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Fruit Quality of Redhaven and Royal Glory Peach Cultivars on Seven Different Rootstocks

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ABSTRACT: Two peach cultivars, Redhaven and Royal Glory, grafted on seven different rootstocks (Adesoto, Barrier 1, GF 677, Ishtara, Monegro, Penta, and peach seedling) were analyzed for tree vigor and yield. Fruit of similar ripeness (fruit firmness) was analyzed in terms of pomological (fruit weight, soluble solids content) and biochemical parameters (individual sugars, organic acids, phenolic acids in the flesh and peel, as well as flavonols and anthocyanins in the peel). A uniform effect of rootstock on tree size was evident in the cases of both cultivars. The Ishtara rootstock induced weak tree growth; Adesoto, Penta and peach seedling semivigorous growth; and Barrier 1, GF 677, and Monegro vigorous tree growth. We recorded higher yields in the Redhaven cultivar, while no significant differences in yield in the fourth growing season were found among the rootstocks for each cultivar. Rootstock had no effect on soluble solids in the Redhaven cultivar, while in the Royal Glory it did. Penta yielded the highest soluble solids content levels, while Adesoto and Monegro were associated with low levels. In the fruit from both cultivars, the rootstock had a significant influence on individual sugars, organic acids, and phenolic acids in the pulp. We also found that phenolic acids in the pulp and skin were more affected by the rootstock than other secondary metabolites analyzed, regardless of the cultivar.

KEYWORDS: *Prunus persica*, sugars, organic acids, phenolics, flavonols, anthocyanins

INTRODUCTION

The selection of an appropriate rootstock is important for any orchard. Production of peach orchards, particularly replanted ones, greatly depends on the selection of the right rootstock. Various species and interspecific hybrids can be used as a peach rootstock.[1] Several aspects are considered in rootstock breeding: vigor,[1−11] adaptation to various soil types[12] and water conditions,[13] biotic stress, compatibility with the selected cultivar, and tolerance to replant soil conditions.[14−16] It has been confirmed that rootstocks of different genetic origin adapt differently to replant conditions. Peach was proven to grow normally after any fruit tree, except after grapevine. A retarded growth of peach trees was reported when these were planted after *Prunus persica* (L.) Batsch.[14] On the other hand, *Prunus domestica* L. trees thrive well when planted after any fruit species, except after peach.[16] The factors influencing replanting problems can be divided into specific and nonspecific replant diseases. Poor growth of trees planted in soil after the same species or after a different species of the same genus can be attributed to specific replant diseases.[15] Therefore, the genetic origin of the rootstock in the previous orchard is also relevant for rootstock selection in the current orchard. The first generations of peach orchards in Slovenia are grafted on peach seedling, while for the second generation, the GF 677 rootstock was used. For most of the surveyed peach growers in Slovenia, the third replantation of peach orchards will take place in the near future. Specific adaptation of rootstocks of different genetic origins to replant conditions led us to include rootstocks of various origin that showed good potential in other regions.

In addition to various abilities of rootstocks to adapt to specific growing conditions, a significant effect of the rootstock on sweet cherry[17] and peach fruit quality has been established by several authors.[2,5,8,18,19] Rootstocks of similar vigor yet of different genetic origin can produce peach fruit of different quality, indicating that vigor is not the only parameter affected by the rootstock.[5,8,17] Sugars and organic acids are affected by the rootstocks[8,9,17] and the levels of primary metabolites define taste.[20] Phenolic compounds in fruit play an important role in several quality characteristics, for example, taste, coloration, and health-promoting properties.[21] Minor effect of three rootstocks of similar genetic origin on antioxidant capacity of peaches was evident in the study of Dragouldi and Tsipouridis.[22] The effect of nine cultivars on quality characteristics and nutritional attributes including total phenolics, antioxidant capacity, and ascorbic acid was previously studied[22] and significant differences were found. Scalzo et al.[23] found differences in antioxidant capacity in the fruit of the Suncrest peach cultivar grafted on different rootstocks. Tavarini et al.[13] studied the effect of water stress and rootstock on quality indices and nutritional characteristics of Suncrest peach cultivar. They found that water management has a significant effect on quality parameters and phytochemical compounds in peach fruit and that each rootstock responded differently to water stress. Little is known of the effect of rootstock on phenolics composition, and our study will provide additional information on whether a similar response of a rootstock is expected when grafted with a different cultivar in terms of fruit quality.

The aim of this study was to continue an earlier study where we compared the effect of 11 rootstocks on the fruit quality of the Redhaven cultivar.[8] We will present the influence of seven rootstocks grafted with the Royal Glory and Redhaven peach cultivars on tree vigor, yield, and quality parameters. We will also establish to what extent the selection of the cultivar and rootstock affects fruit quality. A comparison of tree vigor, yield, crop load,

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Table 1. Rootstocks Used in the Present Study

rootstock	genetic origin	ref
Adesoto	*Prunus insititia* L.	Moreno et al.[41]
Barrier 1	*P. persica* × *Prunus davidiana* L.	Remorini et al.[9]
GF 677	*Prunus amygdalus* × *P. persica*	Bernhard and Grasselly[42]
Ishtara	(*Prunus cerasifera* × *Prunus salicina*) × (*Prunus cerasifera* × *P. persica*)	Renaud et al.[43]
Monegro	*P. amygdalus* Batsch. × *P. persica*	Felipe[44]
Penta	*P. domestica*	Nicotra and Moser[45]
Peach seedling	*P. persica*	Byrne[12]

yield efficiency, and fruit quality will tell us whether the effect of the selected rootstocks is consistent in combination with different cultivars. Significant seasonal influence on quality parameters of various stone fruit[24,25] leads us to include single-season results.

■ MATERIALS AND METHODS

Plant Material and Experimental Design. Our experiment was conducted in an orchard at the Fruit Growing Centre in Bilje near Nova Gorica (N 450 53.528; E 0130 38.606), Slovenia. All measurements presented in this paper were conducted in 2009. Two yellow-flesh cultivars, Royal Glory and Redhaven, were studied, each in combination with seven rootstocks: Adesoto, Barrier 1, GF 677, Ishtara, Monegro, Penta, and peach seedling. The genetic origin of each rootstock is presented in Table 1. The field used in our experiment had previously supported two generations of peach orchard.

Two nearby fields were selected for the study. The first one was assigned to the Redhaven and the second one to the Royal Glory cultivar. Twelve trees of each rootstock were randomly distributed in groups of three in a randomized block design. The rootstocks were planted in a permanent place in spring 2005 with 4 × 2 m tree spacing. Grafting was performed in August 2005. We trained the trees to a free spindle.[26] Uniform thinning was applied to all the trees in early May (stone hardening period), leaving approximately 6 cm between the remaining fruit. The whole orchard was managed according to the standard integrated pest management.

Description of the Treatments and Data Collection. The circumference of each tree was measured in spring and autumn 2009. For each cultivar, peaches were harvested four times, 3 days apart. At each picking time, all ripe fruit from each tree were harvested. The first harvest of the Royal Glory was completed on July 6 [102 days after full bloom (DAFB)] and the first harvest of the Redhaven was on July 16 (112 DAFB); peaches from all the trees were picked at once on the basis of similar maturity (fruit firmness). At each picking all the ripe fruit from each tree were counted and weighed to determine total yield per tree (kg/tree) and crop load (number of fruit/cm^2 TCSA). Yield efficiency was calculated using the total yield to autumn trunk cross-sectional area (TCSA) ratio. The fruit from the first harvest were assorted according to their cultivar/rootstock combination. Fifteen randomly selected fruit from each cultivar/rootstock were transported to the laboratory facilities for further quality analysis. All quality analyses and extractions were made at room temperature (24 °C). Each fruit was weighed on a precision scale to 0.01 g confidence level. From each fruit, the skin was removed on four sides, and fruit firmness was measured four times using a digital penetrometer (TR, Turini, Italy) with an 8 mm tip. In order to determine the soluble solids content (SSC), the pulp from each fruit was crushed and the intact juice was immediately analyzed with a digital refractometer (model WM-7, Atago, Tokyo, Japan).

For further analysis, 15 fruit were randomly distributed into five groups of three fruit. Each fruit was halved and pitted. For extraction of sugars and organic acids, the unpeeled half of each fruit was used, while for individual phenolics the half was peeled, and the skin and the pulp were kept separate. All tissues were frozen immediately and kept at −20 °C until extraction. Concentration of all analyzed chemical compounds was expressed as per fresh weight (FW).

Sugars and Organic Acids Extraction and Analysis. An identical method of extraction was used to extract sugars and organic acids and was previously described by Orazem et al.[8] Three unpeeled halves were ground and 10 g of fruit was brought to a volume of 40 mL using twice distilled water. Samples were homogenized using the T-25 Ultra-Turrax (IKA-Labortechnik, Staufen, Germany) and then left for 0.5 h at room temperature (24 °C) to extract, centrifuged at 10 000 rpm for 7 min at 5 °C, and filtered through a 0.45 μm cellulose filter (Macherey-Nagel, Düren, Germany). The content of individual sugars (sucrose, glucose, fructose, and sorbitol) and individual organic acids (citric, malic, shikimic, and fumaric acids) was determined by high-performance liquid chromatography (HPLC) (Thermo Separation Products, Waltham, MA).

Individual sugars were detected with a refractive index (RI) detector after separation with a Razerex RCM-monosaccharide column (300 × 7.8 mm; Phenomenex, Torrance, CA) kept at 60 °C. The samples were eluted according to the isocratic method.[27] The elution solvent was twice distilled water at a flow rate maintained at 0.6 mL/min.

Organic acids were detected with an ultraviolet UV detector (Knauer, Berlin, Germany) set at 210 nm after separation with HPX 87H, 300 × 7.8 mm (Bio-Rad, Hercules, CA) kept at 60 °C.[27] The elution solvent was 0.4 mmol sulfuric acid diluted with twice distilled water at a flow rate maintained at 0.6 mL/min.

The identification of both sugars and organic acids was made by comparing the retention time (sucrose, 9.5 min; glucose, 11.3 min; fructose, 14.3 min; sorbitol, 23.4 min; malic acid, 10.9 min; citric acid, 8.9 min; shikimic acid, 12.5 min; fumaric acids, 13.5 min) for each peak with those for the corresponding standard, and the concentration was calculated using an external standard. Individual sugars and malic and citric acid contents were expressed in g/kg (FW), while shikimic and fumaric acids were expressed in mg/kg FW.

Extraction of Phenolic Acids, Flavonols, and Anthocyanins and HPLC Analysis. The extraction of individual phenolic acids, flavonols, and anthocyanins was performed according to the modified method.[28] The skin or the pulp from three fruit was ground and 5 g of skin or 10 g of pulp was homogenized with 10 mL of extraction solution, which consisted of methanol containing 3% formic acid and 1% of 2,6-di-*tert*-butyl-4-methylphenol (BHT) using an ultrasonic bath for 1 h. Samples were centrifuged at 10 000 rpm for 7 min at 5 °C, and the supernatant was filtered through the Chromafil AO-45/25 polyamide filter (Macherey-Nagel, Düren, Germany) into a vial. HPLC analysis was preformed with the Surveyor system with a diode array detector (DAD), controlled by a Crom-Quest 4.0 chromatography workstation software system (Thermo Finigan, San Jose, CA). The column used for the separation was a Gemini C_{18} (150 × 4.6 mm; Phenomenex, Torrance, CA) maintained at 25 °C. Phenolic acids (neochlorogenic, chlorogenic, and *p*-coumaric acid) were analyzed at 280 nm at retention times of 8.5, 12.2, and 21.3 min, respectively, flavonols at 350 nm (quercetin 3-galactoside, quercetin 3-glucoside, quercetin 3-rutinoside, and quercetin 3-rhamnoside) at retention times 25.4, 25.53, 27.7, and 24.8 min, respectively, and anthocyanins at 530 nm (cyanidin 3-glucoside and cyanidin 3-rutinoside) at retention times of 12.0 and 12.8 min, respectively.[29] The elution solvents were 1% aqueous formic acid (A) and 100% acetonitrile (B) at a flow rate maintained at 1 mL/min. The gradient method was used.[30] All phenolic acids, flavonols, and anthocyanins presented in our results were identified with a HPLC-Finnigan MS detector and an LCQ Deca XP MAX (Thermo Finigan, San Jose, CA) instrument with electrospray interface (ESI) operating in negative ion mode. The analyses were performed using full-scan data dependent MS^n scanning from m/z 115 to 2000. Column and chromatographic

Table 2. Average Trunk Circumference (cm), Yield (kg/tree), Crop Load (number of fruit/cm^2), Yield Efficiency (kg/cm^2), Soluble Solids Content (SSC, °Bx), and Fruit Weight (g) of Redhaven and Royal Glory on Different Rootstocks[a]

cultivar	rootstock	trunk circumference	yield	crop load	yield efficiency	SSC	weight
Redhaven	Adesoto	23.3 ± 0.7 b	27.2 ± 1.4	3.6 ± 0.3 b	0.6 ± 0.06 bc	9.3 ± 0.22	161.6 ± 3.4 ab
	Barrier 1	25.5 ± 0.7 c	29.2 ± 2.2	3.6 ± 0.2 b	0.6 ± 0.03 abc	9.8 ± 0.29	170.1 ± 5.6 b
	GF 677	25.9 ± 0.7 c	29.0 ± 1.5	3.5 ± 0.3 b	0.6 ± 0.05 ab	9.2 ± 0.14	156.6 ± 3.3 a
	Ishtara	18.0 ± 0.7 a	26.7 ± 1.7	6.7 ± 0.4 d	1.0 ± 0.05 e	9.2 ± 0.24	156.7 ± 2.6 a
	Monegro	28.9 ± 0.7 d	30.7 ± 2.7	1.9 ± 0.3 a	0.4 ± 0.05 a	9.6 ± 0.33	171.5 ± 3.3 b
	Penta	21.7 ± 0.6 b	28.8 ± 1.0	5.0 ± 0.2 c	0.8 ± 0.04 d	9.2 ± 0.25	152.3 ± 3.3 a
	Peach seedling	22.3 ± 0.5 b	26.6 ± 1.3	4.2 ± 0.4 bc	0.7 ± 0.03 cd	8.9 ± 0.18	161.4 ± 5.1 ab
Royal Glory	Adesoto	25.0 ± 1.5 b	15.0 ± 1.8	2.2 ± 0.3 a	0.3 ± 0.06 ab	9.0 ± 0.21 a	162.3 ± 6.6 ab
	Barrier 1	27.7 ± 1.1 c	18.5 ± 1.3	2.0 ± 0.2 a	0.3 ± 0.03 ab	9.2 ± 0.25 ab	147.7 ± 4.6 a
	GF 677	29.0 ± 0.7 c	16.4 ± 0.7	1.6 ± 0.1 a	0.2 ± 0.02 a	9.7 ± 0.13 bc	156.6 ± 5.1 ab
	Ishtara	19.7 ± 0.7 a	18.1 ± 1.0	4.0 ± 0.3 c	0.6 ± 0.04 d	9.6 ± 0.15 bc	148.1 ± 6.6 a
	Monegro	30.0 ± 1.4 c	14.9 ± 0.9	1.6 ± 0.2 a	0.2 ± 0.03 a	8.8 ± 0.15 a	160.3 ± 7.1 ab
	Penta	23.8 ± 0.5 b	17.1 ± 1.0	2.2 ± 0.2 a	0.4 ± 0.03 bc	10.0 ± 0.15 c	173.8 ± 4.1 b
	Peach seedling	23.3 ± 1.1 b	18.3 ± 1.0	3.1 ± 0.3 b	0.5 ± 0.03 c	9.59 ± 0.24 bc	161.0 ± 4.4 ab

[a] Average values ± standard errors are presented. Different letters in columns for each cultivar indicate significantly different values at $p < 0.05$.

conditions were identical to those used for the HPLC-DAD analyses. Quantification of individual phenolic compounds was achieved according to concentrations of corresponding external standard and expressed in mg/kg of FW.

Statistical Analysis. The data were analyzed using the Statgraphics Centurion XV (Statgraphics, Herdon, VA). Two-way analysis of variance (MANOVA) was used to determine the effect of the rootstocks, cultivar, and their interaction on pomological and biochemical properties at a significance level of 0.05. One-way analysis of variance (ANOVA) was used to determine the influence of the rootstocks on various quality parameters for each cultivar. Differences among the rootstocks were tested with the Duncan test at a significance level of 0.05.

RESULTS AND DISCUSSION

Tree Size. In combination with Royal Glory all rootstocks produced significantly bigger trunk circumferences compared to Redhaven, indicating that the cultivar affects tree vigor. Differences in trunk circumference among the rootstocks were also statistically significant (Table 7), which is in accordance with previous publications.[2,3,5,10,11,31,32] There was no significant interaction between rootstock and cultivar (Table 6); hence, a similar ranking of rootstocks according to circumference was found for both cultivars (Table 2). Similar results for rootstock influence on tree vigor have been reported previously; however, these were in combination with a different cultivar.[9] Ishtara induced the smallest trunk circumferences by far in both cultivars. Bigger trunk circumferences were characteristic for Adesoto, Penta, and peach seedling rootstocks. Barrier, GF 677, and Monegro rootstocks induced significantly the biggest circumferences.

Yield. The Redhaven cultivar produced significantly higher average yields (from 26.6 to 30.7 kg per tree) compared to Royal Glory (from 14.9 to 18.5 kg per tree) in the fourth growing season. The absence of interaction between the rootstock and the cultivar (Table 7) indicates that rootstocks had consistent effects on both cultivars. Rootstock had no significant effect on the average yields (Table 2, Table 7). This may be due to the young trees, since similar yields on different rootstocks have previously been reported in the years before full production.[31] There was a significant effect of the rootstock on cumulative yield in combination with the Tebana cultivar; however, the yield was not affected in combination with the Queen Giant cultivar.[11] Other authors,[8,10,32] on the other hand, have reported a significant rootstock-induced effect on the yield. Pronounced effect of the rootstock and cultivar on the crop load as well as on yield efficiency was evident (Table 7). Hrotko et al. also found significant effect of rootstocks on yield efficiency of plum trees,[6] while Larsen et al.[7] researched this using apple trees.

Quality Characteristics. Despite the difference in yields between the cultivars, both of them produced statistically similar average fruit weight, which indicates a greater production capacity of the Redhaven cultivar. A previous study showed a significantly higher fruit weight in the Redhaven cultivar in comparison with the Royal Glory,[33] which is in contradiction to our results. Fruit weight of peach is a function of crop load[32,34] as well as the time of thinning.[34] Since thinning was performed at a nearly identical development stage, only the statistically higher crop loads of Redhaven in comparison to Royal Glory in our study (Table 2) could have influenced a similar fruit weight of both cultivars and also could have influenced lower fruit weight of Redhaven than that reported by Tavarini et al.[33] Rootstocks affected the fruit weight of both cultivars. In combination with Redhaven, GF 677, Ishtara, and Penta produced significantly lighter fruit (156.6, 156.6, and 152.3 g, respectively), while Barrier 1 and Monegro, on average, produced heavier fruit. The lightest Royal Glory fruit were harvested from Barrier 1 and Ishtara grafted trees (147.7 and 148.1 g, respectively), while Penta produced the heaviest fruit on average (173.8 g). Significant interaction between rootstock and cultivar on fruit weight was evident and could have been affected by different crop load among rootstocks. A study of several peach rootstocks showed different susceptibility to alternating crop loads.[4] According to De Salvador[4] Barrier 1 and GF 677 rootstocks were more sensitive to an increased crop load, which resulted in smaller fruit. Ishtara, on the other hand, produced bigger fruit despite high crop loads. This is in accordance with our findings regarding the Royal Glory cultivar. In combination with the Redhaven cultivar, however, Barrier 1 rootstock, with a similar

Table 3. Average Sugars Content (g/kg FW) ± Standard Error of Redhaven and Royal Glory on Different Rootstocks[a]

cultivar	rootstock	sucrose	glucose	fructose	sorbitol	total sugars
Redhaven	Adesoto	52.61 ± 0.58 b	5.50 ± 0.30 a	3.97 ± 0.25 b	1.07 ± 0.10 abc	62.90 ± 0.98 bc
	Barrier 1	52.98 ± 1.57 b	5.43 ± 0.10 a	3.33 ± 0.04 a	1.26 ± 0.12 bcd	63.58 ± 2.02 bc
	GF 677	52.88 ± 0.93 b	5.55 ± 0.18 a	3.99 ± 0.15 b	1.59 ± 0.09 d	63.85 ± 0.81 bc
	Ishtara	45.82 ± 2.08 a	5.24 ± 0.17 a	3.38 ± 0.09 a	0.94 ± 0.05 ab	55.39 ± 2.22 a
	Monegro	49.78 ± 2.53 ab	5.79 ± 0.19 a	3.37 ± 0.16 a	1.33 ± 0.24 cd	59.80 ± 3.10 ab
	Penta	54.06 ± 1.85 b	6.50 ± 0.26 b	4.61 ± 0.14 c	1.63 ± 0.07 d	66.43 ± 2.23 c
	Peach seedling	45.91 ± 2.01 a	5.55 ± 0.31 a	3.25 ± 0.23 a	0.77 ± 0.07 a	55.62 ± 2.00 a
Royal Glory	Adesoto	54.66 ± 0.59 c	8.55 ± 0.22 ab	5.85 ± 0.21 ab	2.44 ± 0.14	71.28 ± 0.52 ab
	Barrier 1	47.50 ± 1.84 ab	9.70 ± 0.44 cd	6.97 ± 0.42 cd	2.84 ± 0.32	69.12 ± 2.90 ab
	GF 677	55.60 ± 0.47 c	10.22 ± 0.31 d	7.52 ± 0.12 d	2.36 ± 0.19	75.50 ± 1.31 b
	Ishtara	51.47 ± 1.29 bc	7.70 ± 0.08 a	6.40 ± 0.38 bc	2.18 ± 0.06	67.11 ± 0.21 a
	Monegro	45.86 ± 2.42 a	9.08 ± 0.28 bc	6.29 ± 0.24 bc	2.20 ± 0.28	66.52 ± 3.81 a
	Penta	60.39 ± 1.07 d	7.77 ± 0.26 a	5.45 ± 0.28 ab	2.51 ± 0.32	76.13 ± 0.77 b
	Peach seedling	53.46 ± 2.18 c	7.91 ± 0.39 a	5.24 ± 0.24 a	2.39 ± 0.24	69.49 ± 2.52 ab

[a] Different letters in columns for each cultivar indicate significantly different values at $p < 0.05$.

Table 4. Average Organic Acids Content (g/kg FW for citric and malic acids and in mg/kg FW for shikimic and fumaric acids) ± Standard Error of Redhaven and Royal Glory on Different Rootstocks[a]

cultivar	rootstock	malic acid	citric acid	shikimic acid	fumaric acid	total acids
Redhaven	Adesoto	3.71 ± 0.09 a	1.32 ± 0.10 a	43.93 ± 0.09	7.09 ± 0.11 a	5.08 ± 0.14 a
	Barrier 1	5.07 ± 0.15 d	1.74 ± 0.06 b	48.66 ± 1.54	10.03 ± 1.34 b	6.55 ± 0.25 c
	GF 677	3.65 ± 0.12 a	1.35 ± 0.06 a	47.94 ± 1.36	6.71 ± 0.18 a	5.06 ± 0.13 a
	Ishtara	3.85 ± 0.11 ab	1.28 ± 0.04 a	44.60 ± 1.27	7.34 ± 0.16 a	5.18 ± 0.10 a
	Monegro	4.27 ± 0.07 c	1.35 ± 0.14 a	45.94 ± 1.60	7.00 ± 0.22 a	5.49 ± 0.10 ab
	Penta	4.12 ± 0.02 bc	1.58 ± 0.16 ab	46.15 ± 0.71	7.84 ± 0.18 a	5.69 ± 0.20 b
	Peach seedling	4.04 ± 0.12 bc	1.80 ± 0.11 b	46.24 ± 1.02	7.04 ± 0.26 a	5.79 ± 0.07 b
Royal Glory	Adesoto	2.68 ± 0.16	1.72 ± 0.04 abc	39.3 ± 0.90 bc	8.40 ± 0.51 c	4.57 ± 0.07
	Barrier 1	2.47 ± 0.20	2.38 ± 0.08 d	37.8 ± 0.61 bc	6.25 ± 0.63 ab	4.61 ± 0.24
	GF 677	2.63 ± 0.12	2.02 ± 0.06 c	41.3 ± 2.22 c	7.20 ± 0.58 abc	4.60 ± 0.17
	Ishtara	2.66 ± 0.09	1.87 ± 0.09 bc	38.0 ± 1.71 bc	6.00 ± 0.00 a	4.48 ± 0.12
	Monegro	2.67 ± 0.09	1.62 ± 0.15 ab	33.5 ± 0.58 a	7.40 ± 0.51 abc	4.33 ± 0.10
	Penta	3.16 ± 0.18	1.48 ± 0.11 a	36.2 ± 1.61 ab	8.40 ± 0.87 c	4.47 ± 0.20
	peach seedling	2.87 ± 0.06	1.47 ± 0.13 a	33.2 ± 1.13 a	8.00 ± 0.45 bc	4.43 ± 0.11

[a] Different letters in columns for each cultivar indicate significantly different values at $p < 0.05$.

crop load as GF 677, produced significantly heavier fruit, indicating that not all cultivar−rootstock combinations work well and that identification of good combinations over several seasons may be necessary.

No significant differences in soluble solids contents were found between the two cultivars (Table 7). Soluble solids content levels were also not affected by the rootstock in the Redhaven fruit, ranging from 8.9 °Bx (peach seedling) to 9.7 °Bx (Barrier 1). On the other hand, the rootstock had a significant effect on soluble solids content in the Royal Glory fruit, which is in accordance with the results of a recent research on a Suncrest cultivar, where two identical rootstocks (GF 677 and Penta) were studied.[13] The Penta rootstock gave the highest soluble solids content (10.04 °Bx). The interaction between the rootstock and the cultivar for soluble solids content was significant. Some authors have reported that soluble solids content was not affected by the rootstocks.[2,5] De Salvador[4] reported that an increase of crop load negatively affected soluble solids contents in the fruit from Barrier 1 grafted trees. Similar soluble solids contents in the Redhaven fruit and significantly different in the Royal Glory fruit at different crop loads imply that each cultivar may interact specifically with the same rootstock.

Sugar and Organic Acid Content. It has been established, that levels of individual sugar contents in peach fruit differ among cultivars,[20] which is consistent with our results (Table 7). Rootstocks influenced the levels of sucrose, glucose, fructose and total sugars in fruit from both cultivars (Table 3), and their content levels are similar to early studies.[8,20,35] The Penta rootstock had a significant influence on high sucrose, glucose, fructose, sorbitol, and total sugar levels in the Redhaven cultivar. Ishtara, on the other hand, influenced the lowest contents of sucrose, glucose, and total sugars contents in the Redhaven fruit. The results are different to those reported in 2008.[8] The differences may have occurred because of different climatic conditions as well as different yields of the trees. In combination with the Royal Glory cultivar, the GF 677 rootstock produced fruit with high levels of glucose, fructose, and total sugars. In combination with Royal Glory, Ishtara produced fruit with low levels of glucose, sorbitol,

Table 5. Phenolics Content in Skin and Pulp (mg/kg FW) in Redhaven and Royal Glory Peach Fruit on Different Rootstocks[a]

		pulp			skin	
cultivar	rootstock	neochlorogenic acid	chlorogenic acid	*p*-coumaric acid	neochlorogenic acid	chlorogenic acid
Redhaven	Adesoto	11.16 ± 1.69 b	7.73 ± 0.86 bc	0.19 ± 0.030 bcd	17.38 ± 2.24 bc	68.12 ± 5.39 b
	Barrier 1	9.81 ± 0.87 b	10.64 ± 0.69 cd	0.20 ± 0.014 cd	14.83 ± 0.49 ab	152.27 ± 9.66 c
	GF677	3.26 ± 0.43 a	2.83 ± 0.34 a	0.15 ± 0.025 abc	15.60 ± 1.29 abc	43.81 ± 6.29 a
	Ishtara	10.05 ± 0.93 b	9.08 ± 1.01 bcd	0.12 ± 0.013 ab	21.08 ± 2.97 cd	56.90 ± 2.55 ab
	Monegro	6.02 ± 0.44 a	6.19 ± 1.15 b	0.11 ± 0.010 a	10.37 ± 1.19 a	50.63 ± 4.37 ab
	Penta	10.44 ± 1.05 b	10.45 ± 0.91 cd	0.23 ± 0.033 de	10.18 ± 1.48 a	50.38 ± 8.14 ab
	Peach seedling	11.29 ± 1.23 b	11.34 ± 1.24 d	0.28 ± 0.030 e	26.16 ± 3.15 d	50.29 ± 8.91 ab
Royal Glory	Adesoto	5.85 ± 0.23 ab	9.44 ± 0.45 ab	0.11 ± 0.0050 b	10.09 ± 1.52	28.14 ± 4.40 a
	Barrier 1	6.54 ± 1.23 ab	7.62 ± 1.79 ab	0.10 ± 0.0061 b	12.72 ± 1.38	57.39 + 1.40 c
	GF677	7.37 ± 0.41 b	11.61 ± 1.02 bc	0.11 ± 0.0051 b	14.34 ± 1.96	77.96 + 5.67 d
	Ishtara	4.43 ± 0.42 a	5.98 ± 0.42 a	0.09 ± 0.0089 ab	11.35 ± 0.72	23.87 ± 3.24 a
	Monegro	4.49 ± 0.42 a	14.21 ± 1.86 c	0.07 ± 0.0075 a	11.53 ± 1.02	37.91 ± 3.53 ab
	Penta	4.52 ± 0.18 a	8.24 ± 0.71 ab	0.11 ± 0.0138 b	10.01 ± 0.92	29.20 ± 4.74 a
	Peach seedling	6.72 ± 0.50 b	9.41 ± 1.03 ab	0.09 ± 0.0035 ab	14.17 ± 1.83	48.63 ± 6.78 bc

[a] Different letters in columns for each cultivar indicate significantly different values at $p < 0.05$.

Table 6. Flavonol and Anthocyanin Content Levels (mg/kg FW) in Skin of Redhaven and Royal Glory Peach Fruit on Different Rootstocks[a]

cultivar	rootstock	Q 3-gal[x]	Q 3-rut[r]	Q 3-glu[y]	Q 3-rham[z]	Cy 3-glu[s]	Cy 3-rut[k]
Redhaven	Adesoto	12.12 ± 1.54	26.08 ± 2.49	34.87 ± 2.00	7.23 ± 0.95	497.10 ± 37.18 ab	16.02 ± 1.96 a
	Barrier 1	11.00 ± 2.08	22.66 ± 4.96	25.12 ± 4.89	5.73 ± 1.29	687.88 ± 104.26 b	35.05 ± 4.99 c
	GF677	8.98 ± 1.13	18.09 ± 4.71	17.01 ± 4.29	5.58 ± 1.05	404.43 ± 94.44 a	16.71 ± 4.85 a
	Ishtara	9.60 ± 2.03	16.74 ± 3.77	28.66 ± 4.36	4.80 ± 1.12	625.35 ± 55.47 ab	22.95 ± 2.28 ab
	Monegro	9.51 ± 1.10	17.80 ± 1.71	27.23 ± 3.31	3.85 ± 0.24	693.89 ± 44.88 b	31.26 ± 4.16 bc
	Penta	9.14 ± 1.94	18.90 ± 4.04	24.75 ± 5.36	4.30 ± 1.00	535.82 ± 79.99 ab	23.70 ± 4.81 ab
	Peach seedling	8.15 ± 0.58	16.24 ± 2.69	20.72 ± 2.63	4.53 ± 0.74	437.15 ± 20.01 a	16.91 ± 0.86 a
Royal Glory	Adesoto	8.51 ± 0.69	21.84 ± 2.15	29.94 ± 4.05 bc	3.29 ± 0.41	580.00 ± 92.92	3.32 ± 0.33
	Barrier 1	7.84 ± 0.48	21.90 ± 0.89	27.86 ± 0.91 ab	3.13 ± 0.17	451.16 ± 32.14	3.45 ± 0.55
	GF677	6.02 ± 0.91	14.58 ± 2.97	17.48 ± 3.44 a	2.99 ± 0.58	460.28 ± 74.35	3.01 ± 0.70
	Ishtara	7.75 ± 0.99	21.09 ± 3.45	24.90 ± 3.15 ab	2.98 ± 0.45	388.03 ± 37.77	1.69 ± 0.19
	Monegro	9.55 ± 0.67	24.31 ± 1.28	37.88 ± 0.50 c	3.71 ± 0.23	515.94 ± 44.75	2.70 ± 0.45
	Penta	7.50 ± 1.02	18.39 ± 1.24	19.25 ± 5.00 a	3.07 ± 0.37	486.04 ± 33.68	2.63 ± 0.50
	Peach seedling	7.43 ± 0.67	18.57 ± 1.44	22.05 ± 1.71 ab	3.14 ± 0.29	344.97 ± 92.81	2.07 ± 0.32

[a] Different letters in columns for each cultivar indicate significantly different values at $p < 0.05$. Legend for superscript letters: x, quercetin 3-*O*-galactoside; y, quercetin 3-glucoside; z, quercetin 3-rhamnoside; r, quercetin 3-*O*-rutinoside; s, cyanidin 3-*O*-glucoside; k, cyanidin 3-*O*-rutinoside.

and total sugars. We can assume that low levels of sucrose, glucose, fructose, and total sugars in Redhaven and glucose and sorbitol in the Royal Glory fruit from the Ishtara rootstock could be affected by a high crop load. Usenik et al.[36] previously reported that higher crop loads (low leaf-to-fruit ratio) caused lower contents of glucose, fructose, and sorbitol levels in cherry fruit. High levels of all individual and total sugars in the Redhaven fruit from the Penta rootstock, however, contradict this assumption, since relatively high crop loads in comparison to other rootstocks were found. The Monegro rootstock in combination with both cultivars produced fruit with low levels of several individual sugars despite a low crop load. It is evident from our results that the content of primary metabolites may be a function of at least three factors, cultivar, rootstock, and crop load, and their interactions.

According to Colaric et al.[20] cultivar affects organic acids levels, which is in accordance with our results (Table 7). We discovered a significant effect of rootstock on citric, malic, fumaric, and total acids in the Redhaven fruit and on citric, shikimic, and fumaric acids in the Royal Glory fruit (Table 4). The values measured are similar to those reported previously.[8,20,35] High levels of malic, citric, fumaric, and total acid were found in the Redhaven fruit on Barrier 1 rootstock. Low levels of all acids were measured in the Redhaven fruit on Adesoto, GF 677, and the Ishtara rootstock. None of the studied rootstocks influenced high levels of organic acids in general in the Royal Glory, while in the fruit from peach seedling low levels of citric and shikimic acid were measured. Usenik et al.[36] reported that higher crop load affected high levels of malic acid and total acids in the sweet cherry fruit. This is in contradiction with our results for the Redhaven fruit on the Ishtara rootstock, where low levels of organic acids were measured despite high crop load. It can even be assumed that crop load marginally influences the organic acid levels, since at similar crop loads of the

Table 7. Significance for the Effect for Rootstock and Cultivar and Their Interaction on Yield, Circumference, Crop Load, Yield Efficiency, Fruit Physical, and Chemical Characteristics of Peach[a]

parameter[b]	rootstock	cultivar	rootstock × cultivar
yield	NS	***	NS
circumference	***	***	NS
crop load	***	***	***
yield efficiency	***	***	*
weight	NS	NS	**
soluble solids	NS	NS	***
sucrose	***	*	**
glucose	***	***	***
fructose	***	***	***
sorbitol	*	***	NS
total sugars	***	***	NS
citric acid	***	***	***
malic acid	***	***	***
shikimic acid	**	***	*
fumaric acid	NS	NS	***
total acids	***	***	***
neochlorogenic acid, pulp	***	***	***
chlorogenic acid, pulp	*	*	***
p-coumaric acid, pulp	***	***	***
neochlorogenic acid, skin	***	***	***
chlorogenic acid, skin	***	***	***
Q 3-gal[x], skin	NS	**	NS
Q 3-rut[r], skin	NS	NS	NS
Q 3-glu[y], skin	***	NS	NS
Q 3-rham[z], skin	NS	***	NS
Cy 3-glu[s], skin	*	**	NS
Cy 3-rut[k], skin	**	***	**

[a] NS, not significant; *, significant differences at *P*-value below 0.05; **, significant differences at *P*-value below 0.01; ***, significant differences at *P*-value below 0.001. [b] Legend for superscript letters: x, quercetin 3-*O*-galactoside; y, quercetin 3-glucoside; z, quercetin 3-rhamnoside; r, quercetin 3-*O*-rutinoside; s, cyanidin 3-*O*-glucoside; k, cyanidin 3-*O*-rutinoside.

Redhaven on Adesoto, Barrier 1, and GF 677 contrasting levels of organic acids were found.

Phenolics. In Table 5, we present phenolic compounds (neochlorogenic acid, chlorogenic acid, and *p*-coumaric acid) in pulp and skin, and in Table 6 we present flavonols (quercetin 3-galactoside, quercetin 3-rutinoside, quercetin 3-glucoside, and quercetin 3-rhamnoside) and anthocyanins (cyanidin 3-glucoside and cyanidin 3-rutinoside) in the skin of Redhaven and Royal Glory fruit.

In the peach fruit skin, chlorogenic acid was present in highest concentrations among the identified phenolics, followed by neochlorogenic acid. Content levels obtained are similar to those from the previous study;[8] however, they are lower compared to those reported by Tomás-Barberán et al.[21] Differences may have occurred because of different extraction and analysis methods.

Significant effect of the rootstock on phenolics compounds in the pulp was evident for both cultivars, which is in accordance with the previous study of total phenolics and individual phenolic contents.[8] High concentrations of neochlorogenic, chlorogenic, and *p*-coumaric acid were found in the pulp of the Redhaven fruit harvested from the Penta and peach seedling rootstocks. The low contents of phenolics were found in the pulp of the Redhaven fruit harvested from the GF 677 and Monegro rootstocks. High concentrations of neochlorogenic, chlorogenic, and *p*-coumaric acid were found in the pulp of the Royal Glory fruit on the GF 677 rootstock. The low content of phenolics was found in the pulp of the Royal Glory fruit from the Ishtara rootstock. Phenolic acids are, among other factors, maturity-dependent.[25] Since fruit from each cultivar were of similar ripeness, these differences can only be attributed to the influence of the rootstock, which is in accordance with the previous studies on peach[8] and sweet cherry.[37] The rootstock effects on levels of phenolics in pulp of the Royal Glory differed from those of the Redhaven, indicating that the interaction between the rootstock and the cultivar also influences the levels of phenolics in the pulp of peach fruit. According to Tomas-Barberan et al.[21] some cultivars contain very high levels of phenolics compounds that could be heightened or lowered with the selection of a certain rootstock. This would have a crucial impact on the health-promoting properties of peach fruit.[21]

Rootstock had a significant influence on various levels of neochlorogenic and chlorogenic acids in the skin of the Redhaven fruit. High levels of neochlorogenic acid were again measured in the peach seedling fruit as well as in the Ishtara fruit. The Monegro and Penta rootstock yielded low levels of neochlorogenic acid in the skin. By far the highest concentrations of chlorogenic acid were found in the skin of fruit from the Barrier 1 grafted trees. These were followed by fruit harvested from the Adesoto grafted trees. The GF 677 rootstock gave the lowest levels of chlorogenic acid in the skin of the Redhaven fruit. Neochlorogenic acid levels were unaffected by rootstocks in the Royal Glory fruit, while significant differences were found in the chlorogenic acid levels. As with the pulp tissue, GF 677 gave the highest levels of chlorogenic acid in the skin of the Royal Glory fruit. Barrier 1 and peach seedling also produced the Royal Glory fruit with elevated levels of chlorogenic acid in the skin.

Among flavonols, quercetin 3-glucoside was present in the highest concentrations, closely followed by quercetin 3-rutinoside, quercetin 3-galactoside, and quercetin 3-rhamnoside. Similar content levels have been reported previously,[21] while somewhat lower values of flavonols in the Redhaven fruit were found in a previous study,[8] which indicates seasonal fluctuations of these metabolites. Except for quercetin 3-glucoside levels in the skin of the Royal Glory, similar levels of quercetin 3-rutinoside and quercetin 3-glucsoide were measured in the skin from both cultivars, indicating that flavonols in the skin are not affected by the rootstock or cultivar in comparison to phenolic acids. According to Awad et al.[38] the regulation of crop load does not affect flavonoids in the skin of an apple, which is in accordance with our results.

Content levels of cyanidin 3-glucoside were twice as high compared to those recorded in the literature, while those of cyanidin 3-rutinoside were similar to previous publications.[8,21] Barrier 1 and Monegro produced fruit with statistically the highest levels of both anthocyanins in the skin of the Redhaven fruit. On the other hand, GF 677 and peach seedling induced low levels of anthocyanins. Anthocyanins in the skin of the Royal Glory peach fruit were unaffected by rootstocks. Anthocyanins are present in higher concentrations in fruit with intensive red coloration.[39] Similar levels of anthocyanins were measured in the skin of the Royal Glory and in the Redhaven cultivar. Royal Glory is the cultivar that in the early stage of maturity gains an intense red coloration covering most of the fruit.[40]

We can conclude that selecting the right combination of the rootstock and cultivar is important for the chemical characteristics of peach fruit. In combination with the Redhaven in general, the Barrier 1 rootstock produced the best fruit (high yields of good average fruit weight). The Penta rootstock also produced good quality fruit in combination with the Redhaven; however, it should be thinned more intensively to improve fruit weight. In combination with the Royal Glory again the Penta rootstock in general produced good quality (high levels of several primary and secondary metabolites) as well as reached similar yields in comparison to other rootstocks. In addition, the Penta rootstock produced the smallest trees, hence easier to cultivate. Unfortunately, none of the rootstocks improved all of the quality parameters.

We have established that the extent to which rootstocks affect certain parameters varies from cultivar to cultivar. We found similar effects of the rootstock on vigor. Fruit weight, sugars, organic acids, and phenolic acid content levels were significantly affected by the rootstock. Flavonols, with the exception of quercetin 3-glucoside, on the other hand, were unaffected by any of the rootstocks.

It is undisputed that the effect of the rootstock on fruit trees is considerably more complex than can be measured by vigor alone. Field performance of the rootstock is still the main criterion for its selection; however, its effect on fruit quality should not be overlooked. Nowadays, good quality fruit is more and more associated with the health-promoting benefits of the fruit and should, therefore, also be included in the studies to provide growers with information about which cultivars and rootstocks will provide the best results.

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