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TOMATO GRAFTING IMPACTS ON YIELD AND FRUIT QUALITY UNDER WATER STRESS CONDITIONS

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KEYWORDS

Durinta cultivar

Grafting

Suitable rootstock

Vitamin C

Water regimes

ABSTRACT

Water deficit in semi-arid areas is the main limiting factor affecting crop production and quality. Suitable strategies for water management, such as water regimes and grafting, can be helpful for the sustainability of agriculture and overcoming drought stress. Responses of two greenhouse-tomato cultivars (Durinta and Valouro F₁) grafted onto three rootstocks (Beaufort, Maxifort, and Spirit) to water stress were evaluated using three irrigation water regimes (50, 75, and 100% crop evapotranspiration [ET_c]). The results showed the efficiency of grafting increases in total yield, and contents of vitamin C (VC), total soluble solids (TSS), calcium (Ca²⁺), and potassium (K⁺). Beaufort rootstocks produced better quality plants and higher yield compared to Maxifort or Spirit rootstocks. Under 100% ET_c, Durinta cultivars had higher fruit number and weight, total yield, and Ca²⁺ and K⁺ concentrations, but under high water stress, VC, TSS, and TS contents increased. Durinta grafted onto Beaufort rootstocks (DB) had higher total yield percentages (40.36–52.49% and 73.78–100.73%) than non-grafted Durinta and Valouro plants, respectively. Thus, we recommend grafting of tomato scions (Durinta) onto Beaufort rootstocks as an acceptable practice for greenhouse producers, because DB increased crop yield while saving approximately 25% of irrigation water. Moreover, it is an effective practice for industrial and fresh market production of tomato because of the high TSS and VC contents.

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1 Introduction

Tomato (*Solanum lycopersicum* L.), which is largely produced in semi-arid areas, characterized by water scarcity (Sanchez-Rodriguez et al., 2014), is the foremost economic vegetable for greenhouse production. In Saudi Arabia, the production of tomato in greenhouses occupies approximately 50% of the total planting area (ASYB, 2014). Furthermore, most of the cultivated soil is sandy soil and is often exposed to water stress (Al-Omran et al., 2010). Water stress not only affects quality, but also inhibits tomato yield (Agbemaflle et al., 2014). Since plants actively take up water and nutrients, the ability of a root system to absorb water and transport nutrients reduces water stress because of a limited transpiration rate, and low active transport and membrane absorbency (Sanchez-Rodriguez et al., 2014; Agbemaflle et al., 2015).

Studies on tomato mainly focus on increasing yield and quality, without considering the effects of abiotic stresses such as water stress. For this purpose, alternative methods and new techniques are continually implemented in tomato farming (Gebologlu et al., 2011). Grafting is one such technique that permits the plant breeder to combine selected shoot structures with a vigorous root system to aid water stress tolerance in plants (Emaratpardaz et al., 2015). Grafting is known to improve growth and increase tomato yield (Flores et al., 2010; Schwarz et al., 2013). However, there are conflicting data on its effects on fruit quality (Davis et al., 2008; Di Gioia et al., 2010; VinkovicVrcek et al., 2011). The use of a suitable rootstock during the grafting process is the key factor in determining the quality of the tomato fruit (Sánchez-Rodríguez et al., 2012). Various studies have shown that irrigation at a stress level (e.g., 50% ETc) has beneficial effects on tomato quality in terms of total solid (TS), total soluble solid (TSS), and vitamin C (VC) levels (Alaoui et al., 2015; Zhang et al., 2016). Irrigation regimes and grafting strategies are quite novel tools for improving water-stress tolerance and quality of tomato (Sánchez-Rodríguez et al., 2012; Sánchez-Rodríguez et al., 2014).

Recently, greenhouse tomato producers have begun using the grafting method to increase productivity and plant vigor (Djidonou et al., 2013). The method of grafting onto various vigorous rootstocks has been adopted to enhance yield production of many vegetable crops, including tomato, under water stress (Rouphael et al., 2008; Schwarz et al., 2010; Estévez-Caparrós et al., 2011; Sánchez-Rodríguez et al., 2014). However, the influence of water stress on the fruit quality of grafted tomato has not been fully explored. Thus, the aims of study were to: a) determine the effect of water regimes on the yield and fruit quality of greenhouse-grafted tomato; and b) assess the ability of tomato cultivars grafted onto different tomato rootstocks to increase water stress tolerance.

2 Materials and Methods

2.1 Plant materials, growth conditions, and experimental design

Two indeterminate commercial tomato cultivars (*Solanum lycopersicum* L. 'Durinta' F₁, Western Seed, USA and 'Valouro' F₁, Rijk Zwaan, Netherlands) were either not grafted (controls) or grafted onto three tomato rootstocks (Beaufort and Maxifort [*S. lycopersicum* and *S. habrochaites*, De Ruiter/Monsanto, Bergschenhoek, Netherlands], and the intraspecific rootstock Spirit (*S. lycopersicon* x *S. pimpinellifolium*, Nunhems Seeds, Netherlands). These were the most common rootstocks available (Estévez-Caparrós et al., 2011).

A two-year greenhouse study was performed at the College of Agriculture Experimental Station, 40 km southwest of Riyadh, Saudi Arabia (24°39'N, 46°44'E) during 2013/2014 and 2014/2015. The day/night temperature and the relative humidity in the greenhouse were maintained at 26/18 ± 2°C and 70 ± 2%, respectively. Seeds of the scion cultivars were sown 5 d earlier (November 28, 2013 and November 22, 2014) than the seeds of the rootstocks (December 1, 2013 and November 26, 2014) to ensure equal stem diameters at the time of grafting (Khah et al., 2006). The tube grafting method was utilized because it is easy to adopt in Solanaceous crops (Lee et al., 2010). At the third-fourth true leaf stage, tomato seedlings were transplanted on Jan. 1, 2014 and Dec. 25, 2014, for the first and second years, respectively.

The experiments were designed as a split-split-plot in a randomized complete block with three replicates. Based on crop evapotranspiration (ETc), three irrigation regimes (50, 75, and 100% ETc) were arranged in the main plots, and the two tomato cultivars (Durinta and Valouro F₁s) in the sub-plots. In addition, six grafting combinations were set in the sub-sub plots with two controls: DB (Durinta scion + Beaufort rootstock), DM (Durinta scion + Maxifort rootstock), DS (Durinta scion + Spirit rootstock), D (non-grafted Durinta, control), VB (Valouro scion + Beaufort rootstock), VM (Valouro scion + Maxifort rootstock), VS (Valouro scion + Spirit rootstock), and V (non-grafted Valouro, control). The area of the sub-plot area was 10 m², including 20 tomato plants.

2.2 Irrigation water regimes

Irrigation water was provided via a drip irrigation system at three levels based on crop evapotranspiration (ETc): no water stress NWS (100% ETc) as a control, moderate MWS (75% ETc) and high water stress HWS (50% ETc). Both grafted and non-grafted transplants were irrigated regularly during the first 12 d for transplant establishment and to assure vigorous roots, then the three water regimes were implemented. Irrigation management based on the daily crop ETc through 'class B' pan evaporation, using the crop coefficients (Kc) equation as defined by Allen et al. (1998): $ET_c = ET_0 \times K_c$, was followed. The total amount of water added throughout the growing season for each regime was 6141, 4606, and 3070 m³/ha and 5930, 4535, and 3023 m³/ha for NWS, MWS, and HWS, respectively, in the first and second years. The irrigation water quality had pH 6.44 and sodium adsorption ratio (SAR) 4.33; EC of 0.7 dS/m.

2.3 Yield and its components' measurements

Total yield (kg/m²) was calculated using all the fruits collected from each plant during the harvest period. Fully ripe fruits were harvested three times weekly from March 27, 2014 and March 21, 2015 until May 29, 2014 and May 27, 2015, respectively. The number of fruits per plant and the average fruit weight (g) were recorded for each treatment.

2.4 Fruit quality measurements

At the peak harvesting period, 10 fully red-ripe tomato fruits, collected at random from each sub-sub-plot, were selected to determine some qualitative characteristics. The fruits were washed once with tap water and twice with distilled water, sliced, and deseeded. They were analyzed for VC (mg/100 g fw), TSS (%), titratable acidity (TA, %), and total sugars (TS, %). VC as ascorbic acid was measured using the 2, 6-dichlorophenolindophenol dye via titration (Patane et al., 2011). The TSS content of the tomato fruit juice was measured with a digital portable refractometer (PR-101 model, ATAGO, Japan). TA was estimated using potentiometric titration with 0.1 M NaOH up to pH 8.1 and the results were expressed as the percentage of citric acid in the fruit juice (Turhan et al., 2011). To analyze TS, the AOAC (2000) method was used. To determine calcium (Ca²⁺) and potassium (K⁺) concentrations, approximately 50 g of fruit slices were placed in a dry forced-air oven at 65°C for 72 h until they reached a constant weight (Di Gioia et al., 2010). The dried samples were then ground separately in a Wiley mill to pass through a 20-mesh screen, and 0.5 g of the samples were analyzed (AOAC, 2000).

2.5 Statistical analysis

All data were statistically analyzed with an ANOVA using the SAS system for windows statistical software version 8.1 (SAS Institute, Inc., Cary, NC, USA, 2008). To distinguish between treatment means within each measured character, a revised least

significant difference (LSD) test was executed at a 0.05 probability level (Steel & Torrie 1980).

3 Results

3.1 Fruit yield and its components

Fruit/plant number, fruit weight, and total yield decreased with the increase in the water stress level. The lowest values of these characteristics were observed under HWS while, the highest values were recorded in tomato plants under NWS (Table 1).

Furthermore, fruit number, weight, and total yield were affected by cultivar characteristics. The Durinta cultivar had higher values of these agronomic characteristics than the Valouro cultivar (Table 1).

The tomato grafted onto the three rootstocks had higher fruit number, heavier fruits, and higher total yield than the non-grafted plants. Of these, plants grafted onto the Beaufort rootstock had the highest fruit number, weight, and total yield (Table 1).

3.2 Fruit quality

Tomato plants grown under HWS produced the best quality fruits represented by higher VC, TSS, TA, and TS contents. These traits were higher in the order 50 > 75 > 100% ETc, implying that an increased water stress level had a positive impact on fruit quality. In contrast, tomato grown under NWS had higher Ca²⁺ and K⁺ levels in their fruit tissues (Table 2).

Durinta had higher levels of VC, TSS, TA, and TS than Valouro. Similarly, Durinta plants accumulated higher Ca²⁺ and K⁺ concentrations in their fruit tissues than Valouro plants (Table 2). The type of rootstock significantly influenced the characteristics defining fruit quality. Plants grafted onto Beaufort rootstocks had higher levels of VC, TSS, TA, TS, Ca²⁺, and K⁺ compositions than those on the other two rootstocks and non-grafted plants (Table 2).

Table 1 Effects of different irrigation water regimes, two commercial tomato cultivars, and three tomato rootstocks on tomato crop yield and its components during 2013/2014 and 2014/2015

Treatments	Fruit/plant number		Fruit fresh weight (g)		Total yield (kg/m ²)	
	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015
Water regimes						
NWS (100% ETc)	71.17 ^a	70.87 ^a	133.358 ^a	131.987 ^a	23.684 ^a	23.139 ^a
MWS (75% ETc)	68.96 ^b	66.96 ^b	122.108 ^b	120.450 ^b	20.991 ^b	20.059 ^b
HWS (50% ETc)	67.42 ^c	64.17 ^c	106.379 ^c	104.825 ^c	17.082 ^c	17.254 ^c
Tomato cultivars						
Durinta F₁	73.69 ^a	71.06 ^a	130.116 ^a	128.511 ^a	23.972 ^a	22.828 ^a
Valouro F₁	62.67 ^b	63.61 ^b	111.113 ^b	109.663 ^b	17.408 ^b	17.439 ^b
Tomato rootstocks						
Beaufort	74.67 ^a	71.83 ^a	131.427 ^a	130.066 ^a	24.537 ^a	23.358 ^a
Maxifort	71.22 ^b	70.22 ^b	119.866 ^b	118.483 ^b	21.346 ^b	20.800 ^b
Spirit	66.55 ^c	65.11 ^c	118.900 ^c	115.677 ^c	19.783 ^c	18.830 ^c
Non-grafted (Control)	60.28 ^d	62.17 ^d	112.266 ^d	112.122 ^d	16.918 ^d	17.425 ^d

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

Table 2 Effects of different water stress levels, two commercial tomato cultivars, and three tomato rootstocks on tomato fruit quality during 2013/2014 and 2014/2015

Treatments	VC (mg/100gfw)		TSS (%)		TA (%)		TS (%)		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
Water stress levels												
NWS (100% ETc)	24.600 ^c	24.766 ^c	4.612 ^c	4.550 ^c	0.422 ^c	0.407 ^c	3.903 ^c	4.002 ^c	1.287 ^a	1.350 ^a	2.677 ^a	2.824 ^a
MWS (75% ETc)	26.962 ^b	27.075 ^b	4.962 ^b	4.920 ^b	0.461 ^b	0.439 ^b	4.220 ^b	4.341 ^b	1.258 ^b	1.321 ^b	2.378 ^b	2.508 ^b
HWS (50% ETc)	28.837 ^a	28.866 ^a	5.400 ^a	5.320 ^a	0.522 ^a	0.503 ^a	4.573 ^a	4.689 ^a	1.142 ^c	1.201 ^c	2.154 ^c	2.271 ^c
Tomato cultivars												
Durinta F ₁	26.991 ^a	27.263 ^a	5.108 ^a	5.077 ^a	0.468 ^a	0.469 ^a	4.335 ^a	4.447 ^a	1.279 ^a	1.345 ^a	2.428 ^a	2.562 ^a
Valouro F ₁	26.608 ^b	26.54 ^b	4.875 ^b	4.783 ^b	0.438 ^b	0.430 ^b	4.129 ^b	4.241 ^b	1.178 ^b	1.236 ^b	2.378 ^b	2.507 ^b
Tomato rootstocks												
Beaufort	27.733 ^a	27.755 ^a	5.166 ^a	5.122 ^a	0.490 ^a	0.459 ^a	4.377 ^a	4.500 ^a	1.316 ^a	1.381 ^a	2.630 ^a	2.772 ^a
Maxifort	27.033 ^b	27.238 ^b	5.050 ^b	5.027 ^b	0.478 ^b	0.458 ^a	4.293 ^b	4.409 ^b	1.267 ^b	1.331 ^b	2.509 ^b	2.647 ^b
Spirit	26.900 ^b	26.916 ^c	4.983 ^c	4.800 ^c	0.473 ^c	0.455 ^a	4.220 ^c	4.327 ^c	1.201 ^c	1.261 ^c	2.353 ^c	2.481 ^c
Non-grafted (Control)	25.533 ^c	25.700 ^d	4.766 ^d	4.772 ^c	0.432 ^d	0.426 ^b	4.002 ^d	4.009 ^d	1.131 ^d	1.188 ^d	2.121 ^d	2.237 ^d

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

3.3 Second interaction effect on fruit yield and its components

Durinta under NWS had higher fruit number, heavier fruit, and higher total yield than under the other water regimes and treatments, whereas the Valouro under HWS had the lowest values of the same components. Furthermore, Durinta plants under MWS produced higher fruit number, heavier fruits, and higher total yield than Valouro plants under NWS (Figures 1a, b, and c).

Tomato plants grafted onto different rootstocks had higher fruit number, heavier fruits, and higher total yield than non-grafted plants, particularly under NWS. Furthermore, non-grafted plants under HWS had the lowest values of these characteristics (Figures 2a, b, and c). Of the different rootstocks evaluated, Beaufort under NWS produced plants with the highest yield and yield components followed by Maxifort, and finally Spirit, especially with respect to fruit number (Figure 2a). Similarly, Beaufort produced plants with heavier fruits and higher total yield under MWS and then HWS than the other rootstocks (Figures 2b and c).

Fruit number, fruit weight, and total yield increased in response to grafting, depending on the scion-rootstock combination (Figures 3a, b, and c). The maximum values of fruit yield and yield components were found in the DB followed by the DM combination. The minimum values were found in non-grafted Valouro plants followed by the VS combination (Figures 3a, b and c).

3.4 Second interaction effect on fruit quality

Fruit quality characteristics (VC, TSS, TA, and TS) significantly increased in Durinta mainly under HWS, whereas Valouro had the lowest values of these traits under NWS. In contrast, Durinta,

under NWS, had significantly higher concentrations of Ca²⁺ than any other treatment (Table 3).

The interaction between grafting and water regimes on VC, TSS, TA, and TS contents was evident as the maximum values of these traits were found when plants were grafted onto the Beaufort rootstock under HWS. On the other hand, the minimum values of these characteristics were found in non-grafted plants under NWS. The Ca²⁺ content was significantly higher in plants grafted onto Beaufort rootstocks under NWS than in those grafted onto Maxifort and Spirit rootstocks or non-grafted plants under any water regime (Table 3).

The type of rootstock affected the quality of the fruits developed on the scion. DB followed by DM combinations tended to have higher values of VC, TSS, TA, TS, and Ca²⁺ than non-grafted fruits and those of any other grafting combination. In contrast, non-grafted Valouro fruits had lower values of VC, TSS, TA, TS, and Ca²⁺ than grafted fruits (Table 3).

3.5 Interaction effect among tomato cultivars, tomato rootstocks, and water regime levels

Under all the water regimes, grafting combinations produced significantly higher fruit/plant number, average fruit weight, and total yield than non-grafted plants. The non-grafted Valouro plants under HWS produced plants with the lowest values of fruit yield components (Table 4). In terms of quality, the highest VC values (29.50–29.77 mg/100 g) were found in DB followed by DM fruits (29.30–29.60 mg/100 g), under HWS. In contrast, the lowest values (22.90–22.64 mg/100 g) were recorded in the non-

Table 3 Interaction effects between water stress levels and tomato cultivars, water stress levels and tomato rootstocks, and tomato cultivars and tomato rootstocks on the fruit quality of tomato during 2013/2014 and 2014/2015

Growing seasons		2013/2014					2014/2015				
Fruit quality		VC (mg/100gfw)	TSS (%)	TA (%)	TS (%)	Ca ²⁺ (%)	VC (mg/100gfw)	TSS (%)	TA (%)	TS (%)	Ca ²⁺ (%)
NWS (100% ETc)	Durinta F ₁	24.950 ^c	4.725 ^e	0.422 ^c	4.000 ^c	1.340 ^a	25.316 ^c	4.750 ^e	0.423 ^d	4.101 ^e	1.406 ^a
	Valouro F ₁	24.250 ^d	4.500 ^f	0.413 ^f	3.806 ^f	1.310 ^b	24.216 ^f	4.350 ^f	0.390 ^f	3.903 ^f	1.376 ^b
MWS (75% ETc)	Durinta F ₁	27.050 ^b	5.000 ^c	0.461 ^c	4.261 ^c	1.233 ^c	27.158 ^c	5.000 ^c	0.462 ^c	4.377 ^c	1.293 ^c
	Valouro F ₁	26.875 ^b	4.925 ^d	0.441 ^d	4.180 ^d	1.206 ^d	26.991 ^d	4.841 ^d	0.415 ^e	4.306 ^d	1.266 ^d
HWS (50% ETc)	Durinta F ₁	28.975 ^a	5.600 ^a	0.522 ^a	4.744 ^a	1.188 ^e	29.316 ^a	5.483 ^a	0.523 ^a	4.865 ^a	1.251 ^e
	Valouro F ₁	28.700 ^a	5.200 ^b	0.519 ^b	4.402 ^b	1.096 ^f	28.416 ^b	5.158 ^b	0.483 ^b	4.514 ^b	1.150 ^f
NWS (100% ETc)	Beaufort	26.116 ^f	4.766 ^f	0.415 ^h	3.993 ⁱ	1.378 ^a	26.116 ^h	4.760 ^h	0.410 ^f	3.976 ^j	1.444 ^a
	Maxifort	25.201 ^h	4.566 ^g	0.408 ⁱ	3.917 ^j	1.327 ^c	25.202 ^j	4.557 ⁱ	0.403 ^g	3.764 ^j	1.393 ^c
	Spirit	24.783 ⁱ	4.450 ^h	0.402 ^j	3.877 ^k	1.257 ^e	24.783 ^k	4.443 ^j	0.400 ^h	3.197 ^k	1.320 ^e
	Non-grafted	22.950 ^j	4.416 ^h	0.401 ^j	3.671 ^l	1.184 ^h	22.950 ^l	4.409 ^k	0.398 ⁱ	3.095 ^l	1.243 ^h
MWS (75% ETc)	Beaufort	28.083 ^c	5.083 ^c	0.449 ^d	4.335 ^c	1.349 ^b	28.083 ^e	5.078 ^c	0.438 ^c	4.882 ^b	1.414 ^b
	Maxifort	27.500 ^d	5.016 ^c	0.444 ^e	4.287 ^f	1.293 ^d	27.500 ^f	5.012 ^f	0.441 ^c	4.417 ^f	1.363 ^d
	Spirit	27.050 ^e	4.833 ^f	0.435 ^f	4.210 ^g	1.230 ^f	27.050 ^g	4.827 ^g	0.432 ^d	4.316 ^g	1.290 ^f
	Non-grafted	25.666 ^g	4.750 ^f	0.427 ^g	4.050 ^h	1.159 ^j	25.666 ⁱ	4.747 ^h	0.422 ^e	4.153 ^h	1.216 ^j
HWS (50% ETc)	Beaufort	29.066 ^a	5.516 ^a	0.525 ^a	4.724 ^a	1.222 ^g	29.066 ^a	5.509 ^a	0.518 ^a	5.617 ^a	1.285 ^g
	Maxifort	29.000 ^a	5.500 ^b	0.520 ^b	4.600 ^b	1.181 ⁱ	29.000 ^b	5.496 ^b	0.511 ^b	4.717 ^c	1.238 ⁱ
	Spirit	28.916 ^a	5.150 ^c	0.519 ^c	4.572 ^c	1.115 ^k	28.916 ^c	5.142 ^c	0.515 ^b	4.688 ^d	1.174 ^k
	Non-grafted	28.483 ^b	5.116 ^d	0.449 ^d	4.396 ^d	1.050 ^l	28.483 ^d	5.112 ^d	0.440 ^c	4.508 ^e	1.106 ^l
Durinta F ₁	Beaufort	27.833 ^a	5.310 ^a	0.483 ^a	4.488 ^a	1.371 ^a	28.066 ^a	5.252 ^a	0.480 ^a	4.602 ^a	1.439 ^a
	Maxifort	27.333 ^b	5.208 ^b	0.479 ^b	4.399 ^b	1.318 ^b	27.788 ^b	5.184 ^b	0.476 ^b	4.510 ^b	1.387 ^b
	Spirit	26.633 ^c	4.900 ^c	0.474 ^c	4.314 ^c	1.250 ^d	26.688 ^e	4.864 ^c	0.470 ^c	4.424 ^c	1.314 ^d
	Non-grafted	25.433 ^e	4.833 ^e	0.472 ^c	4.139 ^f	1.178 ^f	25.911 ^g	4.673 ^e	0.468 ^c	4.195 ^e	1.238 ^f
Valouro F ₁	Beaufort	27.166 ^c	5.100 ^c	0.435 ^d	4.266 ^d	1.262 ^c	27.444 ^c	5.001 ^c	0.431 ^d	4.374 ^d	1.324 ^c
	Maxifort	26.733 ^d	5.033 ^d	0.434 ^{de}	4.188 ^e	1.216 ^e	27.288 ^d	4.982 ^d	0.429 ^{de}	4.265 ^e	1.275 ^e
	Spirit	25.633 ^f	4.866 ^f	0.432 ^e	4.125 ^g	1.151 ^g	26.544 ^f	4.601 ^f	0.426 ^e	4.239 ^f	1.208 ^g
	Non-grafted	24.663 ^h	4.700 ^h	0.428 ^f	3.939 ^h	1.084 ^h	25.488 ^h	4.562 ^h	0.420 ^f	4.108 ^h	1.139 ^h

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

grafted Valouro fruits under NWS (Table 4). Similarly, the highest TSS value (5.80%) was found in DB fruits under HWS, whereas the lowest TSS value (4.20%) was found in non-grafted Valouro fruits under NWS (Table 4).

4 Discussion

4.1 Fruit yield and its components

Irrigation water regimes affected tomato production; there was a decrease in the number of fruit/plants and average fruit weight as water stress increased. The reduction in yield and its components with increasing water stress levels in this study was consistent with the findings of previous studies. Birhanu & Tilahun (2010) and Zhang et al. (2016) found a reduction in the weight and

quantity of fruits in plants exposed to water stress. Water stress reduces the number of fruits and flowers, and fruit set percentage of a plant (Pek et al., 2014). Moreover, water stress during the first growth stage decreases plant development and flower number resulting in a reduction in fruit number and eventually, total yield (Sibomana et al., 2013; Shamim et al., 2014).

The genetic variance between both cultivars explains the superiority of the fruit yield and yield components of Durinta over Valouro (Olaniji et al., 2010), since they were grown under the same environmental conditions in the greenhouse. Shamim et al. (2014) indicated that genotypic variations in tomato fruit yield can be attributed to the differences in either total fruit number or single fruit weight.

Table 4 Interaction effect between irrigation water stress levels, tomato cultivars, and tomato rootstocks on fruit weight, fruit number, total fruit yield and fruit quality (VC and TSS) of tomato during 2013/2014 and 2014/2015

Water stress levels	Tomato cultivars	Tomato rootstocks	2013/2014					2014/2015				
			Fruit number	Fruit fw (g)	Tot. yield (kg/m ²)	VC (mg/100 gfw)	TSS (%)	Fruit number	Fruit fw (g)	Tot. yield (kg/m ²)	VC (mg/100 gfw)	TSS (%)
NWS (100% ETc)	Durinta F ₁	Beaufort	85.33 ^a	149.966 ^a	31.993 ^a	26.100 ^f	4.900 ^f	80.67 ^a	148.432 ^a	29.934 ^a	26.600 ^h	4.898 ^{hij}
		Maxifort	82.67 ^b	143.000 ^c	28.553 ^c	25.600 ^g	4.800 ^g	79.33 ^a	141.534 ^c	27.183 ^c	26.266 ⁱ	4.801 ^{ij}
		Spirit	76.00 ^c	141.200 ^d	26.828 ^d	25.100 ^h	4.700 ^{gh}	72.71 ^d	139.300 ^d	25.322 ^d	25.233 ^k	4.695 ^k
		Non-grafted	64.67 ^f	139.833 ^e	22.606 ^g	23.000 ⁱ	4.500 ⁱ	64.67 ⁱ	138.335 ^e	22.364 ^f	23.164 ^m	4.493 ^{lm}
	Valouro F ₁	Beaufort	68.33 ^e	128.166 ^g	21.995 ^h	25.800 ^g	4.700 ^{gh}	70.67 ^{ef}	127.466 ^h	22.519 ^f	25.633 ^j	4.680 ^k
		Maxifort	68.33 ^e	122.633 ^{hi}	20.950 ⁱ	24.200 ⁱ	4.600 ^{hi}	69.33 ^f	121.600 ⁱ	21.077 ^g	24.266 ^l	4.530 ^l
		Spirit	64.67 ^f	121.500 ⁱ	19.643 ^j	24.100 ⁱ	4.500 ⁱ	65.67 ^{hi}	120.100 ^j	19.716 ^h	24.334 ^l	4.420 ^m
		Non-grafted	59.33 ^h	120.566 ^j	17.884 ^k	22.900 ^k	4.200 ^j	64.00 ⁱ	119.133 ^k	19.061 ⁱ	22.637 ⁿ	4.190 ^o
MWS (75% ETc)	Durinta F ₁	Beaufort	81.67 ^b	144.833 ^b	29.570 ^b	27.900 ^c	5.200 ^d	76.00 ^b	143.066 ^b	28.071 ^b	27.833 ^{ef}	5.198 ^{de}
		Maxifort	76.71 ^c	131.500 ^f	25.219 ^e	27.300 ^{de}	5.100 ^d	74.00 ^c	129.400 ^f	23.939 ^e	27.600 ^{fg}	5.099 ^{efg}
		Spirit	72.67 ^d	130.500 ^f	23.708 ^f	27.400 ^d	5.000 ^{ef}	69.33 ^f	128.533 ^g	22.279 ^f	27.400 ^g	4.997 ^{ghi}
		Non-grafted	63.67 ^f	120.633 ^j	19.201 ⁱ	25.600 ^c	4.700 ^{gh}	62.67 ⁱ	118.932 ^k	18.633 ^{ij}	25.800 ^j	4.697 ^k
	Valouro F ₁	Beaufort	67.67 ^e	123.416 ^h	20.878 ^h	28.000 ^b	5.000 ^e	68.00 ^{fg}	122.150 ⁱ	20.766 ^h	28.333 ^d	4.989 ^{ghi}
		Maxifort	66.00 ^e	112.566 ^k	18.573 ^j	27.300 ^{de}	4.998 ^f	66.67 ^{gh}	110.831 ^m	18.472 ^k	27.400 ^g	4.721 ^{jk}
		Spirit	63.33 ^f	110.500 ^j	17.496 ^k	27.000 ^e	4.889 ^{fg}	60.00 ^j	109.100 ⁿ	16.365 ^m	26.700 ^h	4.501 ^{lm}
		Non-grafted	56.00 ⁱ	102.900 ^m	14.406 ⁿ	25.200 ^h	4.800 ^g	57.00 ^k	101.566 ^o	14.473 ^o	25.533 ^j	4.300 ⁿ
HWS (50% ETc)	Durinta F ₁	Beaufort	78.00 ^c	131.000 ^f	25.545 ^d	29.500 ^a	5.800 ^a	71.67 ^{de}	129.400 ^f	23.184 ^f	29.766 ^a	5.797 ^a
		Maxifort	72.00 ^d	114.000 ^j	20.520 ^h	29.100 ^a	5.700 ^{ab}	69.33 ^f	112.031 ^l	19.419 ^{ij}	29.600 ^a	5.686 ^b
		Spirit	63.67 ^f	112.500 ^k	17.906 ^{jk}	29.000 ^a	5.600 ^b	66.00 ^g	112.334 ^l	18.535 ^k	29.233 ^a	5.600 ^b
		Non-grafted	63.33 ^f	102.433 ^m	16.218 ^l	28.300 ^b	5.300 ^{cd}	61.33 ^j	101.832 ^o	15.614 ⁿ	28.666 ^b	5.297 ^d
	Valouro F ₁	Beaufort	63.00 ^f	111.166 ^{kl}	17.509 ^k	29.100 ^a	5.400 ^c	64.00 ^j	109.866 ⁿ	17.579 ^j	28.600 ^{bc}	5.399 ^c
		Maxifort	61.67 ^g	97.300 ⁿ	15.000 ^m	28.700 ^b	5.200 ^d	62.67 ⁱ	95.500 ^p	14.962 ^o	28.400 ^{cd}	5.195 ^e
		Spirit	59.00 ^h	95.400 ^o	14.072 ⁿ	28.800 ^b	5.100 ^{de}	60.00 ^j	93.233 ^q	13.985 ^p	28.366 ^d	5.099 ^{efg}
		Non-grafted	54.67 ⁱ	87.233 ^p	11.922 ^o	28.200 ^b	5.097 ^e	55.33 ^l	85.400 ^r	11.814 ^q	28.300 ^d	5.026 ^{gh}

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

Increases in fruit/plant number and average fruit weight contributed to increases in the total yield of grafted plants. Similarly, Turkmen et al. (2010), Turhan et al. (2011), and Echevarria et al. (2012) found that grafting tomato plants increased yield and yield components. Total yield was 24.61–34.05% higher in plants grafted on Beaufort rootstocks than non-grafted plants and this was observed in enhanced fruit/plant number (15.54–23.87%), and fruit weight (16.00–17.07%) (Table 1). Similarly, Rahmatian et al. (2014) reported that total yield increased by approximately 17.00% in the tomato Synda cultivar grafted onto the King Kong rootstock than in non-grafted plants because of increased fruit number (up to 18%) and fruit weight (up to 11%). It is well known that plant vigor is related to the root system, which offers sufficient water and nutrients to the scion (Lee, 1994). Therefore, it is reasonable to conclude, based on the increases in total yield observed in grafted plants compared to non-grafted plants, that grafting tomato plants increases growth vigor, particularly when grafted onto Beaufort rootstocks.

4.2 Fruit quality

Increasing water stress levels increased the VC, TSS, TA, and TS contents. This indicates that a reduction in water accumulation resulted in a decrease in water content per fruit and an increase in the soluble solids and VC content (Agbemaflle et al., 2014; Zhang et al., 2016). Similarly, Patane et al. (2011) found that VC, TSS, and TA contents were higher under water stress (50% ETc) than under no water stress (100% ETc). Therefore, some fruit quality characteristics of tomato could be enhanced by decreasing the application of water. On the other hand, HWS significantly reduced Ca²⁺ and K⁺ concentrations in the fruits. This can be attributed to the decreased availability of both elements to plants grown under water stress conditions (Krnak et al., 2001). In contrast, NWS produced plants with higher Ca²⁺ and K⁺ concentrations. These findings concur with Agbemaflle et al. (2015), who reported that the highest concentrations of Ca²⁺ and K⁺ in tomato fruits were recorded under no water stress (100% ETc), whereas the lowest Ca²⁺ and K⁺ concentrations were found under 70% ETc.

Figure 1 Effects of interaction between water regimes and tomato cultivars on: (a) fruit/plant number, (b) average fruit fresh weight, and (c) total fruit yield of tomato during 2013/2014 and 2014/2015

Fruits of Durinta had higher VC, TSS, TA, and TS contents than those of Valouro. Similar trends were observed in relation to mineral Ca^{2+} and K^{+} concentrations. Turhan & Seniz (2009) and Radzevicius et al. (2009) showed clear variations in fruit quality characteristics based on different tomato genotypes and cultivars. The Ca^{2+} concentration in the fruits of the two tomato cultivars ranged from 1.3% (Durinta) to 1.2% (Valouro) and the K^{+} content ranged from 2.5% (Durinta) to 2.4% (Valouro). Similarly, Gebologlu et al. (2011) found that the K^{+} concentration in tomato fruits ranged from 3.0 to 4.0% while, the Ca^{2+} content ranged from 0.10 to 0.13% in the cultivars used.

Grafting may have adverse effects on fruit quality, based on the rootstocks used (Lee, 1994; Davis et al., 2008). In the present study, grafting had no detrimental effect on tomato fruit quality (VC, TSS, TA, TS, Ca^{2+} , and K^{+}). Beaufort rootstocks produced plants with the highest quality fruits followed by Maxifort. However, non-grafted plants had the lowest fruit quality (Table 2). This could be related to the effect of rootstocks on water and nutrient uptake, due to variances in either physical characteristics (vertical and lateral growth) or the functionality of the root system, which is better in grafted than non-grafted plants (Petropoulos et al., 2014). Mohammed et al. (2009) indicated that Cecilia cultivar grafted onto the Beaufort rootstock produced fruits with increased TSS contents. In contrast, Di Gioia et al. (2010) and Gajc-Wolska et al. (2014) found that grafted and non-grafted plants had a similar fruit quality (VC, TSS, TA, content and Ca^{2+} and K^{+} concentrations) except for their TS content; non-grafted plants had a higher sugar content.

4.3 Second interaction effect on fruit yield and its components

Increasing reductions in soil moisture content under HWS reduced the number of fruits/plants and fruit weight of Valouro, which may explain why the lowest yield was found in Valouro plants under HWS. In contrast, under HWS the Durinta had higher fruit/plant number, fruit weight, and total fruit yield than Valouro plants under MWS (Figures 1a, b and c). These results

Figure 2 Effects of interaction between water regimes and tomato rootstocks on: (a) fruit/plant number, (b) average fruit fresh weight, and (c) total fruit yield of tomato during 2013/2014 and 2014/2015

showed that Durinta plants have a greater capacity to tolerate water stress than Valouro plants. Consistent with the results of Sinha (1978) and Sanchez-Rodriguez et al. (2014) that increased K^+ accumulation improves stomatal resistance and promotes drought tolerance in plants, Durinta accumulated higher levels of K^+ in their leaves and fruit tissues than Valouro (Table 2). These findings may explain why Durinta has a higher capacity for water stress tolerance than Valouro.

Regarding increments in fruit yield and yield components in grafting plants, grafting with suitable rootstocks may induce greater differences in fruit/plant number, fruit weight, and total yield than non-grafted plants under different water regimes (Figures 2a, b and c). Our data showed that plants on the Beaufort rootstock under NWS and MWS had higher percentages of total yield production (90.96–91.14% and 79.09–83.78%, respectively) than non-grafted plants (Figure 2c). Thus, grafting plants onto a suitable rootstock may improve the vigor of the root system, primarily under adequate soil moisture conditions in the root zone, which in turn promotes growth and increases yield production.

A high positive impact of grafting was observed when Durinta was used as a scion, and Beaufort as a rootstock. In this DB combination, the fruit number, weight, and total yield reached maximum levels. The minimum values of yield and yield components were observed in non-grafted Valouro plants (Figures 3a, b and c). The increasing percentages of total yield in DB plants were approximately 40.36–52.49% and 73.78–100.73% more than either non-grafted Durinta or Valouro, respectively (Figure 3c). Such increases in the total yield of DB plants may be because of the enhancing effect of the Beaufort root system, which improves water and nutrient uptake, indicated by higher Ca^{2+} and K^+ concentrations in the Durinta fruit, which leads to an increase in fruit weight (Schwarz et al., 2010; Rubio et al., 2010). In a similar finding, Kacjan-

Figure 3 Effects of interaction between tomato cultivars and rootstocks on: (a) fruit/plant number, (b) average fruit fresh weight, and (c) total fruit yield of tomato during 2013/2014 and 2014/2015

Durinta fruits exhibited higher fruit quality characteristics (namely VC, TSS, TA, and TS), primarily under HWS. These results are parallel with those of Nahar & Gretzmacher (2002) who found that water stress enhanced the sweetness of tomato fruits by increasing their sugar content (glucose, fructose, and sucrose) and improving their vital acid concentrations (ascorbic, malic, and citric acid). However, Durinta plants seemed to accumulate more Ca^{2+} in their fruits under NWS. These findings are similar to those of Poudel & Lee (2009) who illustrated that exposure of tomato plants to water stress led to an increase in soluble solids and sugar contents per fruit, but a decrease in mineral content.

We also observed that the positive impact induced by the rootstock increased with the level of water stress applied. When the tomato cultivar Beaufort was used as a rootstock, the best-evaluated quality characteristics (VC, TSS, TA, and TS) were recorded under HWS, with higher differences observed when compared with the fruits derived from non-grafted plants. This could mean that the Beaufort rootstock is better equipped to overcome water stress, because of an efficient root and shoot system, and this was confirmed in the fruit quality characteristics measured (Table 3). These results are in agreement with those of Sánchez-Rodríguez et al. (2012) who proposed that grafting tomato plants onto a compatible rootstock, making it more adapted to water stress, should be considered as a tool to improve the quality of the crop.

Fruit quality traits i.e., VC, TSS, TA, TS, and Ca^{2+} contents were significantly affected by grafting. Fruits of DB plants had the highest values of these quality characteristics. However, the non-grafted Valouro plants had the lowest quality fruits. These results indicated that Durinta was more compatible with the Beaufort rootstock than Valouro. These findings are similar to those of San Bautista et al. (2011) who reported that improved fruit quality could be attributed to a strong union between the scion and rootstock,

simplifying the flow of water and nutrients and enhancing photosynthesis, thereby improving the availability of carbohydrates for fruit development. Thus, grafting can improve tomato fruit quality most effectively when the selection of the rootstock is compatible. Therefore, as a faster alternative to the relatively slow breeding method currently utilized, grafting commercial tomato cultivars onto a well-matched rootstock could be a promising agricultural tool (Flores et al., 2010; VinkovicVrcek et al., 2011).

4.5 Interaction effects between tomato cultivars, tomato rootstocks, and water regime levels

DB plants showed superior crop yield and yield components under NWS followed by MWS. These results perhaps indicate that the Beaufort rootstock acts as a better conductor of water, supplying more water and nutrients to the shoot system under MWS, mainly due to the vigor of the root system (Qaryouti et al., 2007). Estévez-Caparrós et al. (2011) reported that the rootstock could adjust the cultivar in the graft union area, affecting hydraulic resistance and nutrient flow. Hence, cultivating DB plants under MWS may be an acceptable combination for greenhouse producers, since approximately 25% of water is saved in the process and quality is maximized. This supports the view of Patane et al. (2011) that due to water deficits in arid and semi-arid areas, saving water is more valued to the farmers than maximizing crop yield.

Vitamin C and TSS represent two foremost quality criterions for either fresh market or processing industry tomato (Flores et al., 2010; Kuscü et al., 2014). The tomato is one of the crops that are rich in VC with a significant amount of its content subject to cultivars (Sablani et al., 2006). The concentration of VC in 98 tomato cultivars ranges from 13 to 44 mg/100 g (Stevens, 1974). Grafted plants accumulated more VC in their fruits than non-grafted plants. The highest VC values (29.5–29.8 mg/100 g) were found in the DB fruits followed by DM fruits (29.3–29.6 mg/100 g), both under HWS, while the lowest values (22.6–22.9 mg/100 g) were found in non-grafted Valouro fruits under NWS (Table 4).

TSS content is a major quality factor affecting the tomato processing industry. According to Turhan & Seniz (2009) and Kuscü et al. (2014) as TSS in industrial tomato increase, it generally raises tomato paste efficiency and this value must be over 5.00%. In the present study, the highest TSS value (5.80%) was found in DB fruits under HWS, and the lowest TSS value (4.20%) was found in non-grafted Valouro fruits under NWS (Table 4). These results are similar to those in Flores et al. (2010) who indicated that increases in TSS found in fresh market and processing industry tomato exposed to water stress was related with a reduction in the water content of the fruits. The TSS values detected here (Table 4) were relatively higher than those found in the study by Turhan & Seniz (2009) where the TSS in ripe fruits of 33 tomato genotypes ranged from 3.40 to 5.50%. The negative impact of grafting on TSS content was also observed in earlier

studies (Pogonyi et al., 2005; Qaryouti et al., 2007). Our results supported the idea that when using a compatible rootstock/scion combination, grafting can improve the productivity and fruit quality (VC and TSS) of tomato. Therefore, this study recommended that grafting tomato (Durinta) scions on a suitable rootstock (Beaufort) was effective for commercial production as well as for the industrial and fresh market production of tomato under greenhouse conditions.

Conclusions

Variations in tomato crop yield and fruit quality could be attributed to the different growth parameters of both cultivars (Durinta is more vigorous and has a higher fruit productivity than Valouro), and their compatibility with suitable rootstocks. The use of a vigorous rootstock, such as Beaufort, in combination with a vigorous commercial cultivar, such as Durinta, as a scion can increase yield production and improve fruit quality under water stress conditions. Our results showed the many benefits of such a practice including a high fruit yield while saving water (25%) which is the main target of greenhouse-tomato producers in arid areas. In addition, better fruit quality in terms of high TSS and VC contents, are both criteria for processing industry and fresh market tomato in arid areas.

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