

Effects of different training systems on growth, fruit quality, and yield in peaches

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Abstract

This study evaluates the effects of Vase, Catalan Vase, and Quad-V training systems on the growth, yield, and fruit quality of three peach cultivars ('Extreme® 314,' 'Extreme® 436,' and 'Extreme® 568') in the mid-northern Anatolia region of Türkiye. The study was conducted from 2018 to 2022. The findings indicate that modern systems provide significant advantages over the traditional system, including improved light penetration, uniform tree growth, earlier yields, and reduced labor costs. Among these, the Catalan Vase system emerged as an economically sustainable alternative, offering early yields and labor efficiency. Similarly, the Quad-V system demonstrated superior performance in enhancing light management and fruit quality. However, the adoption of these systems in Türkiye remains limited due to low awareness and skepticism among growers. The study highlights the potential of modern training systems not only to increase productivity but also to enhance the global competitiveness of the peach sector in Türkiye. It emphasizes the importance of bridging the knowledge gap and conducting comprehensive field trials to encourage their adoption. Future research should focus on long-term evaluations of these systems across diverse regions and cultivars, as well as on integrating mechanized practices to further optimize labor efficiency. The results provide crucial insights into transitioning to more sustainable, profitable peach production practices, aligning with global horticultural innovation trends. This research underscores the strategic role of modern orchard systems in addressing economic and environmental challenges in the peach industry.

Introduction

Peach (*Prunus persica* L. Batsch) is an important type of fruit among temperate climate fruit types that is popular worldwide. Total world peach production is around 27 891 645 tons annually [1]. China ranks first in world peach production, with 17.6 million tons. China is followed by Spain (1 376 900 tons), Türkiye (1 179 041 tons), and Italy (1 092 160 tons), respectively. Spain ranks first in exports with (690 902 tons), followed by Türkiye (261 375 tons), Greece (126 033 tons), Italy (117 853 tons), and Chile (116 468 tons) [1]. Türkiye has an important place in worldwide peach production and exports. Despite these data, Türkiye faces challenges in maintaining competitiveness against leading producers such as Spain, Greece, and Italy. These nations have implemented advanced orchard management systems and technologies that improve productivity while minimizing labor costs [2, 3, 4, 5].

Traditional peach cultivation is characterized by low-density orchards with high spacing between rows. In recent years, increasing planting density and limiting canopy growth have become prominent worldwide [6]. Therefore, research focuses on selecting cultivar-rootstock combinations adaptable to high-density systems, as well as implementing training systems and pruning strategies that provide optimized yield and fruit quality in smaller canopy sizes [7, 8]. Indeed, peach orchards in Türkiye are still grown using the vase training system with traditional methods. Although this system is used extensively, it also creates some disadvantages, such as low planting densities, increased labor and cost requirements for pruning and harvesting due to large tree sizes, and low productivity per unit area [8, 9]. These disadvantages require optimization of orchards using modern training systems suitable for high-density planting. In

recent years, modern training systems such as Catalan Vase, Quad-V, and Perpendicular-V have started to be used in peach orchards in the world. Studies have shown that these systems optimize tree size, increase light penetration, reduce labor, and improve fruit quality [2, 8, 10, 11, 12, 13, 14]. In Türkiye, these systems are still in the experimental phase [8]. Adopting systems that reduce labor input without compromising yield or quality is therefore vital for improving the sector's competitiveness.

The aim of this study was to determine the performances of early 'Extreme 314', mid-season 'Extreme 436', and late 'Extreme 568' peach cultivars grafted onto (Garnem) rootstock in terms of growth, yield, and fruit quality on Vase, Vase Catalan, and Quad-V training systems.

Material and method

Material

Research site

This study was conducted at the Agricultural Research Station (Bafra) of Samsun Ondokuz Mayıs University from 2018 to 2022. The experimental orchard was situated at an altitude of 16 m, with geographic coordinates of 41°33' N and 35°51' E in the North Anatolia region of Türkiye. During the study, the highest average temperature was recorded on July 21, 2021, at 27.57°C, while the lowest temperature was noted on February 17, 2022, at -1.9°C (Datalogger Instruments, Kistock KH 200). The soil structure at the experimental site consisted of silty clay, composed of 55% silt, 34% clay, and 10% sand. The soil pH was slightly alkaline (8.03) with no salinity. The lime content was moderately low (10.2%), and the organic matter content was considered low (2.7%).

Plant material

The plant material included early-maturing 'Extreme® 314', mid-season 'Extreme® 436', and late-season 'Extreme® 568' peach cultivars grafted onto the GxN15 (Garnem) rootstock (Garfi × Nemared) [15]. These peach cultivars (*Prunus persica* L. Batsch) were developed at the R&D center in Don Benito (Badajoz, Spain) under the Provedo breeding program. 'Extreme® 314' (PRO 314) is characterized as an early-maturing, high-yielding cultivar with dark red skin and yellow flesh. 'Extreme® 436' (PRO 436) is a mid-season maturing, high-yielding cultivar with bright red skin and yellow flesh. 'Extreme® 568' (PRO 568) is a late-season maturing, very productive cultivar with uniform-sized red skin and yellow-fleshed fruits [8]. Peach trees were obtained from a commercial nursery.

The nursery trees were planted in spring 2017. Three training systems were employed: Vase (V), Catalan Vase (CV), and Quad-V (QV). The row spacing was 5.0 m, with plant spacing of 4 m in Vase, 3.0 m in Catalan Vase, and 2.5 m in Quad-V systems [3, 8, 13]. The Vase system was used as the control. The experiment was designed as a randomized block design with four replications and five trees per replication. Standard cultural practices such as irrigation, fertilization, pruning, and pest and disease

management were regularly applied. Fruit thinning was performed manually 30 days after full bloom, leaving one fruit per 10 cm of shoot.

Method

Phenological observations

The dates of first bloom, full bloom, fruit set, and harvest were recorded.

Tree growth characteristics

Tree height was measured from the soil level to the top during dormancy. For the canopy volume, the tree canopy radius (r) and the tree canopy length (h) were determined using the formula $2.\pi.r^2.h/3$ [16]. Trunk diameter was measured at 10 cm from the grafting point, and trunk cross-sectional area (TCSA) was calculated with the formula $\pi.r^2$. Also, winter pruning was done during dormancy, summer pruning in May-June, and the pruning residue weights (kg) were measured. The term pruning residue refers to the amount of woody material removed and discarded during pruning. The pruning times for the trees were determined in 2021–2022.

Yield (kg tree⁻¹), yield efficiency (kg cm⁻²)

Yield per tree (kg), per hectare (kg), and yield efficiency were determined. Fruits were hand-harvested at commercial maturity.

Fruit traits

Fruit traits were analyzed at commercial maturity, with 10 fruits sampled per replication and per cultivar and training system. Fruit weight (g) was measured using a precision scale, fruit diameter (mm) with a digital caliper, and fruit firmness (kg cm⁻²) using an 8 mm-tip digital penetrometer (FHT 200, Extech Instruments, Nashua, NH, USA). Fruit skin colour (L^* , a^* , b^* values) was assessed with a digital colorimeter (CE Minolta CR300). Soluble solids content (SSC) was measured using a digital refractometer (Abbe refractometer, Carl-Zeiss, Jena, Germany), and titratable acidity (TA) was evaluated using 0.1 N NaOH.

Statistical analysis

To determine the performance of the cultivars under different training systems, phenological observations were conducted on the experimental plants. In addition, tree growth characteristics, yield, and fruit traits were evaluated. Analysis of variance (ANOVA) was conducted to evaluate differences among cultivars and training systems regarding growth, yield, and fruit quality using SPSS 20.0 (SPSS

Inc., Chicago, IL, USA). Means were separated using Duncan's multiple range test at significance levels of 1% and 5%.

Results and Discussion

Phenological observations

The phenological observations (first bloom, full bloom, fruit set, and harvest dates) for the cultivars and training systems evaluated from 2019 to 2022 are presented in Table 1. Although there were differences among cultivars in phenological observations, no significant differences were observed among the training systems. Indeed, in a study conducted on the 'Barbosa' and 'Chiripa' peach cultivars using Vase Ypsilon and Central Leader training systems, Uberti et al. [17] reported that the training systems had no significant effect on phenological periods. However, differences in phenological periods were observed among years. Similarly, Almeida et al. [18] reported that variations in flowering and harvest times in peaches occur from year to year and are mainly associated with climatic conditions, particularly chilling requirements and high temperatures.

In the 'Extreme® 314' cultivar, first bloom occurred in the first half of March (3–10), full bloom in the second half of March (March 9–15), and fruit set at the end of March (19 March– 1 April). In the 'Extreme® 436' cultivar, first bloom occurred between March 8–21, full bloom occurred between March 17–April 3, and fruit set occurred between March 25–April 9. In the 'Extreme® 568', first bloom occurred between March 9–15, full bloom occurred between March 17–26, and fruit set occurred between March 24–April 1. Harvesting dates took place on June 24–July 5 for the 'Extreme® 314' (early), on August 5–8 for the 'Extreme® 436' (mid-season), and on August 27–September 9 for the 'Extreme® 568' (late). Phenological observations conducted between 2019 and 2022 revealed that, in general, flowering is directly proportional to the early maturity of the varieties, and that first bloom, full bloom, and fruit set occur earlier in early-maturing cultivars compared to mid-season and late-maturing cultivars. In fact, in the study conducted by Oran et al. [8], they reported that the 'Extreme® 314' cultivar bloomed earlier than other cultivars.

Table 1
Phenological observations for 2019 to 2022

Training systems	Cvs.	First bloom	Full bloom	Fruit set	Harvest date
Vase	E 314	3–10 March	9–15 March	19 March-1 April	24 June- 5 July
	E 436	8–21 March	17 March-3 April	25 March-9 April	5–8 August
	E 568	9–15 March	19–26 March	24 March-1 April	27 August- 9 September
Catalan Vase	E 314	3–10 March	9–15 March	22 March-1 April	24 June- 5 July
	E 436	9–21 March	18 March-3 April	25 March-9 April	5–8 August
	E 568	10–15 March	17–26 March	24 March-1 April	27 August- 9 September
Quad-V	E 314	3–10 March	9–14 March	22 March-1 April	24 June- 5 July
	E 436	9–21 March	19 March-3 April	25 March-9 April	5–8 August
	E 568	10–15 March	19–26 March	24 March-1 April	27 August- 9 September
Cvs: Cultivar E: Extreme®					

Tree growth characteristics

Tree height, canopy volume, trunk diameter, and trunk cross-sectional area (TCSA) measurements for each training system and cultivar are detailed in Fig. 1 and Fig. 2.

No significant differences in tree height were observed among the cultivars in 2018 and 2019. However, by 2020, when the trees reached their final shapes, 'Extreme® 436' exhibited trees that were statistically larger than those of the other cultivars. Canopy volume differences among the cultivars were not significant in 2018 and 2020, but in 2019, 'Extreme® 436' trees had smaller canopy volumes than those of the other cultivars.

The interaction between cultivar and training system for tree height and canopy volume is presented in Fig. 2. The cultivar × training system interaction for tree height was statistically significant in all three trial years. In 2018 and 2019, the highest tree height was obtained from the 'Extreme® 436' × Quad-V interaction (respectively 127.20 cm, 194.50 cm), while in 2020, the highest trees (260.25 cm) were recorded for the 'Extreme® 436' × Vase interaction. However, in 2018 and 2019, the highest tree height

was observed in the cultivar × training system interaction of 'Extreme® 314' Quad V (127.20 cm, 194.50 cm, respectively), while in 2019, 'Extreme® 436' Vase (260.25 cm) was observed.

While there was a significant cultivar × training system interaction in canopy volume in 2018 and 2019, there was no such interaction in 2020. The highest canopy volume was obtained from the 'Extreme® 314' × Vase interaction in 2018, and in 2019, Extreme® 314' × Vase (1.49 m³), 'Extreme® 568' × Vase Catalan (1.42 m³), 'Extreme® 314' × Vase Catalan (1.41 m³), and 'Extreme® 314' × Quad V (1.40 m³). The trees with the smallest canopy volume were obtained from the 'Extreme® 436' × Quad V (0.63 m³) cultivar × training system combination.

Oran et al. [8] reported that the Vase system produced the highest number of trees in all cultivars in their study with four different training systems. Iglesias et al. [19] reported that the Catalan Vase system achieved its maximum canopy volume in the fourth year, with optimum light penetration.

No statistically significant differences were observed among the cultivars for trunk diameter and trunk cross-sectional area (TCSA) in 2018. This result indicates that the saplings planted in 2017 were of highly homogeneous size. However, significant differences emerged in 2019 and 2020 (Fig. 3). In 2019 and 2020, the largest trunk diameters and TCSA values were recorded for the cultivars 'Extreme® 314' and 'Extreme® 568'.

No statistically significant differences were found among the training systems for trunk diameter and TCSA in 2019 and 2020. However, significant differences were observed in the cultivar × training system interaction for these traits during the trial period (Fig. 4). By 2020, when the trees had reached their final shapes, the largest trunk diameters were recorded for 'Extreme® 314' × Catalan Vase (74.89 mm), 'Extreme® 568' × Catalan Vase (72.16 mm) and Extreme® 314' × Vase (67.43 mm) interactions. In contrast, the smallest trunk diameters were observed in the 'Extreme® 436' × Quad-V (46.92 mm) interaction. Similarly, the largest TCSA values in 2020 were obtained from the 'Extreme® 314' × Catalan Vase (44.91 cm²) and 'Extreme® 568' × Catalan Vase (41.73 cm²) interactions, while the smallest TCSA was recorded for the 'Extreme® 436' × Quad-V (17.13 cm²) interaction.

These findings indicate that trunk diameter and TCSA development were strongly influenced by the interaction between cultivar vigor and training system architecture. The superior performance of 'Extreme® 314' and 'Extreme® 568', particularly under the Catalan Vase system, suggests that this training system provides a more favorable balance between vegetative growth and canopy management. The wider branch angles and improved light distribution characteristic of the Catalan Vase system may have enhanced photosynthetic efficiency and assimilate allocation, thereby promoting stronger trunk development.

In contrast, the relatively lower trunk diameter and TCSA values observed in the 'Extreme® 436' × Quad-V combination may be attributed to increased competition among scaffold branches and more restricted vegetative growth under higher planting density. Similar trends have been reported in previous studies, in

which high density training systems were associated with reduced TCSA but improved canopy light interception and yield efficiency [8, 20].

Overall, these results suggest that the Catalan Vase system is particularly suitable for moderately to highly vigorous cultivars in terms of supporting structural strength and long-term orchard stability. Therefore, selecting appropriate cultivar × training system combinations is essential for optimizing tree architecture, productivity, and sustainability in modern peach orchards.

Summer and winter pruning residue weights for the cultivars and training systems are shown in Fig. 5. No statistically significant differences were observed among the cultivars for either summer or winter pruning weight.

Examining the effects of training systems on pruning residue weight, some variations were observed in the early years of the trial. In 2018, the highest summer and winter pruning residue weights were obtained from the Vase system (0.51 and 0.36 kg/tree, respectively). However, by 2020, when the trees had reached their final shape, no statistically significant differences in pruning residue weight were detected among the training systems. In fact, the difference observed in 2018 was not due to the pruning requirement of the training system itself, but rather to system-specific variations associated with the initial training and shaping stage.

Regarding cultivar × training system interaction, statistically significant differences in pruning residue weight were observed only for the winter pruning in 2018 (Fig. 6). During that year, the highest winter pruning residue weight was recorded for the 'Extreme® 314' × Vase (0.41 kg/tree) and 'Extreme® 436' × Vase (0.40 kg/tree) interactions.

Pruning residue weight, both summer and winter, serves as a practical indicator of the vegetative growth and canopy management requirements of fruit trees. In this study, no statistically significant differences in pruning weight were observed across cultivar × training system interactions, except in 2018. The higher winter pruning weight recorded in the vase training system for all three cultivars suggests that these interactions promote vigorous early growth and require more extensive pruning. To obtain more reliable and conclusive information, it would be beneficial to continue observations for at least another 5 years. Day et al. (2005) also stated in their study that the Vase system needs more annual pruning. By 2020, as the trees reached their final shapes, pruning weight differences among cultivars and training systems diminished. Iglesias et al. [19] reported that the main cost in peaches/nectarines is labor, mostly spent on harvesting, fruit thinning, and pruning. The researchers reported that 6% of all costs were spent on winter pruning and 2% on summer pruning. Therefore, reducing this amount to a more economically efficient level will be much more important for achieving profitable production.

Yield

Since the nursery trees were planted just before flowering in 2017, insufficient bloom and fruit set resulted in no harvestable yield in 2018. The first yield data were collected in 2019 (Figs. 7 and 8). When the yield per tree and per hectare among the cultivars tested were examined, it was determined that the

highest values were obtained from the mid-season cultivar 'Extreme® 436' ($4.81 \text{ kg tree}^{-1}$, 3.05 t ha^{-1} , respectively) (Figs. 7 and 8).

In 2019, training systems did not show statistically significant differences in yield; however, the cultivar × training system interaction was significant. The highest yields per tree and per hectare were obtained from the 'Extreme® 436' × Vase, 'Extreme® 436' × Catalan Vase and 'Extreme® 436' × Quad-V combinations.

In 2020, adverse spring weather, including cold and rainy periods, caused significant flower bud damage and a severe fungal infection, resulting in no harvestable yield.

In 2021, significant differences were observed in yield per tree among cultivars, training systems, and their interactions (Figs. 7 and 8). Among the cultivars, the highest yield per tree and per hectare was obtained from 'Extreme® 314.' Among the training systems, Catalan Vase training system produced the highest yield per tree and per hectare. When examining the cultivar × training system interactions, 'Extreme® 436' × Quad-V and 'Extreme® 314' × Catalan Vase combination yielded the highest values. When evaluated in terms of cumulative yield, the highest yield both per tree and per hectare was obtained from the 'Extreme® 436' cultivar among the cultivars, and from the training systems, the Quad-V system and 'Extreme® 436' × Catalan Vase and 'Extreme® 436' × Quad-V were the most efficient combinations in the cultivar × training system interaction. Similarly, Oran et al. [8] in a study conducted across four training systems and three cultivars, demonstrated that, consistent with our findings, the highest yield per unit area was obtained with the Quad-V training system across all cultivars.

As is well known, the dominant training system in peach cultivation is the Vase system. However, our experiment showed that, in terms of yield, the Vase system did not perform better than the other two systems. Notably, Dejong et al. [12] reported that the formation of vigorous sprout shoots in the inner parts of the canopy in a vase training system would negatively affect fruit yield and quality. Gullo et al. [21] reported that the vase training system intercepts less light and that there was no decrease in yield per tree with intensive summer pruning. In another study, Uberti et al. [22] conducted a study with 3 different (Center Leader, Open Center, and Ipsilon) training systems in which the estimated and cumulative yield in the first year of the experiment was 239.4% higher in trees trained with Center Leader than in other systems. This difference decreased in the second year of the study, but the estimated yield was still 27.7% higher than for trees trained with Ipsilon and 46.6% higher than for trees trained with Open Center.

In 2022, the yield of 'Extreme® 314' was lower than that of the other cultivars, likely due to unfavorable weather conditions during the flowering period and subsequent damage caused by fungal infections (*Taphrina deformans*) under rainy conditions. As this early-maturing cultivar flowered approximately one week earlier than the others, it was more exposed to these adverse factors, resulting in higher fruit losses.

Fruit characteristics

In 2019, no statistically significant differences were observed among the tested cultivars in fruit weight, fruit diameter, or SSC. However, the mid-season cultivar 'Extreme® 436' exhibited higher acidity compared to the other cultivars (Table 2). In 2019, there were significant differences among the training systems in terms of fruit weight, fruit diameter, and fruit firmness. Similarly, DeJong et al. [21] reported that different tree forms and planting densities affected fruit weight. In the study, the largest fruits were obtained from trees trained in the Catalan Vase system, followed by the Vase and Quad-V systems. The firmest fruits were recorded in the Quad-V system, while TA and SSC parameters were not significantly affected by the training systems. Taylor [24] reported no significant differences in firmness among fruits from different training systems (Perpendicular-V, Vase, Quad-V). Considering the cultivar × training system interactions, the largest fruits were obtained from the 'Extreme® 314' × Catalan Vase (209.56 g) and 'Extreme® 436' × Catalan Vase (204.07 g) combinations, whereas the firmest fruits (7.51 kg cm^{-2}) and highest titratable acidity (%0.38) were obtained from the 'Extreme® 436' × Quad-V combinations (Table 2).

Table 2
Some fruit characteristics of training systems and cultivars for 2019–2022

Year	Cultivar Training System Cultivar×System	Fruit weight (g)	Fruit diameter (mm)	Fruit firmness (kg cm ⁻²)	TA (%)	SSC (°Brix)
2019	Extreme®314	158.86	86.19	3.56	0.21 b	13.1
	Extreme®436	150.81	83.60	3.92	0.34 a	12.5
	Extreme®568	142.42	81.19	3.75	0.24 b	12.8
	<i>Probability</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>< 0.01</i>	<i>ns</i>
	Vase	107.31 c	67.30 c	3.34 b	0.25	12.3
	Catalan Vase	198.11 a	101.84 a	1.83 c	0.26	13.0
	Quad-V	146.67 b	81.83 b	6.05 a	0.28	13.1
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>	<i>ns</i>
	E314VA	119.07 cd	71.16 bc	3.64 cd	0.20 c	12.8
	E314CV	209.56 a	105.14 a	1.19 f	0.21 c	13.4
	E314QV	147.96 bc	82.29 b	5.84 b	0.23 c	12.9
	E436 VA	102.84 d	66.05 c	2.79 de	0.32 ab	12.0
	E436CV	204.07 a	103.27 a	1.45 ef	0.32 ab	12.7
	E436QV	145.52 bc	81.49 b	7.51 a	0.38 a	12.8
	E568 VA	100.03 d	64.70 c	3.59 cd	0.23 c	12.0
	E568CV	180.70 ab	97.13 a	2.86 de	0.26 bc	13.0
	E568QV	146.54 bc	81.73 b	4.81 bc	0.24 bc	13.4
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>
2021	E314	193.0 c	55.6 c	5.7 b	0.25 b	10.2 c
	E436	220.0 b	68.7 a	13.6 a	0.46 a	15.1 a
	E568	270.0 a	65.2 a	5.9 b	0.28 b	12.5 b
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>
	Vase	240.0 a	64.1 a	9.2 a	0.35	13.3

Year	Cultivar Training System Cultivar×System	Fruit weight (g)	Fruit diameter (mm)	Fruit firmness (kg cm ⁻²)	TA (%)	SSC (°Brix)
	Catalan Vase	223.0 b	62.3 b	7.8 b	0.31	12.5
	Quad-V	222.0 b	63.1 ab	8.0 b	0.32	12.0
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.05</i>	<i>< 0.01</i>	<i>ns</i>	<i>ns</i>
	E314×VA	210.0 e	56.7 c	5.2 c	0.28 bc	9.92
	E314×CV	182.6 f	55.2 c	5.8 c	0.22 c	10.3
	E314×QV	186.3 f	54.8 c	6.2 c	0.24 bc	10.6
	E436×VA	236.0 cd	71.1 a	17.3 a	0.48 a	15.4
	E436×CV	201.0 ef	66.3 b	12.1 b	0.45 a	15.2
	E436×QV	223.0 de	68.8 a	11.1 b	0.46 a	12.6
	E568×VA	273.4 ab	64.6 b	5.5 c	0.31 b	14.7
	E568×CV	285.0 a	65.4 b	5.2 c	0.26 bc	12.1
	E568×QV	260.0 bc	65.7 b	7.0 c	0.28 bc	10.7
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.05</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>
2022	E314	121.4 c	49.8 c	6.0 b	0.28	10.4 b
	E436	218.2 a	64.4 a	8.2 a	0.32	12.6 a
	E568	183.1 b	60.3 b	7.6 a	0.28	12.3 a
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>	<i>< 0.01</i>
	Vase	170.7 b	57.7 b	7.3	0.29	11.5
	Catalan Vase	161.2 c	57.1 b	7.3	0.32	11.7
	Quad-V	190.8 a	59.8 a	7.3	0.29	12.1
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>
	E314×VA	122.6 d	50.1 e	5.9 c	0.29	10.2
	E314×CV	119.7 d	49.3 e	6.7 bc	0.32	9.8
	E314×QV	121.9 d	50.1 e	5.3 c	0.26	11.2

Year	Cultivar Training System Cultivar×System	Fruit weight (g)	Fruit diameter (mm)	Fruit firmness (kg cm ⁻²)	TA (%)	SSC (°Brix)
	E436× VA	199.3 b	61.8 c	8.6 a	0.31	12.4
	E436×CV	201.3 b	63.6 b	7.6 ab	0.34	12.4
	E436×QV	254.0 a	67.8 a	8.4 a	0.30	12.9
	E568 ×VA	190.6 b	61.1 c	7.3 ab	0.27	12.0
	E568×CV	162.5 c	58.5 d	7.5 ab	0.28	12.8
	E568×QV	196.7 b	61.4 c	8.1 ab	0.30	12.2
	<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.05</i>	<i>ns</i>	<i>ns</i>

Different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test, E= Extreme®, ns = non-significant, VA = Vase, CV = Catalan Vase, QV = Quad-V.

In 2021, there was a significant difference among cultivars in terms of all fruit characteristics. In 2021, the largest fruits were produced by the late cultivar 'Extreme® 568,' followed by 'Extreme® 436' and 'Extreme® 314'. This year, the mid-season cultivar 'Extreme® 436' produced fruits with the highest fruit firmness, titratable acidity, and SSC, while these parameters were lower in the early cultivar 'Extreme® 314'. There were statistically significant differences in fruit weight, diameter, and firmness among the training systems, but no differences in acidity or SSC. Among the training systems, the largest and firmest fruits were obtained from trees trained in the Vase system. Similarly, Uberti et al. [17] reported that fruit sizes and fruit weight were larger in the Central Leader system than in the Vase and Ypsilon (Y system) systems. And also, Taylor [24] informed that fruit sizes were close to each other in Vase and Quad-V systems. However, Robinson et al. [24] stated that average fruit weight was negatively affected by planting systems. In the trial, statistically significant differences were observed in the cultivar × training system interaction for fruit weight, diameter, firmness, and acidity. Examining the cultivar × training system interactions, the heaviest fruits were recorded in the 'Extreme® 568' × Catalan Vase combination, while the firmest fruits with the highest acidity were found in the 'Extreme® 436' combinations.

In 2022, there was a significant difference among cultivars in terms of fruit weight, diameter, fruit firmness, and SSC. The largest and hardest fruits were obtained from the 'Extreme® 314.' In 2022, there was a significant difference among training systems in terms of fruit weight and diameter. Among the training systems, the largest fruits were obtained from the Quad-V system. In 2022, there was a significant difference between the cultivar × training system interaction in terms of fruit weight, diameter, and hardness, while there was no difference in terms of acidity and SSC. Examining the cultivar × training

system interactions, the heaviest and firmest fruits were recorded in the 'Extreme® 436' × Quad-V combination.

Table 3
Fruit skin colour values of training systems and cultivars

Cultivar	2019			2021			2022		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
Extreme®314	65.57	12.56	17.31	36.21 b	24.00 a	24.18 b	25.0 c	18.2 b	21.4 a
Extreme®436	61.56	12.68	17.25	57.37 a	19.51 b	30.12 a	34.9 b	21.2 a	12.8 c
Extreme®568	62.69	12.47	17.32	35.66 b	13.98 c	15.53 c	40.3 a	17.8 b	18.0 b
Probability	ns	ns	ns	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Training system									
Vase	32.44 c	22.85 a	10.49 c	41.78 b	19.76	20.42	32.25	20.29 a	16.01 b
Catalan Vase	74.82 b	9.03 b	26.58 a	45.39 a	19.42	24.38	33.92	19.89 a	15.12 b
Quad-V	82.56 a	5.83 c	14.81 b	42.06 b	18.32	25.02	34.20	17.14 b	21.18 a
Probability	< 0.01	< 0.01	< 0.01	< 0.05	Ns	ns	ns	< 0.01	< 0.01
Cultivar × Training system interaction									
E314VA	34.25 d	22.33 a	12.91 bc	36.63 c	24.10 a	21.63 bcd	27.11 e	19.08	21.42
E314CV	76.95 bc	9.52 b	25.74 a	36.18 c	23.67 a	21.98 bcd	27.22 e	19.32	17.39
E314QV	85.53 a	5.83 c	13.27 bc	35.71 c	24.09 a	29.64 b	20.93 f	16.37	25.53
E436 VA	30.61 d	22.66 a	8.35 c	51.99 b	17.65 b	40.78 a	31.21 d	21.44	9.31
E436CV	72.76 c	9.64 b	27.23 a	69.61 a	23.58 a	24.34 bc	34.86 c	21.91	11.57
E436QV	81.32 ab	5.75 c	16.18 b	50.50 b	17.32 b	25.23 bc	38.84 b	20.2	17.62
E568 VA	32.47 d	23.56 a	10.20 bc	36.64 c	16.36 bc	14.13 cd	38.44 b	19.15	17.32
Different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test, E= Extreme®, ns = non-significant, VA = Vase, CV = Catalan Vase, QV = Quad-V									

Cultivar	2019			2021			2022		
	L*	a*	b*	L*	a*	b*	L*	a*	b*
E568CV	74.76 c	7.95 bc	26.78 a	30.77 d	12.02 d	11.40 d	39.68 ab	19.64	16.39
E568QV	80.84 ab	5.92 c	14.98 bc	39.96 c	13.55 cd	21.07 bcd	42.84 a	14.79	20.38
<i>Probability</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>< 0.01</i>	<i>ns</i>	<i>ns</i>
Different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test, E= Extreme®, ns = non-significant, VA = Vase, CV = Catalan Vase, QV = Quad-V									

While no statistically significant difference was observed among cultivars in terms of fruit skin colour in 2019, a significant difference occurred among the training system and the cultivar × training system interaction. However, considering the L* value (brightness), fruits from the Quad-V system were found to be brighter than those from the other two systems. Similarly, Lal et al. [26] reported in their study that the fruits with the highest L* values in the 'Fantasia' nectarine cultivar were in the Quad-V system and the lowest values were in the Vase system. Regarding the a* value (redness), fruits from the Vase system were redder, while the b* value (colour transition from blue to yellow) was found to be higher in fruits in the Catalan Vase system. Indeed, DeJong et al. [12] reported that the vase system tends to produce darker coloured fruit. When examining the cultivar × training system interactions, the brightest fruits (highest L* value) were obtained from the 'Extreme® 314' × Quad-V combination. The reddest fruits were observed in the 'Extreme® 314' × Vase, 'Extreme® 436' × Vase, and 'Extreme® 568' × Vase systems, while the most pronounced blue-to-yellow transition occurred in the Catalan Vase combinations (Table 3).

In 2021, the brightest fruits (highest L* value) were obtained from the mid-season cultivar 'Extreme® 436,' while the reddest fruits (highest a* value) were from the early cultivar 'Extreme® 314.' Additionally, 'Extreme® 436' exhibited the most pronounced transition from blue to yellow (b* value). Among the training systems, the best results were obtained with the Catalan Vase system. However, there were no significant differences among the training systems for the a* and b* values. Regarding cultivar × training system interactions, the brightest fruits were primarily observed in the Vase, Vase-Catalan, and Catalan Vase combinations. The reddest fruits were associated with 'Extreme® 314' combinations and the 'Extreme® 436' × Catalan Vase interaction. The most notable blue-to-yellow transition was recorded for the 'Extreme® 436' × Vase combination (Table 3).

In 2022, the brightest fruits (highest L* value) were obtained from the late cultivar 'Extreme® 568,' followed by the mid-season cultivar 'Extreme® 436' and the early cultivar 'Extreme® 314.' The reddest fruits were observed in 'Extreme® 436,' while 'Extreme® 314' exhibited the most pronounced transition from blue to yellow. Among the training systems, there were no statistically significant differences in fruit brightness (L* value). However, the best green-to-red transition (a* value) occurred in the Vase and

Catalan Vase systems, while the most pronounced blue-to-yellow transition (b^* value) was observed in the Quad-V system. While the L value was found to be significant in terms of cultivar $\times$ training system interaction, there was no difference among the interactions in terms of 'a' and 'b' values. However, the brightest fruits were obtained from 'Extreme® 568' $\times$ Quad-V interaction. No statistically significant differences were observed in the a^* and b^* values among the interactions (Table 3).

The effect of training systems on fruit colour was not consistent throughout the trial.

Conclusion

Peach production is traditionally based on the vase (goble) training system; however, this system presents several limitations, including intensive pruning requirements, increased tree height, higher labor costs, lower planting density, and reduced yield efficiency per unit area. Despite these drawbacks, the adoption of alternative training systems has remained limited, largely due to insufficient scientific evidence and limited practical experience among growers.

The present study provides empirical evidence supporting the advantages of modern training systems. The Catalan Vase and Quad-V systems demonstrated clear improvements in vegetative growth, canopy structure, fruit quality, and overall productivity compared to the traditional Vase system. In particular, the cultivar 'Extrem 436' exhibited superior performance in these systems, achieving higher yield potential and more uniform growth. Improved light distribution within the canopy appears to be a key mechanism underlying these benefits, contributing to enhanced fruit development and quality.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

D.S.: data curation and writing-original draft, analysis and interpretation; İ.M.: data curation, pruning and formation of training systems, investigation; D.E.D.: data curation; A.L.: data curation; R.B.O.: pruning and formation of training systems, conceptualization, investigation; Ü.E.: project administration, methodology; M.A.C.: statistical analysis; B.A.: data curation; H.D.: conceptualization, methodology, interpretation, writing-review and editing; All authors have read and agreed to the published version of the manuscript.

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Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

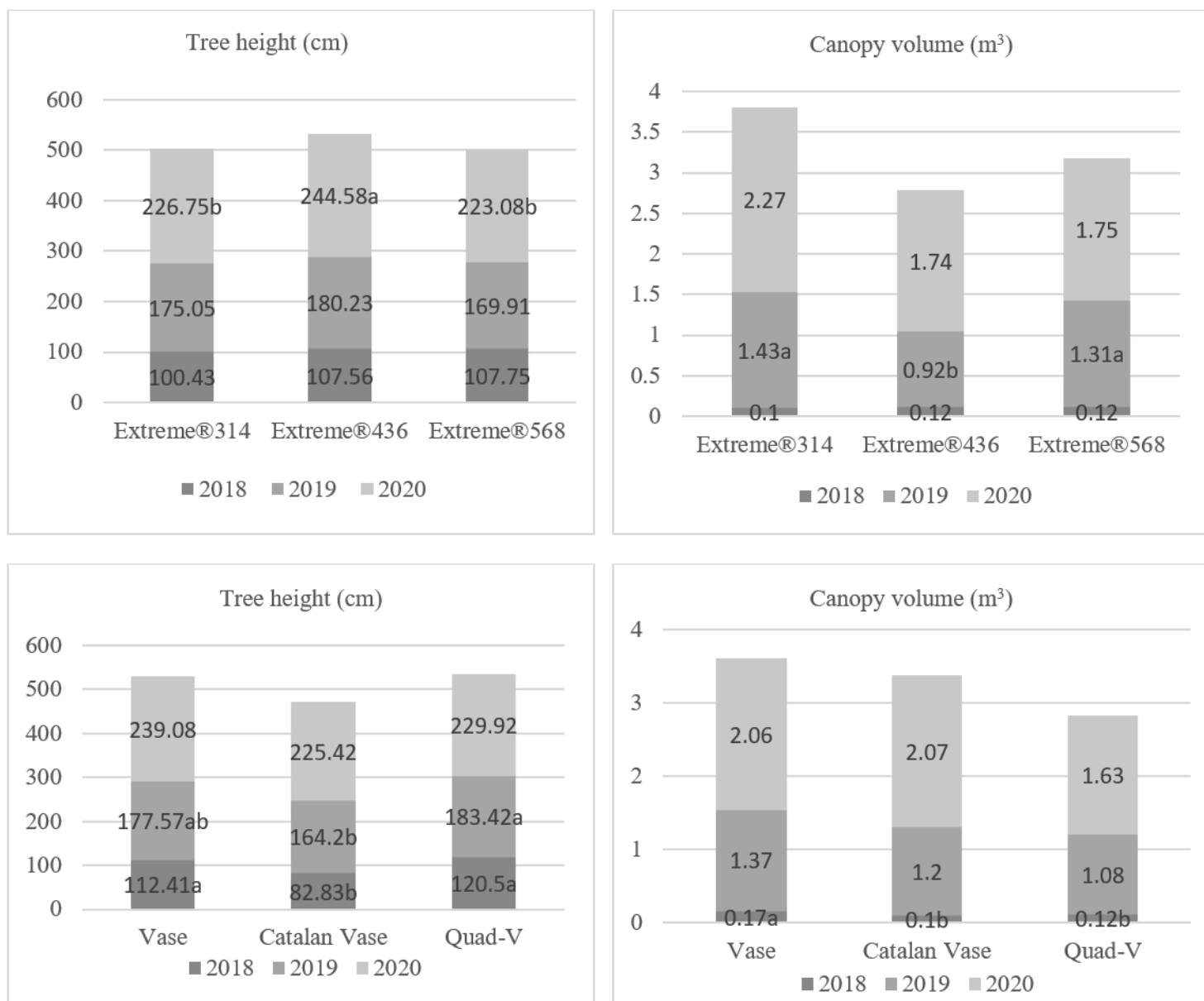


Figure 1

Tree height (cm) and canopy volumes (m³) of training systems and cultivars (different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

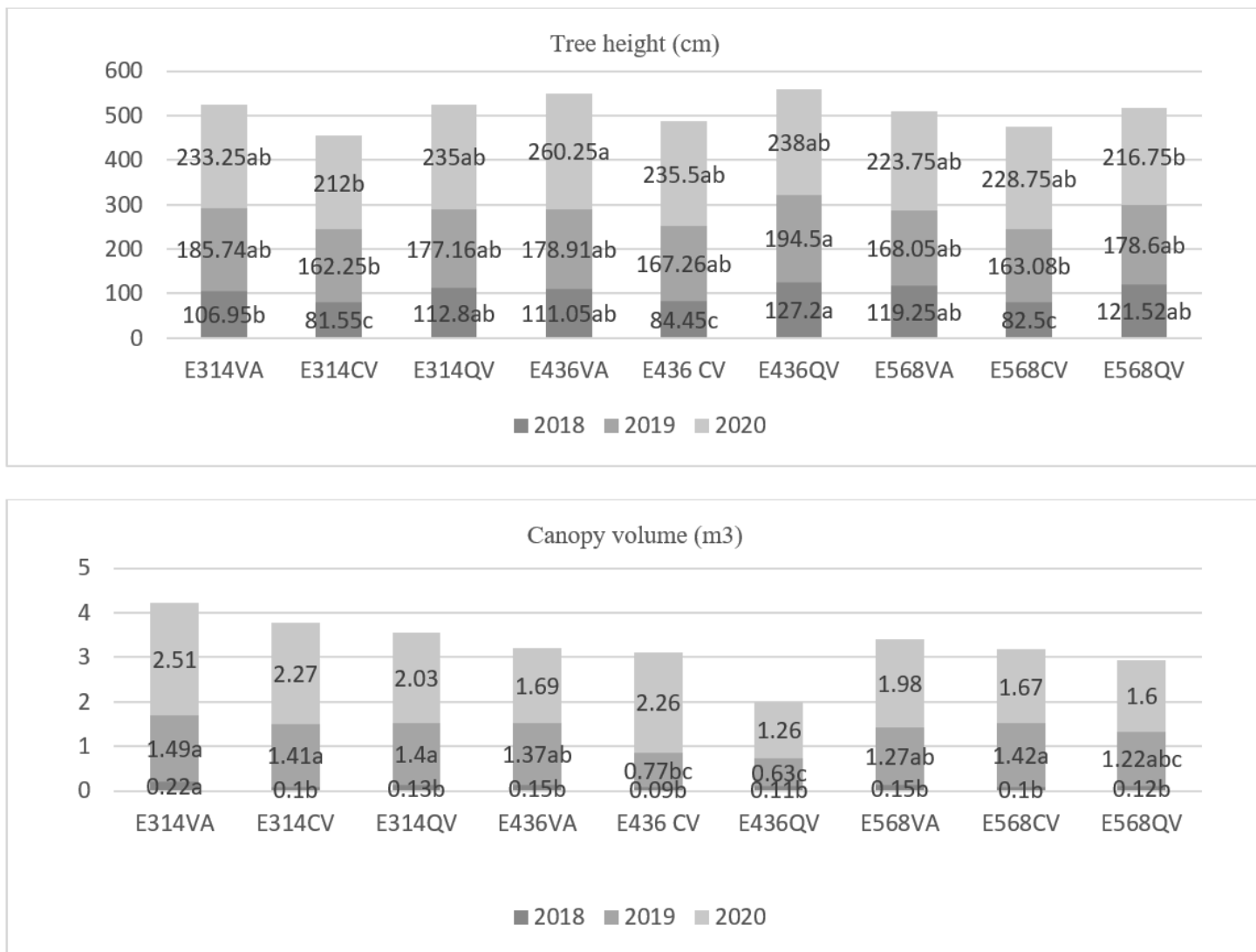


Figure 2

Tree height (cm) and canopy volumes (m³) of cultivar × training system interactions (E= Extreme®, VA = Vase, CV = Catalan Vase, QV = Quad-V, different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

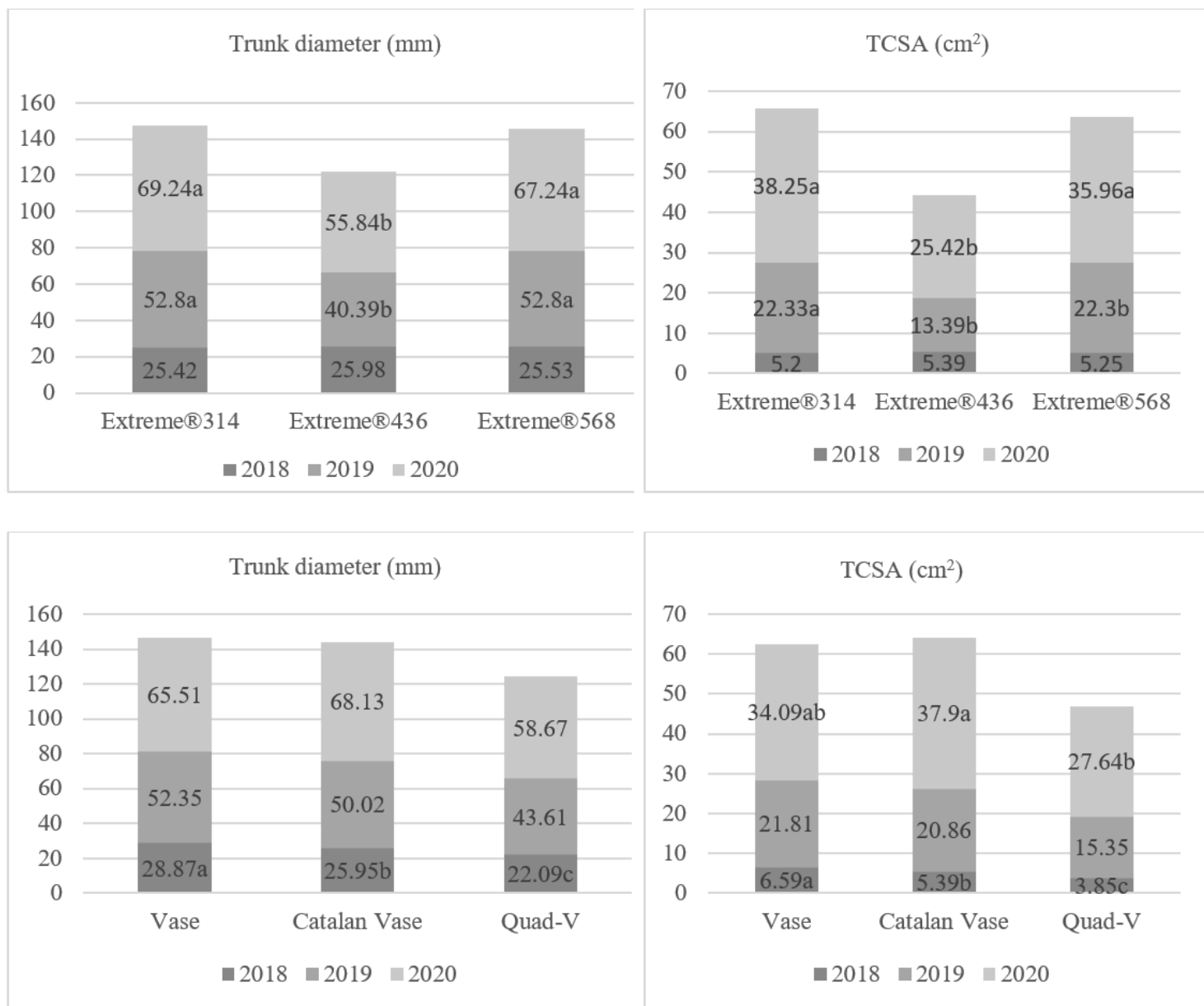


Figure 3

Trunk diameter (mm) and TCSA (cm²) of training systems and cultivars (Different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

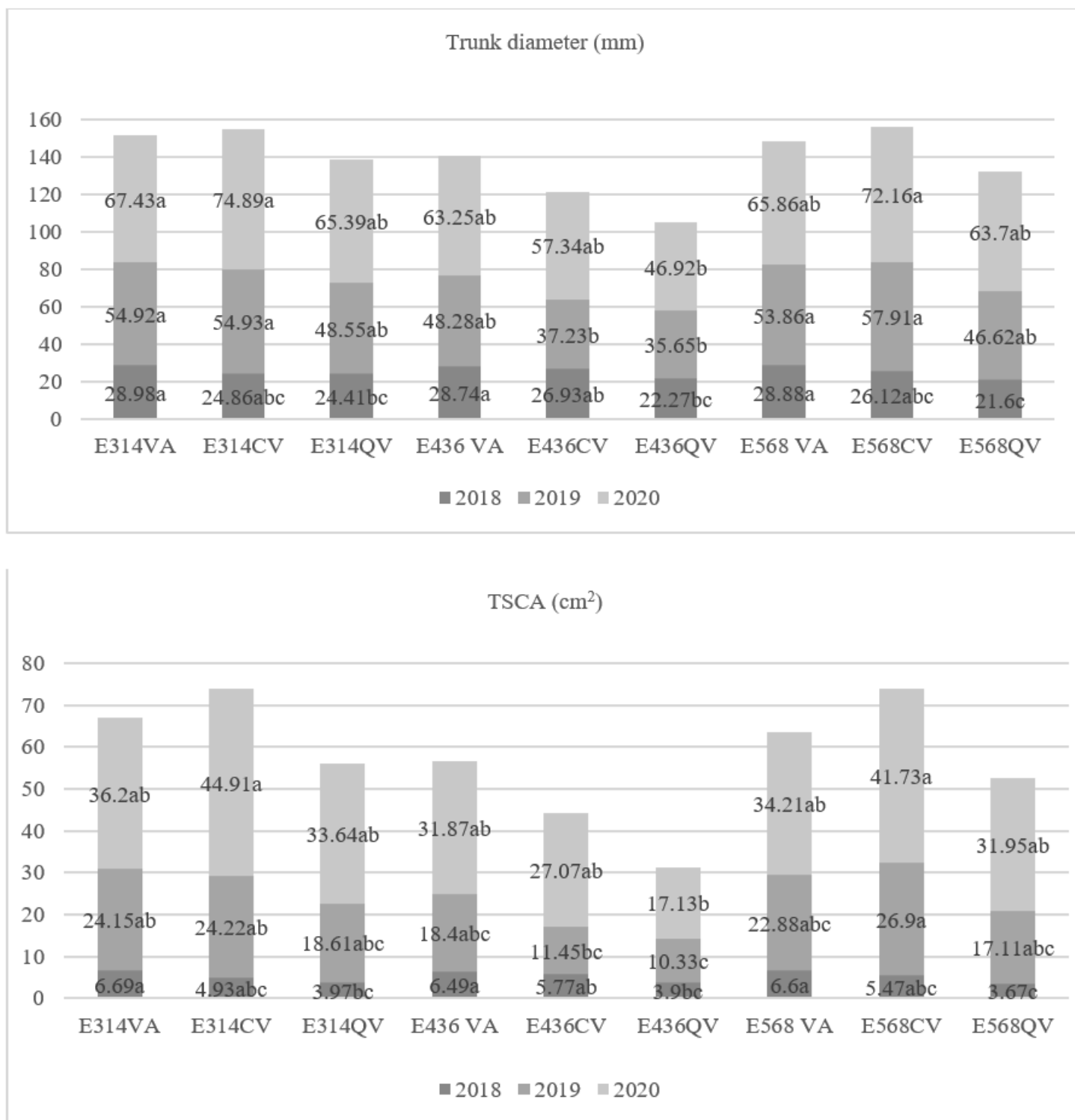


Figure 4

Trunk diameter (mm) and TSCA (cm²) of cultivar × training system interactions (E= Extreme®, V = Vase, CV = Catalan Vase, QV = Quad-V, different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

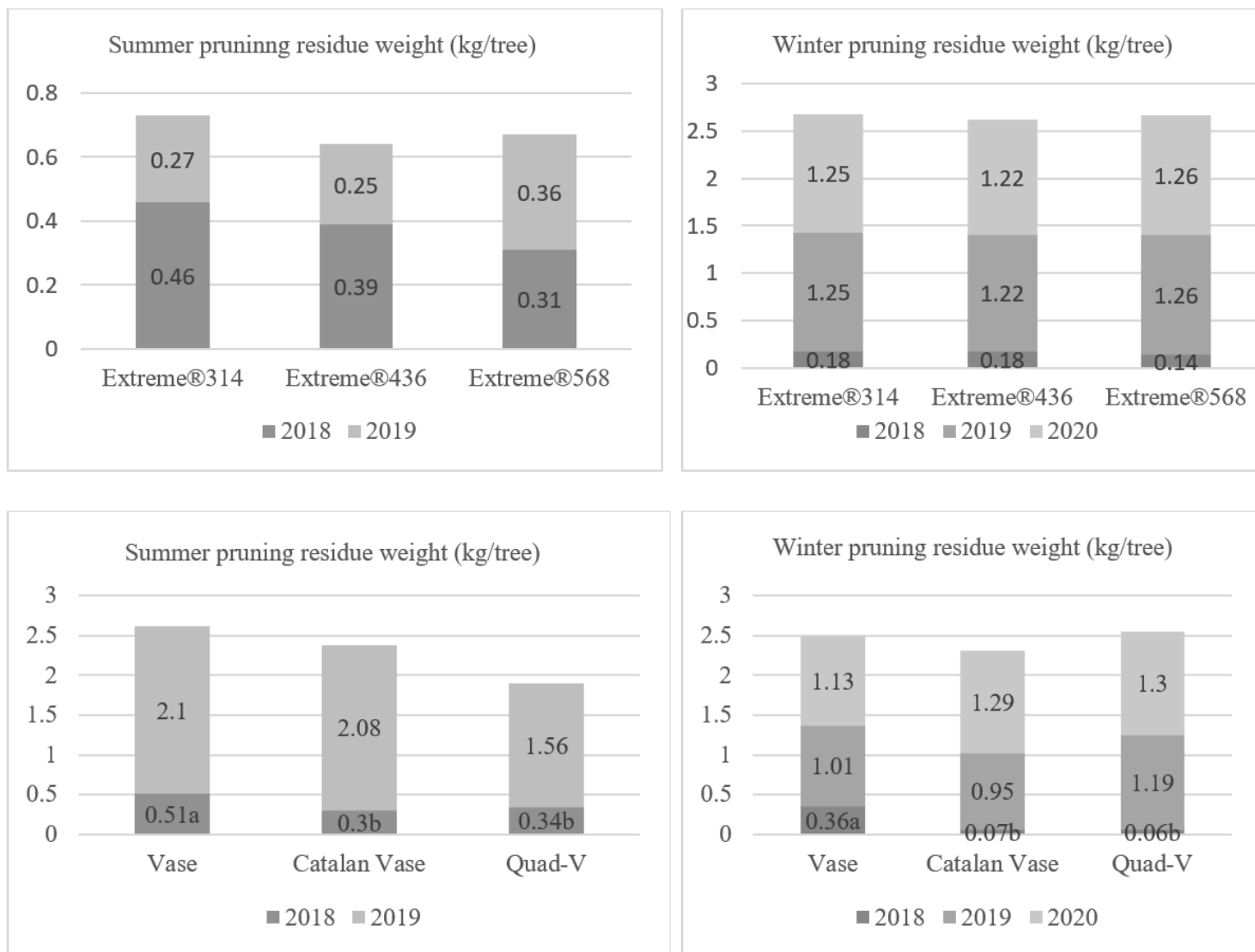


Figure 5

Summer and winter pruning weight (kg/tree) of training systems and peach cultivars (Different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

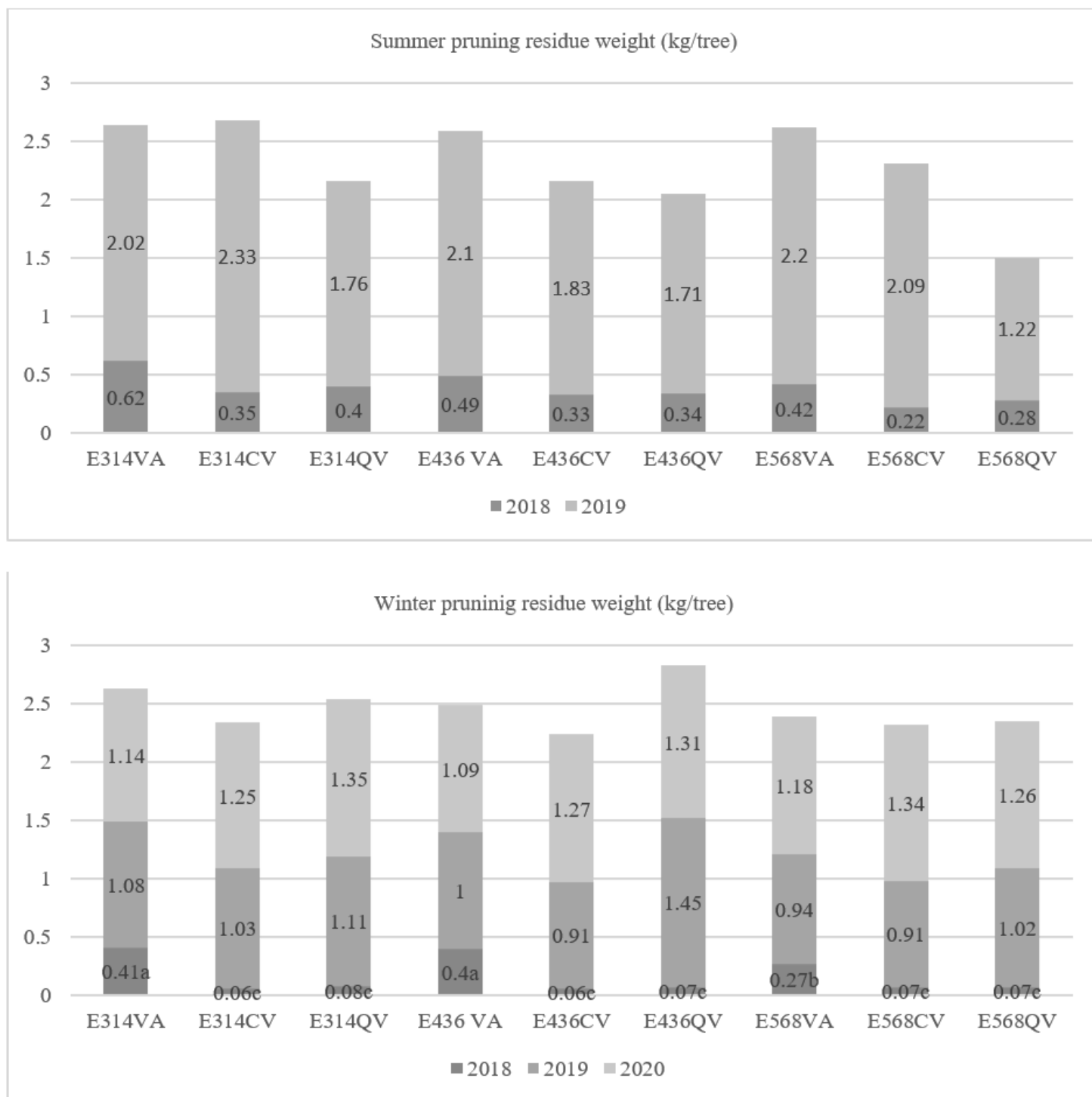


Figure 6

Summer and winter pruning weight (kg/tree) of cultivar × training system interactions (E= Extreme®, VA = Vase, CV = Catalan Vase, QV = Quad-V, different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

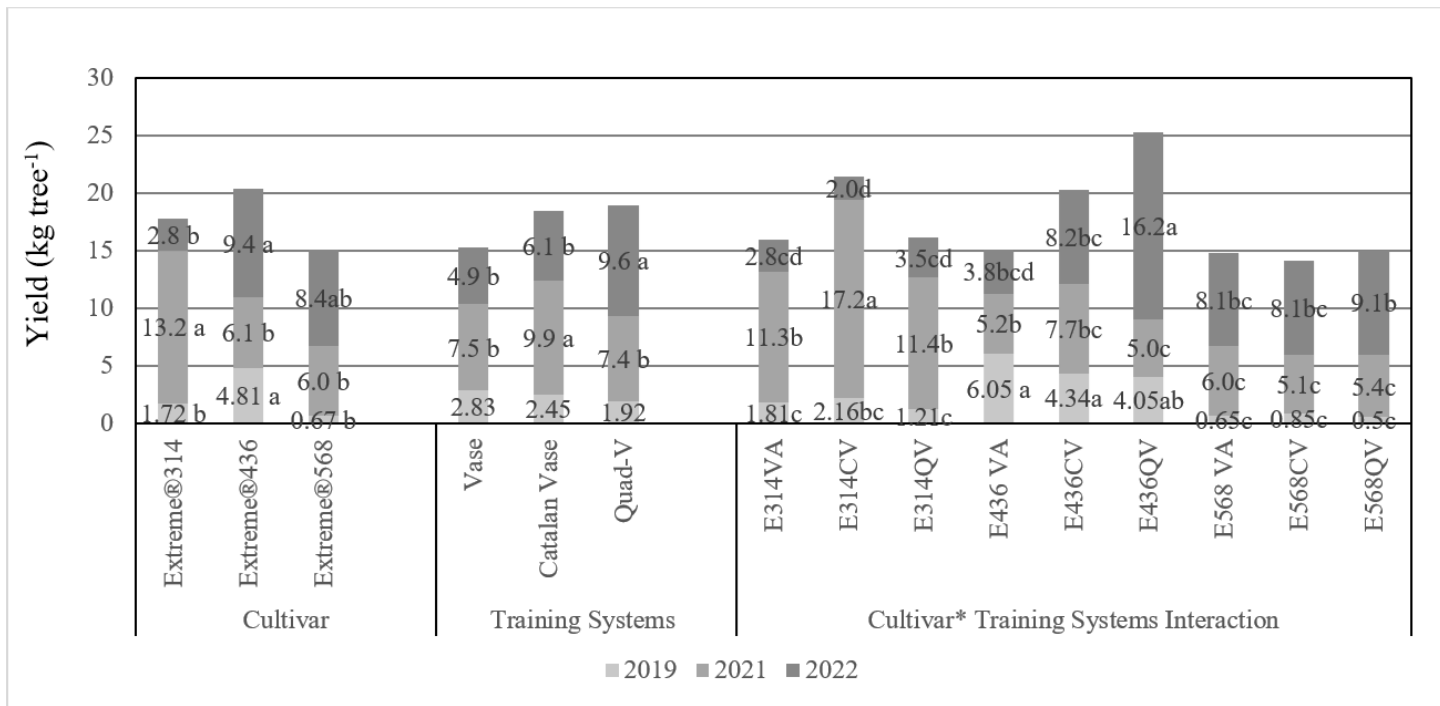


Figure 7

Yield (kg tree⁻¹) values for 2019-2022 according to training systems and cultivars (E= Extreme®, VA = Vase, CV = Catalan Vase, QV = Quad-V, different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).

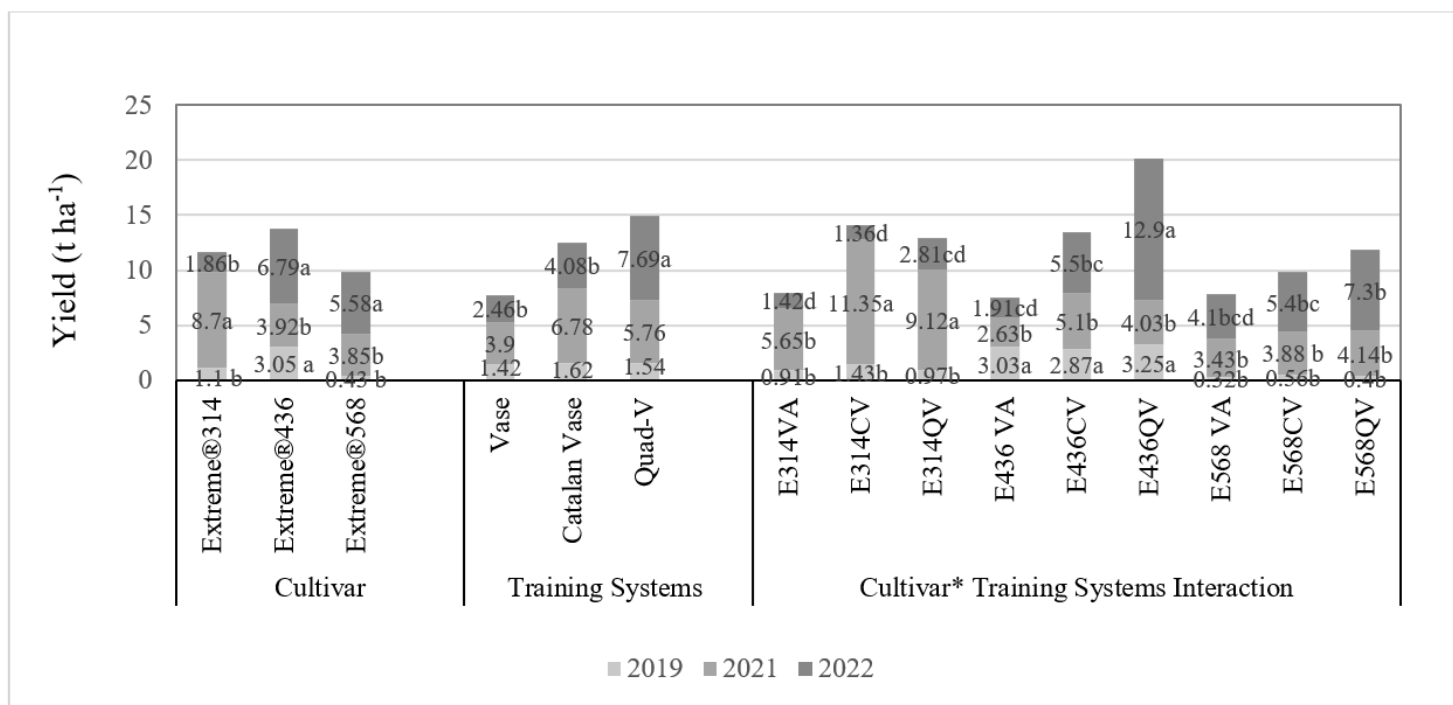


Figure 8

Yield (t ha^{-1}) values for 2019-2022 according to training systems and cultivars (E= Extreme®, VA = Vase, CV = Catalan Vase, QV = Quad-V, different lowercase letters indicate differences between training systems according to cultivars, while uppercase letters indicate cultivar differences according to the Duncan test).