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


ABSTRACT

The effects of grafting two greenhouse tomato cultivars (Durinta and Valouro F1) 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, Ca2+ 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
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 Ca²⁺ 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⁺, Ca²⁺, K⁺, HCO₃⁻, Cl⁻, and SO₄²⁻ 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’ F₁, Western Seed, USA, and Solanum lycopersicum L. ‘Valouro’ F₁, 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,
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:

\[ \text{ETc} = E_p \times K_p \times K_c \]

where \( E_p \) is daily Evaporation from class A pan in mm, \( K_p \) is pan coefficient (ranging between 0.70-0.88), and \( K_c \) 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⁺, Ca²⁺, 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
(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.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Plant height (cm)</th>
<th>Stem diameter (cm)</th>
<th>Leaf area (cm²)</th>
<th>Total fruit yield (t ha⁻¹)</th>
<th>TYWUE (kg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Water regimes</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>W1 (50% ETo)</td>
<td>221.63 c</td>
<td>225.60 c</td>
<td>11.58 c</td>
<td>13.72 c</td>
<td>16339.14 c</td>
</tr>
<tr>
<td>W2 (75% ETo)</td>
<td>271.11 b</td>
<td>275.05 b</td>
<td>12.84 b</td>
<td>15.08 b</td>
<td>17189.12 b</td>
</tr>
<tr>
<td>W3 (100% ETo)</td>
<td>299.35 a</td>
<td>303.44 a</td>
<td>13.43 a</td>
<td>16.03 a</td>
<td>19887.30 a</td>
</tr>
<tr>
<td>(b) Tomato cultivars</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Durinta F₁</td>
<td>269.00 a</td>
<td>273.36 a</td>
<td>15.13 a</td>
<td>15.04 a</td>
<td>19080.74 a</td>
</tr>
<tr>
<td>Valira F₁</td>
<td>259.05 b</td>
<td>262.71 b</td>
<td>14.75 b</td>
<td>14.85 b</td>
<td>18454.63 a</td>
</tr>
<tr>
<td>(c) Tomato rootstocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beaufort</td>
<td>280.71 a</td>
<td>284.21 a</td>
<td>16.09 a</td>
<td>16.47 a</td>
<td>20776.71 a</td>
</tr>
<tr>
<td>Maxifort</td>
<td>272.21 b</td>
<td>276.63 b</td>
<td>15.65 b</td>
<td>15.38 b</td>
<td>17804.75 b</td>
</tr>
<tr>
<td>Spirit</td>
<td>267.27 c</td>
<td>270.36 c</td>
<td>15.50 c</td>
<td>15.33 c</td>
<td>17371.05 c</td>
</tr>
<tr>
<td>Control (Non-grafted)</td>
<td>235.93 d</td>
<td>240.94 d</td>
<td>12.52 d</td>
<td>12.59 c</td>
<td>15268.25 d</td>
</tr>
</tbody>
</table>

* 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
Table 2. Interaction effects between irrigation water regimes\texttimes tomato cultivars, irrigation water regimes and tomato rootstocks, and tomato cultivars\texttimes tomato rootstocks on some agronomic traits of tomato plants.$^a$

<table>
<thead>
<tr>
<th>Growing seasons</th>
<th>First season 2013/2014</th>
<th>Second season 2013/2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agromonic traits</td>
<td>Plant height (cm)</td>
<td>Stem diameter (cm)</td>
</tr>
<tr>
<td>W1 (50% ETC)</td>
<td>Durinta F$_1$</td>
<td>226.90 e</td>
</tr>
<tr>
<td></td>
<td>Valero F$_1$</td>
<td>216.35 f</td>
</tr>
<tr>
<td>W2 (75% ETC)</td>
<td>Durinta F$_1$</td>
<td>275.10 c</td>
</tr>
<tr>
<td></td>
<td>Valero F$_1$</td>
<td>267.12 d</td>
</tr>
<tr>
<td>W3 (100% ETC)</td>
<td>Durinta F$_1$</td>
<td>305.01 a</td>
</tr>
<tr>
<td></td>
<td>Valero F$_1$</td>
<td>293.68 b</td>
</tr>
<tr>
<td>W1 (50% ETC)</td>
<td>Beaufort</td>
<td>237.80 h</td>
</tr>
<tr>
<td></td>
<td>Maxifort</td>
<td>234.90 j</td>
</tr>
<tr>
<td></td>
<td>Spirit</td>
<td>220.75 jk</td>
</tr>
<tr>
<td></td>
<td>(Non-grafted)</td>
<td>203.05 k</td>
</tr>
<tr>
<td>W2 (75% ETC)</td>
<td>Beaufort</td>
<td>289.45 d</td>
</tr>
<tr>
<td></td>
<td>Maxifort</td>
<td>281.75 e</td>
</tr>
<tr>
<td></td>
<td>Spirit</td>
<td>276.95 f</td>
</tr>
<tr>
<td></td>
<td>(Non-grafted)</td>
<td>236.30 i</td>
</tr>
<tr>
<td>W3 (100% ETC)</td>
<td>Beaufort</td>
<td>314.87 a</td>
</tr>
<tr>
<td></td>
<td>Maxifort</td>
<td>309.97 b</td>
</tr>
<tr>
<td></td>
<td>Spirit</td>
<td>304.10 c</td>
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<tr>
<td></td>
<td>(Non-grafted)</td>
<td>268.45 g</td>
</tr>
<tr>
<td>Durinta F$_1$</td>
<td>Beaufort</td>
<td>283.74 a</td>
</tr>
<tr>
<td></td>
<td>Maxifort</td>
<td>285.41 b</td>
</tr>
<tr>
<td></td>
<td>Spirit</td>
<td>256.20 cd</td>
</tr>
<tr>
<td></td>
<td>(Non-grafted)</td>
<td>247.93 d</td>
</tr>
<tr>
<td>Valero F$_1$</td>
<td>Beaufort</td>
<td>277.67 ab</td>
</tr>
<tr>
<td></td>
<td>Maxifort</td>
<td>257.00 c</td>
</tr>
<tr>
<td></td>
<td>Spirit</td>
<td>255.33 cd</td>
</tr>
<tr>
<td></td>
<td>(Non-grafted)</td>
<td>223.93 e</td>
</tr>
</tbody>
</table>

$^a$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⁻, Ca²⁺, 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⁺, Ca²⁺, 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 Ca²⁺ 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⁻, Ca²⁺, 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⁻, Ca²⁺, 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⁻, Ca²⁺, and K⁺. Durinta plants under the full water treatment showed the highest Na⁺, Cl⁻, Ca²⁺, 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⁻, Ca²⁺ 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⁻, Ca²⁺, and K⁺ concentrations than
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.4

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Chlorophyll (g) 2013-14</th>
<th>Chlorophyll (g) 2014-15</th>
<th>Proline (mg g⁻¹ fw) 2013-14</th>
<th>Proline (mg g⁻¹ fw) 2014-15</th>
<th>Na⁺ (%) 2013-14</th>
<th>Na⁺ (%) 2014-15</th>
<th>Ca²⁺ (%) 2013-14</th>
<th>Ca²⁺ (%) 2014-15</th>
<th>K⁺ (%) 2013-14</th>
<th>K⁺ (%) 2014-15</th>
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<tr>
<td>(a) Water regimes</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1 (50% ETc)</td>
<td>37.421 c</td>
<td>38.531 c</td>
<td>8.076 a</td>
<td>8.290 a</td>
<td>0.172 a</td>
<td>0.167 c</td>
<td>1.307 c</td>
<td>1.375 c</td>
<td>1.424 c</td>
<td>1.401 c</td>
</tr>
<tr>
<td>W2 (75% ETc)</td>
<td>48.957 b</td>
<td>50.328 b</td>
<td>6.374 b</td>
<td>6.556 b</td>
<td>0.175 a</td>
<td>0.176 b</td>
<td>1.419 b</td>
<td>1.437 b</td>
<td>1.525 b</td>
<td>1.542 b</td>
</tr>
<tr>
<td>W3 (100% ETc)</td>
<td>58.237 a</td>
<td>59.921 a</td>
<td>4.638 c</td>
<td>4.816 c</td>
<td>0.178 a</td>
<td>0.184 a</td>
<td>1.518 a</td>
<td>1.637 a</td>
<td>1.721 a</td>
<td>1.576 a</td>
</tr>
<tr>
<td>(b) Tomato cultivars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durinta F₁</td>
<td>50.300 a</td>
<td>51.693 a</td>
<td>6.721 a</td>
<td>6.902 a</td>
<td>0.190 b</td>
<td>0.176 a</td>
<td>1.503 a</td>
<td>1.581 a</td>
<td>1.621 a</td>
<td>1.570 a</td>
</tr>
<tr>
<td>Valiro F₁</td>
<td>46.110 b</td>
<td>47.494 b</td>
<td>6.034 b</td>
<td>6.206 b</td>
<td>0.186 a</td>
<td>0.175 a</td>
<td>1.327 a</td>
<td>1.385 a</td>
<td>1.492 b</td>
<td>1.443 b</td>
</tr>
<tr>
<td>(c) Tomato rootstocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beaufort</td>
<td>49.528 a</td>
<td>50.805 a</td>
<td>6.573 a</td>
<td>6.760 a</td>
<td>0.208 a</td>
<td>0.183 a</td>
<td>1.591 a</td>
<td>1.668 a</td>
<td>1.665 a</td>
<td>1.613 a</td>
</tr>
<tr>
<td>Maxifort</td>
<td>49.311 a</td>
<td>50.795 a</td>
<td>6.497 b</td>
<td>6.682 b</td>
<td>0.192 a</td>
<td>0.179 a</td>
<td>1.418 b</td>
<td>1.486 b</td>
<td>1.605 b</td>
<td>1.554 b</td>
</tr>
<tr>
<td>Spirit</td>
<td>47.026 b</td>
<td>48.442 b</td>
<td>6.232 c</td>
<td>6.388 c</td>
<td>0.177 a</td>
<td>0.177 a</td>
<td>1.348 b</td>
<td>1.413 b</td>
<td>1.522 c</td>
<td>1.472 c</td>
</tr>
<tr>
<td>Control (Non-grafted)</td>
<td>46.955 b</td>
<td>48.332 b</td>
<td>6.209 c</td>
<td>6.386 c</td>
<td>0.164 b</td>
<td>0.162 b</td>
<td>1.303 b</td>
<td>1.365 b</td>
<td>1.433 d</td>
<td>1.387 d</td>
</tr>
</tbody>
</table>

4 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.

<table>
<thead>
<tr>
<th>Growing seasons</th>
<th>Chemical compositions</th>
<th>First season 2013/2014</th>
<th>Second season 2014/2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. treatments</td>
<td></td>
<td>Proline (mg g⁻¹ fw)</td>
<td>Na⁺ (%)</td>
</tr>
<tr>
<td>W1</td>
<td>Durini F₁</td>
<td>8.502 a</td>
<td>0.173 c</td>
</tr>
<tr>
<td>(50% ETC)</td>
<td>Valiro F₁</td>
<td>8.522 b</td>
<td>0.172 c</td>
</tr>
<tr>
<td>W2</td>
<td>Durini F₁</td>
<td>8.712 c</td>
<td>0.176 c</td>
</tr>
<tr>
<td>(75% ETC)</td>
<td>Valiro F₁</td>
<td>8.636 d</td>
<td>0.174 c</td>
</tr>
<tr>
<td>W3</td>
<td>Durini F₁</td>
<td>8.495 e</td>
<td>0.195 a</td>
</tr>
<tr>
<td>(100% ETC)</td>
<td>Valiro F₁</td>
<td>8.414 f</td>
<td>0.192 b</td>
</tr>
<tr>
<td>W1</td>
<td>Beaufort (50% ETC)</td>
<td>8.301 a</td>
<td>0.180 b</td>
</tr>
<tr>
<td>Maxfort</td>
<td>8.210 b</td>
<td>0.178 b</td>
<td>1.306 i</td>
</tr>
<tr>
<td>W2</td>
<td>(75% ETC)</td>
<td>8.790 c</td>
<td>0.175 b</td>
</tr>
<tr>
<td>Spirit</td>
<td>8.856 d</td>
<td>0.158 b</td>
<td>1.204 h</td>
</tr>
<tr>
<td>(Non-grafted)</td>
<td>Beaufort</td>
<td>6.575 e</td>
<td>0.182 b</td>
</tr>
<tr>
<td>Maxfort</td>
<td>6.499 f</td>
<td>0.180 b</td>
<td>1.470 d</td>
</tr>
<tr>
<td>W3</td>
<td>(100% ETC)</td>
<td>6.212 g</td>
<td>0.177 b</td>
</tr>
<tr>
<td>Spirit</td>
<td>6.201 g</td>
<td>0.160 b</td>
<td>1.310 l</td>
</tr>
<tr>
<td>(Non-grafted)</td>
<td>Beaufort</td>
<td>4.781 i</td>
<td>0.270 a</td>
</tr>
<tr>
<td>Maxfort</td>
<td>4.554 j</td>
<td>0.263 a</td>
<td>1.521 c</td>
</tr>
<tr>
<td>Spirit</td>
<td>4.842 h</td>
<td>0.264 a</td>
<td>1.447 e</td>
</tr>
<tr>
<td>(Non-grafted)</td>
<td>4.553 j</td>
<td>0.259 a</td>
<td>1.398 g</td>
</tr>
<tr>
<td>Durini F₁</td>
<td>Beaufort</td>
<td>6.840 b</td>
<td>0.215 b</td>
</tr>
<tr>
<td>Maxfort</td>
<td>6.585 c</td>
<td>0.185 c</td>
<td>1.383 bc</td>
</tr>
<tr>
<td>Spirit</td>
<td>6.541 d</td>
<td>0.178 b</td>
<td>1.241 c</td>
</tr>
<tr>
<td>(Non-grafted)</td>
<td>Beaufort</td>
<td>6.226 c</td>
<td>0.234 b</td>
</tr>
<tr>
<td>Maxfort</td>
<td>6.153 f</td>
<td>0.170 c</td>
<td>1.320 bc</td>
</tr>
<tr>
<td>Spirit</td>
<td>5.889 g</td>
<td>0.169 c</td>
<td>1.314 bc</td>
</tr>
<tr>
<td>(Non-grafted)</td>
<td>5.878 g</td>
<td>0.167 c</td>
<td>1.311 bc</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Experimental treatments</th>
<th>Water stress levels</th>
<th>Tomato F1 cultivars</th>
<th>Tomato rootstocks</th>
<th>Proline (mg g^{-1} fw)</th>
<th>Total yield (t ha^{-1})</th>
<th>Yield ratio to cont. (%)</th>
<th>\textit{WUE} ratio to cont. (%)</th>
<th>Proline (mg g^{-1} fw)</th>
<th>Total yield (t ha^{-1})</th>
<th>Yield ratio to cont. (%)</th>
<th>\textit{WUE} ratio to cont. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1</td>
<td>Beaufort</td>
<td>Durinta F1</td>
<td>8.719</td>
<td>236.121</td>
<td>106.34</td>
<td>63.652</td>
<td>193.47</td>
<td>8.968</td>
<td>225.434</td>
<td>100.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maxifort</td>
<td></td>
<td>8.624</td>
<td>181.414</td>
<td>81.71</td>
<td>58.536</td>
<td>177.92</td>
<td>8.870</td>
<td>192.898</td>
<td>85.77</td>
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<tr>
<td></td>
<td></td>
<td>Spirit</td>
<td></td>
<td>8.394</td>
<td>178.088</td>
<td>80.21</td>
<td>58.018</td>
<td>176.35</td>
<td>8.500</td>
<td>182.029</td>
<td>80.93</td>
</tr>
<tr>
<td></td>
<td>(non-grafted)</td>
<td></td>
<td></td>
<td>8.263</td>
<td>151.340</td>
<td>68.16</td>
<td>49.963</td>
<td>151.84</td>
<td>8.499</td>
<td>156.317</td>
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</tr>
<tr>
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<td>(50% ETC)</td>
<td>Beaufort</td>
<td>Valiro F1</td>
<td>7.884</td>
<td>174.803</td>
<td>78.73</td>
<td>59.207</td>
<td>179.96</td>
<td>8.109</td>
<td>176.763</td>
<td>78.59</td>
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<td>58.501</td>
<td>177.81</td>
<td>8.018</td>
<td>146.555</td>
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<tr>
<td></td>
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<td>Spirit</td>
<td></td>
<td>7.465</td>
<td>140.655</td>
<td>63.35</td>
<td>58.013</td>
<td>176.33</td>
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<td>7.464</td>
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<td>53.68</td>
<td>49.956</td>
<td>151.84</td>
<td>7.677</td>
<td>118.544</td>
<td>52.71</td>
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<td>Durinta F2</td>
<td>6.922</td>
<td>282.587</td>
<td>127.28</td>
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<td>155.06</td>
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<tr>
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<td>(75% ETC)</td>
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<td>Valiro F1</td>
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<td>209.385</td>
<td>94.31</td>
<td>50.480</td>
<td>153.43</td>
<td>6.406</td>
<td>210.513</td>
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<td></td>
<td>6.156</td>
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<td>150.37</td>
<td>6.331</td>
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<td>152.915</td>
<td>67.99</td>
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<td>Durinta F3</td>
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<td>4.818</td>
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<td>218.667</td>
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<td></td>
<td>4.290</td>
<td>178.634</td>
<td>81.69</td>
<td>32.895</td>
<td>99.98</td>
<td>4.411</td>
<td>137.447</td>
<td>61.11</td>
</tr>
</tbody>
</table>

\textit{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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تأثیر پیوندزدن گوجه فرنگی روی رشد، بهره وری، و کارآیی مصرف آب در رژیم های مختلف آبیاری

ا. ر. الحربی، ا. م. العوراى، و. ا. الكاردایی، ه. س. عبذالرزاق، ک. ر. الحربی، و. عبادی، و. ا. سعد

چکیده

اثرات پیوند زدن دو کولتیور گوجه فرنگی (Valouro F1 و Durinta) تحت سه رژیم آبیاری (50/50/100% تبخير و تعرق) بر روی شد و برای این منظور رشد سبزینه ای، محتوای پروپوندی، کلروفیل، و عناصر معدنی گیاگی و نیز تولید گوجه و کارآی مصرف آب عملکرد کل (TYWUE) ارزیابی شد. با افزایش گیاه، افزایش قطر ساقه، و عملکرد کل کم شد در حالیکه پروتين و TYWUE افزایش یافت. در میان دو کولتیور مطالعه شده، Valouro رشد بیشتری از Durinta داشت. رشد بیشتری در گیاهان پیوندی بیشتر از گیاهان غیر Valouro داشت. اثرات منفی تنش آبی زیاد (ETc50%) در گیاهان غیر پیوندی به ویژه در Durinta بیشتر ظاهر شد. بیشتری از آنها در Durinta بود که روز با تغییر در آب شد و عملکرد بیشتر (75% ETc) بیشتر (55–55.1) از آبیاری کامل (100% ETc) و نیز شاهد عملکرد بیشتری (غیر پیوندی) نشان داد. نتایج حاکی از دست دادن، دو کولتیور مصرف آب روی گیاه را کاهش دهد.