (N, P, K) uptake, and fruit setting with these two rootstocks. This is the first report of the use of grafting to improve tomato productivity under heat stress in open field conditions. Improvement using the KFS-16 rootstock is interesting because it is locally produced, and seeds could be produced at low cost. This could contribute directly to reducing tomato grafting costs in Egypt, which may encourage farmers to use grafted seedlings to protect their crop from abiotic and biotic stresses. Further studies of KFS-16 and other improved local rootstocks under other abiotic stress (cold and salinity conditions) are currently ongoing.

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