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Grafting Affects Tomato Growth, Productivity, and Water Use Efficiency under Different Water Regimes

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ABSTRACT

The effects of grafting two greenhouse tomato cultivars (Durinta and Valouro F_1) onto three tomato rootstocks (Beaufort, Maxifort, and Spirit) under different irrigation regimes [(50%, 75%, and 100% crop EvapoTranspiration (ETc)] were studied by evaluating the vegetative growth, proline, chlorophyll, and mineral content of the leaves as well as fruit yield and Total Yield Water Use Efficiency (TYWUE). Plant height, stem diameter, leaf area, and total yield decreased, whereas proline and TYWUE increased, with increasing water stress. Between the two tested cultivars, Durinta showed more vigorous growth than Valouro. Plant growth, proline, Ca^{+2} and K^+ concentrations, fruit yield, and TYWUE were higher in grafted plants than in non-grafted plants. Adverse effect of high water stress (50% ETc) was evident in the non-grafted plants, particularly in Valouro. A positive effect of grafting was observed when Beaufort was used as the rootstock. Durinta grafted onto Beaufort (DB) under moderate irrigation regime (75% ETc) exhibited water savings (25%) and higher yield (21.6–30.8%) and TYWUE (55.1–55.5%) than fully irrigated (100% ETc) control (non-grafted Durinta). The results indicated that grafting onto appropriate rootstock could alleviate some of the negative effects of water limitation on greenhouse tomato plants.

Keywords: Abiotic stress, Beaufort rootstock, Durinta cultivar, Total yield, Water productivity.

INTRODUCTION

The ecosystem of Saudi Arabia is impoverished by scarcity of water resources. Practices that increase Water Use Efficiency (WUE) and reduce irrigation frequency are important for water conservation. Thus, grafting may play a vital role in water conservation as it has been reported to minimize losses in production of high-yielding genotypes under stress conditions by grafting them onto appropriate rootstocks (Schwarz *et al*., 2010; Kumar *et al*., 2017). Choosing the right combination of scion and rootstock may become an important practice for commercial tomato production, to overcome abiotic stresses (Nilsen *et al*., 2014). Grafting is widely used to increase production and improve crop quality, especially under stressful conditions (Sánchez-Rodríguez *et al*., 2012; Nawaz *et*

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al., 2016). By selecting the appropriate rootstock, grafting can manipulate scion morphology and manage biotic stresses like soil-borne pathogens and nematodes; induce tolerance to abiotic environmental stresses such as salinity, thermal stress, organic pollutants, and drought/waterlogging; and increase nutrient and *WUE* (Schwarz *et al*., 2010; Semiz and Suarez, 2015; Kumar *et al*., 2015a; 2017).

Tomato (*Solanum lycopersicum* L.) is one of the most important greenhouse vegetables worldwide, even in semi-arid areas, where water scarcity is common. Therefore, it is necessary to determine if grafting is an effective strategy to enhance water stress tolerance (Sánchez-Rodríguez *et al*., 2014). Finding the right combination of commercial cultivars and vigorous rootstock cultivars through grafting techniques could provide a tool for adapting tomato to drought conditions. However, more tomato rootstocks must be first tested for their ability to reduce the adverse effects of water stress. Moreover, phenotypic screening of various rootstock-scion combinations is crucial to determine the most water-conservative and highest-output combinations for tomato production (Nilsen *et al*., 2014).

Developing water-saving agricultural practices, creating effective irrigation schedules, and improving *WUE* are prerequisites for increasing the sustainability of agriculture and water resources and overcoming drought problems (Zhang *et al*., 2017). Several breeding programs have been directed at improving water stress tolerance in tomato, but with limited commercial success (Nilsen *et al*., 2014). One solution to this problem could be grafting commercial tomato cultivars onto appropriate rootstocks. Therefore, the objectives of this study were to: (a) Investigate the effects of grafting two commercial greenhouse tomato cultivars onto three tomato rootstocks under three water regimes on plant growth, chlorophyll, proline, mineral concentrations, and fruit yield, (b) Assess the Total Yield Water Use Efficiency (TYWUE), and (c) Determine the best grafting combination for increasing water stress tolerance.

MATERIALS AND METHODS

Two greenhouse experiments were carried out in two consecutive seasons during 2013–2014 and 2014–2015, at the College of Agriculture Experimental Station (24° 39' N, 46° 44' E), 40 km southwest of the Riyadh region, Saudi Arabia, where greenhouse tomato is an economically important vegetable crop.

Soil and Irrigation Water Analyses

Soil samples were collected from the experimental site (depth up to 30 cm) for analysis of their physical and chemical properties. In addition, some chemical properties of the irrigation water were determined. The soil texture was sand (86.32% sand, 8% silt, and 5.68% clay) with an average pH= 8.09, Organic Matter (OM)= 0.16%, and Electrical Conductivity of saturated soil paste (ECe)= 2.39 dS m^{-1}. Available soil Na^+, K^+, and Ca^{2+} content was 8.18, 1.18, and 11.6 meq L^{-1}, respectively (Chapman and Pratt, 1978). The irrigation water had an *EC* value of 1.04 dS m^{-1} and Na^+, Ca^{2+}, K^+, HCO_3^-, Cl^-, and SO_4^- content of 3.61, 0.76, 0.19, 0.35, 2.39, and 1.82 meq L^{-1}, respectively.

Plant Materials, Growth Conditions, and Experimental Design

Two commercial greenhouse tomato cultivars (*Solanum lycopersicum* L. 'Durinta' F_1, Western Seed, USA, and *Solanum lycopersicum* L. 'Valouro' F_1, Rijk Zwaan, De Lier, The Netherlands) were used as scions. Both scion cultivars were grafted onto three commercial interspecific tomato hybrid rootstocks, Beaufort and Maxifort (*S. lycopersicon*×*S. habrochaites*, De Ruiter Seeds/Monsanto, Bergschenhoek,

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The Netherlands) and Spirit (*S. lycopersicon*×*S. pimpinellifolium*, Nunhems Seeds, Nunhem, The Netherlands). Non-grafted plants of two tomato cultivars, Durinta and Valouro, were used as the control. Rootstock seeds were sown five days earlier (November 28, 2013 and November 22, 2014) than the seeds of the scion (December 1, 2013 and November 26, 2014, for the first and second year, respectively) to ensure similar stem diameter at the time of grafting, due to the differences in growth vigor (Khah *et al*., 2006). As rootstock cultivars tend to germinate and emerge slower than scion cultivars (Djidonou *et al*., 2013). Tomato rootstocks and scion seedlings at similar growth stages and with identical stem diameter were selected for grafting. Tube grafting technique was used to graft the plants because it is easy to adopt in Solanaceous crops (Lee *et al*., 2010). A slant cut was made in the stem of rootstocks as well as in scions and a plastic tube was placed on the cut end of the rootstock, and the cut end of the scion was then placed into the tube in direct contact with the rootstock. Grafted seedlings were kept for 7 days under controlled conditions (24–26°C, 90–95% RH, and 45% shade) for their better survival (Khah *et al*., 2006). Healthy seedlings of grafted and non-grafted tomato of uniform size were transplanted at the four-leaf stage on January 1, 2014 (first season) and December 25, 2014 (second season), into a fiberglass greenhouse.

For both experiments, a split-split-plot system in a randomized complete block design with three replicates was used. Three irrigation regime levels designed as low (50%), moderate (75%), and full-water regime (100%) based on crop EvapoTranspiration (ETc) were established in the main plots and the two tomato cultivars, Durinta and Valouro, were located in the sub-plots. The crop EvapoTranspiration (ETc) in greenhouse was assessed through a pan evaporation method (Al-Omran *et al*., 2013). The *ETc* was calculated using the following equation: $ETc= Ep\times Kp\times Kc$, where *Ep* is daily Evaporation from class A pan in mm, *Kp* is pan coefficient (ranging between 0.70-0.88), and *Kc* the crop coefficient (ranging between 0.50-1.20). Grafting combinations DB (scion Durinta and rootstock Beaufort), DM (scion Durinta and rootstock Maxifort), DS (scion Durinta and rootstock Spirit), and D (non-grafted Durinta, as control), as well as VB (scion Valouro and rootstock Beaufort), VM (scion Valouro and rootstock Maxifort), VS (scion Valouro and rootstock Spirit), and V (non-grafted Valouro as control) were set up in the sub-sub-plots. A single plot area was 10 m^2 and contained 2 plants per m^2.

Data Recording and Statistical Analysis

Two months after transplantation, random samples of three plants from each sub-sub-plot were chosen to measure vegetative growth characteristics, including plant height, stem diameter, and leaf area, using a Portable Area Meter (LI-COR model 3000A). Leaf chlorophyll content was estimated for five plants per treatment (two leaves per plant), 60 days after transplantation, by a portable colorimeter apparatus (CCM-200 Chlorophyll Meter, Opti-Sciences, Inc. NH, USA) and expressed as CCM-200 units. Extraction and estimation of proline content (based on the reaction of proline with ninhydrin solution) in the fresh leaf samples was then performed (Bates *et al.*, 1973). Samples from the upper young leaves (4 or 5 clusters) were detached, washed in distilled water, and dried at 70°C inside a forced air-oven, to a constant weight. The dried leaf samples were ground and used to determine the concentrations of Na^+, Ca^{+2}, K^+, and Cl^- (AOAC, 2000). Total fruit yield was recorded based on ripe fruits, which were gently hand-picked at intervals and taken to the lab, where they were weighed (kg m^{-2}). The weight values were used to calculate the total yield (t ha^{-1}). For each irrigation treatment, *WUE* based on total yield

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(TYWUE) (kg m^{-3}) was estimated as the ratio between total yield and total amount of water used during the whole growing season (ET, m^3 ha^{-1}), as described by Lovelli *et al*. (2007). Statistical analysis was performed using the SAS System for Windows statistical software version 8.1 (SAS Institute, 2008). Differences among the means were compared using a revised Least Significant Difference (LSD) test at the 0.05 probability level (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

Vegetative Growth, Total Fruit Yield, and TYWUE

The best vegetative growth (plant height, stem diameter, and leaf area) traits and the highest fruit yield were recorded under the most favorable moisture conditions of the full-water regime (W3, 100% ETc). However, the poorest vegetative growth and the lowest fruit yield were obtained under the most severe stress conditions of the low-Water regime (W1, 50% ETc) (Table 1). Full water conditions lead to higher water and nutrient uptake, which can increase growth of aerial plant parts (Kakita *et al*., 2015). Generally, water stress induced reduction in the yield of fruit produced. The percent increase in total yield under W3 was 34.1–38.6% higher than under W1. This could be attributed to the reduction in flower development under water stress conditions (Shamim *et al*., 2014).

By contrast, TYWUE significantly increased under the low-Water regime (W1), and its value was maximum with the minimum water supply (50% ETc). This finding is in agreement with Lovelli *et al*. (2007), who reported that TYWUE in eggplant showed a general increment with increasing water stress. These results suggest that the crop does not benefit from the application of water at a full level (100% ETc) and that it is possible to save irrigation water and improve *WUE* (Patanè *et al*., 2014). The present study indicates that water should be applied to the crop throughout the growing season, even at a moderate level (75% ETc), in order to achieve an acceptable yield. This finding supports a recent study by Zhang *et al*. (2016), which found that compared with a full irrigation level (100% ETc), the yield at 80% *ETc* was not significantly affected, implying that an appropriate decrease in the irrigation rate and *ETc* may not decrease fruit yield. In addition, Patanè *et al*. (2014) suggested that irrigation should be applied throughout the growing season, even at a low rate (50% ETc), to achieve a satisfactory yield, particularly in arid areas that face water scarcity.

Variations in plant growth and fruit yield owing to irrigation treatment levels were also observed between tomato cultivars. Durinta had higher vegetative growth and fruit yield than Valouro (Table 1). The differences in plant growth performance and fruit yield between both cultivars could be attributed to the genetic makeup of the individual cultivars. Similar results were obtained by Nahar and Ullah (2011). In addition, Durinta showed significantly higher *TYWUE* values than Valouro (Table 1). Regarding the response of tomato cultivars to *WUE*, Mahadeen *et al*. (2011) also reported higher Irrigation Water Use Efficiency (IWUE) values for the TY-DANA tomato cultivar than the GS12 cultivar, depending on the irrigation treatments (50 or 100% pan Evaporation, Ep). In general, tomato farmers can increase crop *WUE*; however, data on cultivar characteristics can also help them select the best cultivars to increase crop performance under water stress conditions.

Grafted tomato plants showed a significantly higher vegetative growth, fruit yield, and TYWUE than the non-grafted plants (Table 1). Beaufort rootstock was found to be superior in these traits, followed

Table 1. Influence of different irrigation water regimes, two commercial tomato cultivars, and three tomato rootstocks on vegetative growth characteristics, total fruit yield, and *TYWUE* of tomato plants.[a]

	Plant height (cm)		Stem diameter (cm)		Leaf area (cm^2)		Total fruit yield ($t\ ha^{-1}$)		*TYWUE* ($kg\ m^{-3}$)	
Treatments	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015
(a) Water regimes										
W1 (50% ETc)	221.63 c	225.60 c	11.58 c	13.72 c	16339.14 c	17615.88 c	179.259 c	172.542 c	58.230 a	57.887 a
W2 (75% ETc)	271.11 b	275.05 b	12.84 b	15.08 b	17189.12 b	18220.47 b	211.174 b	200.593 b	47.356 b	47.755 b
W3 (100% ETc)	299.35 a	303.44 a	13.43 a	16.03 a	19887.30 a	21951.67 a	234.875 a	231.393 a	38.469 c	36.956 c
(b) Tomato cultivars										
Durinta F_1	269.00 a	273.36 a	15.13 a	15.04 a	19805.74 a	19301.42 a	244.410 a	228.428 a	48.706 a	48.453 a
Valiro F_1	259.05 b	262.71 b	14.75 b	14.85 b	18454.63 a	18223.92 b	174.671 b	175.376 b	47.330 b	46.612 b
(c) Tomato rootstocks										
Beaufort	280.71 a	284.21 a	16.09 a	16.47 a	20776.71 a	22465.70 a	233.463 a	231.893 a	52.926 a	50.596 a
Maxifort	272.21 b	276.63 b	15.65 b	15.38 b	17804.75 b	19232.52 b	211.867 b	206.898 b	49.618 b	49.605 b
Spirit	267.27 c	270.36 c	15.50 c	15.33 b	17371.05 c	18779.45 c	200. 764 c	193.758 c	48.771 c	48.990 c
Control (Non-grafted)	235.93 d	240.94 d	12.52 d	12.59 c	15268.25 d	16573.02 d	187.348 d	173.656 d	40.758 d	40.939 d

[a] Means followed by the same letter in each season are not significantly different at 0.05 level.

by Maxifort rootstock. Di Gioia *et al*. (2010) reported similar results using tomato rootstocks Beaufort and Maxifort to increase the leaf area of greenhouse heirloom tomato Cuore di Bue. In addition, tomato plants grafted onto the Beaufort and Maxifort rootstocks showed 34.1–45.0% and 19.4–26.2% higher fruit yield, respectively, than non-grafted plants. Similarly, Djidonou *et al*. (2013) reported that grafting tomato cultivar Florida 47 onto Beaufort and Multifort rootstocks led to higher *WUE* and significantly higher yield (by 30%) than non-grafted plants. These authors indicated that the higher yield of grafted tomato was because of the vigorous root system of the interspecific rootstocks. In the present study, TYWUE ranged from 48.8–49.0 kg m^{-3} in Spirit to 50.6–52.9 kg m^{-3} in Beaufort rootstock-grafted plants, while the overall lowest TYWUE value (40.8–40.9 kg m^{3}) was found in non-grafted plants (Table 1).

Interaction Effects

The results presented in Table 2 show that the cultivar Durinta is more tolerant to water stress than Valouro. This is reflected in its higher vegetative growth and yield, especially under the high water stress. TYWUE variation between cultivars in response to different water regimes was more apparent in Durinta, whose TYWUE under the low-Water regime (W1) was greater by 50.0–56.0% and 56.1–65.8% than that for Durinta and Valouro, respectively, under the full-Water regime (W3). Similar findings were reported by Patanè *et al*. (2014), who observed that the difference in *WUE* in response to deficit irrigation was more evident in processing tomato cultivar Season. *WUE* of this cultivar at 50% *ETc* was 60% greater than that at 100% *ETc*. All these results confirm that tomato used irrigation water more efficiently under stress conditions (Lovelli *et al*., 2017).

Among the used tomato rootstocks, Beaufort has been identified as more resistant against water stress compared to Maxifort and Spirit due to the higher performance which it represented in the measured vegetative growth and yield parameters. This reaction of grafted plants is primarily associated with both the genetic structure and root characteristics of rootstock, and rootstock/scion compatibility (Lee, 1994; Oztekin and Tuzel, 2011). Thus, Beaufort rootstock is more appropriate for water deficit condition and showed more tolerance to water stress under our experimental conditions.

In the present study, a higher TYWUE value was also recorded in tomato plants grafted onto Beaufort than those grafted onto the other rootstocks and non-grafted plants, under the low-Water regime (W1). Moreover, non-grafted plants growing at W1 showed the lowest plant growth, yield, and TYWUE (Table 2). These results support the findings of Schwarz *et al*. (2010) that, to reduce losses in crop yield under water stress conditions in high-fruit yielding genotypes like tomato, they should be grafted onto the appropriate rootstock, to decrease the effect of water regime on plant growth.

Durinta and Valouro cultivars performed better in term of growth and yield when grafted onto Beaufort than onto the other rootstocks (Table 2). Oztekin *et al*. (2009) also found that the leaf area of Durinta was significantly higher in plants grafted onto Beaufort rootstock under an open soilless growing system. It is interesting to observe that grafted DB plants exhibited higher TYWUE values than Valouro plants grafted onto different rootstocks or non-grafted plants, particularly under the low-water regime treatment. In this case, Durinta was able to tolerate suboptimal water conditions better than Valouro, particularly when grafted onto the Beaufort rootstock. Plants grafted onto an appropriate rootstock are able to uptake more water and nutrients from the root zone as compared to non-grafted plants because grafted plants have a stronger and denser root structure, which increases the amount of internal plant hormones and, consequently, the photosynthesis rate, which

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Table 2. Interaction effects between irrigation water regimes×tomato cultivars, irrigation water regimes and tomato rootstocks, and tomato cultivars×tomato rootstocks on some agronomic traits of tomato plants.[a]

Growing seasons		First season 2013/2014					Second season 2013/2014				
Agronomic traits Exp. treatments		Plant height (cm)	Stem diameter (cm)	Leaf area (cm^2)	Total yield ($t\ ha^{-1}$)	*WUE* ($kg\ m^{-3}$)	Plant height (cm)	Stem diameter (cm)	Leaf area (cm^2)	Total yield ($t\ ha^{-1}$)	*WUE* ($kg\ m^{-3}$)
W1 (50% ETc)	Durinta F_1	226.90 e	14.51	17879.63	212.641	60.042	230.68 e	13.90	17298.44	183.417	58.223
	Valiro F_1	216.35 f	13.93	16340.22	145.479	56.419	220.53 f	13.53	14827.51	145.630	57.550
W2 (75% ETc)	Durinta F_1	275.10 c	15.35	18630.98	248.211	47.597	279.05 c	15.33	18218.75	220.500	48.331
	Valiro F_1	267.12 d	14.75	17187.50	180.834	47.114	271.06 d	14.83	17421.04	184.934	47.179
W3 (100% ETc)	Durinta F_1	305.01 a	15.98	19889.51	273.163	38.479	310.34 a	16.25	21050.13	264.090	38.804
	Valiro F_1	293.68 b	15.58	19146.75	199.440	38.458	296.54 b	15.81	20583.42	216.686	35.107
W1 (50% ETc)	Beaufort	237.80 hi	15.07	19239.47	243.789	66.429	241.40 g	15.38	20682.48	210.049	60.577
	Maxifort	224.90 j	14.85	16746.81	188.482	58.518	230.72 h	14.48	18002.78	177.468	60.387
	Spirit	220.75 jk	14.75	15687.48	166.687	58.016	224.02 i	13.47	16864.02	165.052	59.730
	(Non-grafted)	203.05 k	11.30	13682.80	153.724	49.959	206.28 j	11.53	14914.25	140.824	50.852
W2 (75% ETc)	Beaufort	289.45 d	16.20	20013.31	253.352	50.747	291.20 d	16.43	21214.11	239.036	50.936
	Maxifort	281.75 e	15.95	17245.08	220.791	49.975	285.32 e	15.87	18279.78	223.437	50.182
	Spirit	276.95 f	15.85	16812.97	204.757	49.283	280.72 e	15.80	17821.74	203.122	50.075
	(Non-grafted)	236.30 i	12.20	14685.14	189.001	39.418	242.98 g	12.22	15566.25	177.231	39.828
W3 (100% ETc)	Beaufort	314.87 a	17.00	23077.33	253.636	41.601	320.03 a	17.58	25500.51	249.015	40.274
	Maxifort	309.97 b	16.15	19854.47	235.964	40.362	313.85 b	16.65	21873.04	225.463	38.246
	Spirit	304.10 c	15.90	19180.59	232.304	39.014	306.33 c	15.85	21194.55	219.892	37.164
	(Non-grafted)	268.45 g	14.05	17436.79	196.146	32.897	273.55 f	14.03	19238.56	190.322	32.139
Durinta F_1	Beaufort	283.74 a	15.80	20778.54	298.403	55.431	287.58 a	16.89	22521.33	244.224	51.546
	Maxifort	b269.41	16.43	18806.36	247.311	49.797	281.08 b	15.24	19303.45	239.146	50.636
	Spirit	256.20 cd	15.60	17371.16	215.047	48.835	272.42 c	15.14	18826.02	235.857	49.824
	(Non-grafted)	247.93 d	12.67	15269.36	206.443	40.762	252.34 d	12.60	16554.89	195.084	41.804
Valiro F_1	Beaufort	277.67 ab	15.74	20674.87	214.206	50.421	280.84 b	16.04	22410.07	202.292	49.646
	Maxifort	257.00 c	15.53	17803.14	178.615	49.440	272.18 c	15.24	19161.59	179.203	48.573
	Spirit	255.33 cd	15.10	16370.94	167.991	48.707	268.29 c	15.12	18732.88	168.197	48.155
	(Non-grafted)	223.93 e	12.60	15167.13	153.100	40.754	229.53 e	12.59	16591.15	153.440	40.075

[a] Means followed by the same letter in each season are not significantly different at 0.05 level.

in turn promotes plant growth and fruit development (Lee, 1994; Oztekin and Tuzel, 2011).

Chlorophyll, Proline, and Leaf Mineral Composition

The results presented in Table 3 show a significant increase in the proline content of leaves under water stress conditions, whereas the leaf chlorophyll content decreased with increasing water stress. Leaf chlorophyll content is a physiological characteristic influenced by abiotic stress and it differs among tomato genotypes (Poudyala *et al*., 2015). The concentrations of Na^+, Cl^-, Ca^{+2}, and K^+ in leaf tissues decreased with increasing water stress (Table 3). These results support the findings of Nahar and Gretzmacher (2002), who reported a trend toward decreasing concentrations of several minerals, including Na^+, Ca^{+2}, and K^+, in tomato leaf tissues with increasing water stress. Generally, water stress resulted in reduction not only in nutrient uptake by the plant root system but also in nutrient transfer from the root to the shoot. This is the result of factors such as limited transpiration rate, lower active transport, and decreased membrane permeability (Sánchez-Rodríguez *et al*., 2014).

The results also showed that the cultivar Durinta had significantly higher levels of proline and chlorophyll content and Ca^{+2} and K^+ concentrations in the leaves than Valouro. Na^+ and Cl^-levels were higher in Durinta leaves, but the difference was not significant (Table 3). These results were in accord with those of Nahar and Gretzmacher (2002), who reported significant and insignificant variations in K^+ and Na^+ concentrations, respectively, among four tested tomato cultivars.

Plants grafted onto Beaufort and Maxifort rootstocks showed significantly higher chlorophyll content than those grafted onto Spirit rootstock and non-grafted plants. Furthermore, plants grafted on Beaufort rootstock showed higher proline, Cl^-, Ca^{+2}, and K^+ concentrations than those grafted onto Maxifort and Spirit rootstocks and non-grafted plants (Table 3). This might be due to the higher rate of absorption of water and minerals from the soil, by roots of the Beaufort rootstock, which could improve the uptake of Cl^-, Ca^{+2}, and K^+ (Khah *et al*., 2006). On the other hand, tomato plants grafted onto the three rootstocks showed higher Na^+ uptake than non-grafted plants. This finding suggests that the rootstocks can modulate Na^+ accumulation and partitioning within the shoot (Albacete *et al*., 2015).

Interaction Effects

Proline content of Durinta leaf tissues under the low-Water regime (W1) (8.5–8.7 mg g^{-1} fresh weight (fw)) was almost double that of plants under the full-Water regime (W3) treatment (4.41–4.54 mg g^{-1} fw). Proline accumulation was significantly higher for Durinta as compared to Valouro under different irrigation regimes (Table 4). In general, Jureková *et al*. (2011) showed that proline content was affected by tomato genotype and water deficiency. Leaf tissues of Valouro plants under low Water regime (W1) had the lowest concentrations of Cl^-, Ca^{+2}, and K^+. Durinta plants under the full water treatment showed the highest Na^+, Cl^-, Ca^{+2}, and K^+ concentrations. However, insignificant differences were observed in Na^+ concentration between tomato cultivars under the low and moderate water regimes (Table 4). The variations in these mineral concentrations indicated the strength of uptake of Cl^-, Ca^{+2} and K^+ under W1 and for Na^+ by Durinta under W3 in comparison with Valouro.

Proline content in tomato plants grafted onto the Beaufort rootstock under low water regime was significantly higher (8.3–8.5 mg g^{-1} fw) than that of the non-grafted plants (4.6–4.7 mg g^{-1} fw) under the full-water regime (W3). However, the plants grafted onto Beaufort rootstock under W3 showed higher Cl^-, Ca^{+2}, and K^+ concentrations than

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Table 3. Influence of different irrigation water regimes, two commercial tomato cultivars, and three common tomato rootstocks on chlorophyll and proline content and some mineral concentrations of tomato leaf tissues.[a]

Treatments	Chlorophyll (g)		Proline (mg g^{-1} fw)		Na^+ (%)		Cl^- (%)		Ca^{+2} (%)		K^+ (%)	
	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15
(a) Water regimes												
W1 (50% ETc)	37.421 c	38.531 c	8.076 a	8.290 a	0.172 a	0.167 c	1.307 c	1.375 c	1.424 c	1.401 c	2.745 c	2.751 c
W2 (75% ETc)	48.957 b	50.328 b	6.374 b	6.556 b	0.175 a	0.176 b	1.419 b	1.437 b	1.525 b	1.542 b	3.027 b	3.035 b
W3 (100% ETc)	58.237 a	59.921 a	4.638 c	4.816 c	0.178 a	0.184 a	1.518 a	1.637 a	1.721 a	1.576 a	3.410 a	3.503 a
(b) Tomato cultivars												
Durinta F_1	50.300 a	51.693 a	6.721 a	6.902 a	0.190 a	0.176 a	1.503 a	1.581 a	1.621 a	1.570 a	3.093 a	3.128 a
Valiro F_1	46.110 b	47.494 b	6.034 b	6.206 b	0.186 a	0.175 a	1.327 a	1.385 a	1.492 b	1.443 b	3.028 b	3.064 b
(c) Tomato rootstocks												
Beaufort	49.528 a	50.805 a	6.573 a	6.760 a	0.208 a	0.183 a	1.591 a	1.668 a	1.665 a	1.613 a	3.349 a	3.388 a
Maxifort	49.311 a	50.795 a	6.497 b	6.682 b	0.192 a	0.179 a	1.418 b	1.486 b	1.605 b	1.554 b	3.195 b	3.232 b
Spirit	47.026 b	48.442 b	6.232 c	6.388 c	0.177 a	0.177 a	1.348 b	1.413 b	1.522 c	1.472 c	2.998 c	3.033 c
Control (Non-grafted)	46.955 b	48.332 b	6.209 c	6.386 c	0.164 b	0.162 b	1.303 b	1.365 b	1.433 d	1.387 d	2.700 d	2.731 d

[a] Means followed by the same letter in each season are not significantly different at 0.05 level.

Table 4. Interaction effects between irrigation water regimes×tomato cultivars, irrigation water regimes × tomato rootstocks, and tomato cultivars × tomato rootstocks on some chemical compositions of tomato leaf tissues.[a]

Growing seasons		First season 2013/2014					Second season 2014/2015				
Chemical compositions Exp. treatments		Proline (mg^{-1} g fw)	Na^+ (%)	Cl^- (%)	Ca^{+2} (%)	K^+ (%)	Proline (mg^{-1} g fw)	Na^+ (%)	Cl^- (%)	Ca^{+2} (%)	K^+ (%)
W1 (50% ETc)	Durinta F_1	8.500 a	0.173 c	1.388 d	1.481 d	2.771 d	8.709 a	0.172 c	1.479 c	1.460 e	2.781 e
	Valiro F_1	7.652 b	0.172 c	1.227 f	1.366 f	2.094 f	7.870 b	0.171 c	1.271 e	1.342 f	2.721 f
W2 (75% ETc)	Durinta F_1	6.712 c	0.176 c	1.507 c	1.589 c	3.060 c	6.904 c	0.177 c	1.526 b	1.607 b	3.064 c
	Valiro F_1	6.036 d	0.174 c	1.331 e	1.461 e	2.718 e	6.209 d	0.174 c	1.348 d	1.477 d	3.006 d
W3 (100% ETc)	Durinta F_1	4.951 e	0.195 a	1.612 a	1.793 a	3.447 a	5.092 e	0.198 a	1.739 a	1.642 a	3.541 a
	Valiro F_1	4.414 f	0.192 b	1.524 b	1.648 b	3.373 b	4.540 f	0.193 b	1.535 b	1.510 c	3.465 b
W1 (50% ETc)	Beaufort	8.301 a	0.180 b	1.352 h	1.522 f	3.001 e	8.538 a	0.174 b	1.548 e	1.500 g	3.011 f
	Maxifort	8.210 b	0.178 b	1.306 i	1.467 h	2.865 g	8.444 b	0.172 b	1.378 h	1.445 h	2.872 g
	Spirit	7.930 c	0.175 b	1.246 j	1.395 i	2.692 h	8.089 c	0.169 b	1.310 j	1.369 j	2.692 gh
	(Non-grafted)	7.863 d	0.158 b	1.204 h	1.310 j	2.421 h	8.008 d	0.153 b	1.264 k	1.290 k	2.427 i
W2 (75% ETc)	Beaufort	6.575 e	0.182 b	1.596 b	1.632 d	3.314 c	6.762 e	0.185 b	1.616 c	1.651 b	3.317 d
	Maxifort	6.499 f	0.180 b	1.470 d	1.573 e	3.160 d	6.684 f	0.177 b	1.440 g	1.590 d	3.167 d
	Spirit	6.212 g	0.177 b	1.422 f	1.490 g	2.964 f	6.390 g	0.170 b	1.369 h	1.507 f	2.979 f
	(Non-grafted)	6.201 g	0.160 b	1.310 i	1.404 i	2.671 h	6.388 g	0.166 b	1.324 i	1.420 i	2.676 h
W3 (100% ETc)	Beaufort	4.781 i	0.270 a	1.707 a	1.842 a	3.732 a	4.980 h	0.291 a	1.841 a	1.687 a	3.835 a
	Maxifort	4.554 j	0.263 a	1.521 c	1.775 b	3.561 b	4.918 i	0.289 a	1.640 b	1.626 c	3.658 b
	Spirit	4.842 h	0.264 a	1.447 e	1.681 c	3.337 c	4.684 j	0.276 a	1.560 d	1.540 e	3.429 c
	(Non-grafted)	4.553 j	0.259 a	1.398 g	1.584 e	3.009 e	4.663 j	0.268 a	1.508 f	1.452 h	3.090 e
Durinta F_1	Beaufort	6.919 a	0.282 a	1.862 a	1.735 a	3.383 a	7.116 a	0.186 a	1.959 a	1.680 a	3.422 a
	Maxifort	6.840 b	0.215 b	1.525 b	1.672 ab	3.230 c	7.035 b	0.184 a	1.605 b	1.619 b	3.268 c
	Spirit	6.585 c	0.185 c	1.383 bc	1.583 bc	3.028 e	6.727 c	0.180 a	1.455 bc	1.534 d	3.063 e
	(Non-grafted)	6.541 d	0.178 c	1.241 c	1.493 c	2.730 g	6.509 d	0.149 d	1.307 c	1.440 f	2.761 g
Valiro F_1	Beaufort	6.226 e	0.234 b	1.364 bc	1.596 b	3.315 b	6.404 e	0.175 abc	1.424 bc	1.545 c	3.353 b
	Maxifort	6.153 f	0.170 c	1.320 bc	1.538 c	3.160 d	6.329 f	0.170 bc	1.378 c	1.488 e	3.197 d
	Spirit	5.889 g	0.169 c	1.314 bc	1.461 ce	2.967 f	6.057 g	0.167 c	1.371 c	1.410 f	3.004 f
	(Non-grafted)	5.878 g	0.167 c	1.311 bc	1.373 e	2.671 h	6.045 g	0.141 d	1.367 c	1.329 g	2.701 h

[a] Means followed by the same letter in each season are not significantly different at 0.05 level.

those grafted onto Maxifort and Spirit rootstocks or non-grafted plants. In general, non-grafted plants under the low-water regime tended to have lower concentrations of Cl^-, Ca^{+2}, and K^+ than grafted plants (Table 4). The use of Beaufort as a rootstock resulted in a higher content of proline and Cl^-, Ca^{+2}, and K^+ when grown under low water regime. Hence, the higher proline content with increased uptake and translocation of Cl^-, Ca^{+2}, and K^+ to the plant shoot might be one of the reasons for the higher water stress tolerance in tomato grafted onto Beaufort rootstock. This finding agrees with Altunlu and Gul (2012) who showed that drought resistance of grafted tomato plants onto rootstock Beaufort was due to improved osmoregulation, partially induced by higher proline content, and relative water content in tomato scion under water stress. Hence, Beaufort rootstock could increase proline content and improve absorption, upward transfer, and accumulation of Cl^-, Ca^{+2}, and K^+ in leaf tissues.

Grafted DB and DM plants showed higher proline content and Na^+, Cl^-, and Ca^{+2} concentrations than DS and D plants, as well as grafted VB, VM, and VS combinations and V plants. However, K^+ concentration in the leaf tissues was higher in DB, followed by the VB combination, than plants with the other grafting combinations and non-grafted plants (Table 4). These results confirmed the suggestion of Goto *et al*. (2013) that the differences in leaf nutrient concentrations were related to the combination of the rootstocks and scions. Hence, DB grafted plants can absorb and transport nutrients (e.g., Na^+, Cl^-, Ca^{+2} and K^+) to the leaves more efficiently, resulting in higher concentration of minerals in the scion leaves. This supports the vigorous growth and higher yield of DB plants in comparison with other grafted- or non-grafted plants. This, along with disease resistance, is one of the main reasons for the prevalent use of grafted rootstocks in fruiting vegetable production (Lee *et al*., 2010; Sánchez-Rodríguez *et al*., 2014).

Interaction Effects among Water Regimes, Tomato Cultivars, and Rootstocks

The heaviest yield production (295.1–320.5 t ha^{-1}) was recorded in grafted DB plants under the full-water regime. The highest TYWUE value (63.6–63.8 kg m^{-3}) was also recorded in DB plants, but under the low-water regime (Table 5). These results indicated that DB plants might use water more efficiently than other grafting combinations and non-grafted plants. Similarly, Semiz and Yurtseven (2010) reported that grafted tomato plants showed higher *WUE* than non-grafted plants. Grafted DB plants under a moderate water regime (75% ETc) showed higher yield improvement (13.6–27.3%) than non-grafted Durinta (control) plants. Although this yield improvement was relatively lower in value than that for DB plants under the full-water regime (31.2–44.3%), it saved approximately 25% of the irrigation water (which is one of the main objectives of study). Moreover, Grafted DB plants under a moderate water regime (75% ETc) showed a TYWUE higher than not only non-grafted Durinta (by 55.06–55.54%), but also grafted DB plants under the full-water regime (26.1–26.5%). Thus, in the DB graft combination, the vigorous root system of Beaufort rootstock can efficiently absorb water so that less-frequent irrigation may be applied (Kumar *et al*., 2015b).

CONCLUSIONS

Grafted tomato plants exhibited higher vegetative growth and yield under different water regimes than non-grafted plants. Using Beaufort as a rootstock resulted in higher fruit yield and TYWUE under water stress conditions. Beaufort seems to be a more compatible rootstock with

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Table 5. Interaction effects among irrigation water stress levels, tomato cultivars and tomato rootstocks on proline content, total yield, yield ratio to the control, *WUE* and *WUE* ratio to the control.

Experimental treatments			First season 2013/2014					Second season 2014/2015				
Water stress levels	Tomato F_1 cultivars	Tomato rootstocks	Proline (mg^{-1} g fw)	Total yield ($t\ ha^{-1}$)	Yield ratio to cont (%)	*TUWUE* ($kg\ m^{-3}$)	*TYWUE* ratio to cont. (%)	Proline (mg^{-1} g fw)	Total yield ($t\ ha^{-1}$)	Yield ratio to cont. (%)	*TYWUE* ($kg\ m^{-3}$)	*TYWUE* ratio to cont. (%)
W1 (50% ETc)	Durinta F_1	Beaufort	8.719	236.121	106.34	63.652	193.47	8.968	225.434	100.23	63.847	191.69
		Maxifort	8.624	181.414	81.71	58.536	177.92	8.870	192.898	85.77	60.680	182.18
		Spirit	8.394	178.088	80.21	58.018	176.35	8.500	182.029	80.93	59.656	179.11
		(non-grafted)	8.263	151.340	68.16	49.963	151.84	8.499	156.317	69.50	51.709	155.25
	Valiro F_1	Beaufort	7.884	174.803	78.73	59.207	179.96	8.109	176.763	78.59	60.308	181.07
		Maxifort	7.796	149.691	67.42	58.501	177.81	8.018	146.555	65.16	60.093	180.42
		Spirit	7.465	140.655	63.35	58.013	176.33	7.678	143.147	63.65	59.806	179.56
		(non-grafted)	7.464	119.189	53.68	49.956	151.84	7.677	118.544	52.71	49.995	150.10
W2 (75% ETc)	Durinta F_1	Beaufort	6.922	282.587	127.28	51.014	155.06	7.119	255.577	113.63	51.806	155.54
		Maxifort	6.842	253.019	113.96	50.480	153.43	7.038	246.203	109.47	50.613	151.96
		Spirit	6.544	248.488	111.92	49.471	150.37	6.731	237.609	105.64	50.510	151.65
		(non-grafted)	6.543	195.175	87.91	39.424	119.83	6.730	205.565	91.40	40.396	121.28
	Valiro F_1	Beaufort	6.229	209.385	94.31	50.480	153.43	6.406	210.513	93.60	50.067	150.32
		Maxifort	6.156	185.101	83.37	49.471	150.37	6.331	185.115	82.31	49.751	149.37
		Spirit	5.881	178.775	80.52	49.095	149.22	6.050	178.924	79.55	49.640	149.04
		(non-grafted)	5.870	151.900	68.42	39.412	119.79	6.047	152.915	67.99	39.260	117.87
W3 (100% ETc)	Durinta F_1	Beaufort	5.117	320.462	144.33	41.627	126.53	5.263	295.090	131.20	41.985	126.05
		Maxifort	5.054	296.257	133.43	40.375	122.72	5.199	256.934	114.24	40.616	121.94
		Spirit	4.818	256.677	115.61	39.015	118.59	4.955	252.864	112.43	39.308	118.02
		(non-grafted)	4.817	222.027	100.00	32.900	100.00	4.950	224.912	100.00	33.307	100.00
	Valiro F_1	Beaufort	4.567	218.667	98.49	41.576	126.37	4.697	221.851	98.64	38.563	115.78
		Maxifort	4.509	209.194	95.67	40.349	122.64	4.637	210.648	93.66	35.876	107.71
		Spirit	4.291	192.046	87.83	39.013	118.58	4.413	180.663	80.33	35.021	105.15
		(non-grafted)	4.290	178.634	81.69	32.895	99.98	4.411	137.447	61.11	30.970	92.98
	LSD at 0.05		0.019	0.152		2.244		0.020	0.037		0.511	

both commercial tomato cultivars, particularly with the Durinta cultivar than Maxifort or Spirit rootstocks. Grafting Durinta scion onto a Beaufort rootstock (DB) could increase water savings owing to higher yield and TYWUE. Thus, grafting tomato plants could be a useful means of alleviating the negative effects of water stress on tomato plants. In addition, choosing the right combination of rootstock and scion could increase the benefit of grafting tomato plants, under water stress conditions.

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تاثیر پیوندزدن گوجه فرنگی روی رشد، بهره وری، و کارآیی مصرف آب در رژیم های مختلف آبیاری

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چکیده

اثرات پیوند زدن دو کولتیوار گوجه فرنگی(Durinta و F_1 Valouro) روی سه گوجه فرنگی پایه (Beaufort ، Maxifort، وSpirit) تحت سه رژیم آبیاری(۵۰٪، ۷۵٪، و ۱۰۰٪ تبخیر وتعرق(ETc)) بررسی شد وبرای این منظور رشد سبزینه ای، محتوای پرولین، ،کلروفیل، و عناصر معدنی برگ و نیز تولید گوجه و کارآی مصرف آب عملکرد کل (TYWUE) ارزیابی شد. با افزایش تنش آبی، ارتفاع گیاه، قطر ساقه، و عملکرد کل کم شد در حالیکه پرولین و TYWUE افزایش یافت. در میان دو کولتیوار مطالعه شده، Durinta رشد بیشتری از Valouro نشان داد. رشد گیاه، پرولین، Ca^{+2} و K^{+}، عملکرد میوه، و TYWUEدر گیاهان پیوندی بیشتر از گیاهان غیر پیوندی بود. اثرات منفی تنش آبی زیاد(ETc ۵۰٪) در گیاهان غیر پیوندی، به ویژه درValouro آشکار بود . یک تاثیر مثبت پیوندزدن در موردی مشاهده شد که Beaufort به عنوان پایه استفاده شده بود. کولتیوار Durinta که روی Beaufort پیوند زده شده بود (با سمبل DB) در تنش آبی متوسط (75% ETc) منجر به ۲۵٪ صرفه جویی در آب شد و عملکرد بیشتر(21.6–30.8%) و TYWUE بیشتر(55.1–55.5%) از آبیاری کامل(100% ETc) و تیمار شاهد(یعنی Durintaغیر پیوندی) نشان داد. نتایج حاکی بود که پیوند زدن گوجه فرنگی گلخانه ای روی پایه مناسب می تواند اثرات منفی محدودیت و کمبود آب روی گیاه را کاهش دهد.