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Original Research Paper

Performance of high-density loquat orchard with quince rootstocks: effects on yield, fruit quality and vegetative growth

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Abstract: This study evaluated the effects of three quince rootstocks (Quince-A, Quince-C, and BA-29) on the flowering, fruit set, yield, fruit quality, and vegetative growth of the 'Hafif Çukurgöbek' loquat (*Eriobotrya japonica* Lindl.) cultivar under Mediterranean climatic conditions. The experiment was conducted in Hatay, Türkiye, between 2018 and 2020 using a factorial arrangement based on a randomized complete block design (RCBD). Each rootstock treatment consisted of 30 trees with six trees per replicate and five replications. Significant effects of the Year, Rootstock, and their interaction were detected for most parameters measured. Frost (–2.5 °C) during flowering and heat stress (42 °C) before harvest in 2020 significantly reduced fruit set and yield. Quince-C and BA-29 rootstocks consistently induced higher flowering and fruit set rates, larger fruit size, and greater fruit yield than Quince-A. Trees grafted on Quince-A induced smaller but sweeter fruits with higher total soluble solids (TSS) and pH. Vegetative growth, including shoot length, trunk diameter, and canopy size, was the most vigorous in trees on Quince-C, followed by those on BA-29, whereas Quince-A reduced tree vigor. These preliminary results suggest that dwarfing quince rootstocks, particularly BA-29 and Quince-C, are suitable for high-density loquat orchards.

Keywords: fruit quality; loquat; quince rootstocks; vegetative growth; yield.

1. Introduction

Loquat (*Eriobotrya japonica* Lindl.) is an evergreen fruit species of the family Rosaceae, typically cultivated under subtropical conditions between latitudes 20° - 35° in both hemispheres. While trees can tolerate winter temperatures down to -10 °C, flowers and fruits are damaged at about -3 °C (Polat, 2023). Global loquat production is approximately 982,000 metric tons, with China contributing 93.6% (919,000 t), followed by Spain (28,836 t) and Türkiye (16,402 t) (Polat, 2021a).

Due to its early ripening period, which coincides with a time when most other fruits are not yet harvested, loquat enjoys high market demand and fetches premium prices. Therefore, loquat is a valuable fruit for both producers and consumers (Polat and Kaşka, 1991; Polat, 1996; Özçağıran et al., 2011). Loquat trees typically grow 5-10 meters tall with large, spreading canopies. The cultivation of such large trees involves high production costs. Controlling tree vigor is essential to reduce these costs, and one of the most effective methods for this is the use of dwarfing rootstocks. Using dwarfing rootstocks allows the adoption of high-density planting, which in turn facilitates pruning, spraying, thinning, and especially harvesting - making the cultivation easier and more cost-effective. Additionally, fruit yield, quality, and marketable output are generally higher.

Many studies have been conducted to identify suitable dwarfing rootstocks for various fruit species (Webster 1980, 1993, 2001; Rom and Carlson,1987; Knowles et al., 1994; Hummer 1998; Franken-Bembenek et al., 1999; Fideghelli, 2002; Reighard, 2002; Jackson, 2003; Webster and Wertheim, 2003; Basile et al., 2003a; Vercammen, 2004 a, b; DeJong et al., 2005; Solari et al., 2006a;

Reighard and Loreti, 2008; Prassinos et al., 2009; DeJong et al. 2011; Brewer and Palmer, 2011; Vercammen and Gomand, 2011; Quartieri et al., 2011; Marini and Fazio, 2017). Among these, studies involving clonal quince rootstocks and their use in pear production have yielded noteworthy results (du Plooy and van Huyssteen, 2000; Loreti et al., 2002; Akçay et al., 2009; Sugar and Basile, 2011; Erdem and Öztürk, 2012; Francescatto et al., 2014; İkinci et al., 2014; Uysal et al., 2015; Küçüker et al., 2015; Askari-Khorasgani et al., 2019; Öztürk, 2021a, 2021b). Clonal quince rootstocks, having potential use as dwarfing rootstocks in loquats, have been successfully used in pear cultivation for many years. However, the number of studies exploring their potential use in loquats is limited and they mainly focused on (a) graft compatibility and success with various wild *Eriobotrya* species (Zhang et al., 2007, 2010, 2011), (b) graft success on loquat seedlings, hawthorn and quince rootstocks (Polat and Kaşka, 1992a, 1992b; Pio et al., 2010; Polat, 2018a, 2019, 2020, 2021b, 2021c), (c) their effects on vegetative growth (Polat and Kaşka, 1992a, 1992b; Polat, 1995; Baratta et al., 2001; Pio et al., 2007), and (d) tolerance to salinity (Garcia-Legaz et al., 2005; Lopez et al., 2007; Manuel et al., 2008). However, identifying suitable dwarfing rootstocks for loquats - as previously done for apples and pears - is necessary to promote high-density cultivation.

Large canopy size on seedling rootstocks is a major constraint to expand loquat cultivation due to increased labor needs, particularly for thinning and pruning. In Spain, the leading exporter country, labor for thinning and harvesting accounts for over 75% of production costs, limiting the cultivation expansion of this fruit tree species (Hueso et al., 2007). High-density planting studies have produced promising results (Polat et al., 2003, 2004; Hueso et al., 2007; Pio et al., 2007; etc.). For instance, the 'Magdal' cultivar grafted onto Quince-C and planted at a 2.5 × 1.7 m spacing had a fruit yield of 2.8 kg tree^{-1} in the second year and of 10.8 and 13.0 kg tree^{-1} in the following two years (Hueso et al., 2007). Small tree size also reduced labor costs for thinning. These results demonstrated that high-density loquat cultivation using dwarf trees is more profitable than standard methods, offering early production, higher yields, and reduced costs.

Therefore, in order to promote high-density loquat cultivation and increase yield per unit area, the use of dwarfing rootstocks is essential. Some studies suggested that quince can be used as a rootstock for loquats (Morton, 1987; Lin et al., 1999; Pio et al., 2007; Hummer and Janick, 2010; Badenes et al., 2013; Polat, 2018b), indicating that trees grafted onto this rootstock exhibit dwarf growth, enter fruiting earlier, mature their fruits earlier, and produce larger and higher-quality fruits (Demir, 1987; Polat and Kaşka, 1992a; Polat, 1995; Baratta et al., 2001). Previous studies (Polat and Kaşka, 1992a, 1992b; Polat, 1995) reported that the use of quince rootstocks results in 20-25% dwarfing compared to loquat seedlings. In a high-density planting experiment on loquats, yields were three to four times higher at a 3 × 3 m spacing compared to 6 × 6 m spacing. Consequently, it was recommended that quince rootstocks - particularly BA-29 - should be tested in high-density loquat plantations (Polat et al., 2003, 2004). Pio et al. (2007) also emphasized that quince is a significant option for loquat cultivation due to its ability to reduce tree size and ease orchard management operations.

Although some literature indicates that quince rootstocks have a dwarfing effect on loquats, the number of studies that evaluate the effects of these rootstocks on fruit yield, quality, and vegetative growth is scarce (Ochse et al., 1961; Hızal et al., 1982; Demir, 1987; Polat and Kaşka, 1992a; Polat, 1995; Lin, 2007). Therefore, a field trial was initiated in 2016 (and still ongoing) to study the effects of clonal quince, hawthorn, and loquat seedling rootstocks on the vegetative growth, flowering phenology, fruit set, fruit quality, and yield of loquat trees. Preliminary data have been reported regarding the effects of these quince rootstocks on the vegetative development, phenological traits, yield, and fruit quality parameters of loquat cultivars, but these results were not conclusive yet (Akkuş and Polat, 2021, 2022). This study presents a comparative analysis of the effects of Quince-A, Quince-C, and BA 29 rootstocks on yield and fruits quality of the 'Hafif Çukurgöbek' loquat cultivar.

2. Material and Methods

2.1. Experimental site and plant material

This study was conducted in Hatay, Türkiye (36°12′E, 36°52′N; 80 m a.s.l.) over three consecutive years: 2018, 2019, and 2020. The experimental site is characterized by a typical Mediterranean climate, with an average annual temperature of 18.3 °C and an annual precipitation of 1168 mm, most of which occurs during winter and spring. The soil at the site is alkaline (pH 7.76), has low levels of lime (2.4%), moderate salinity (EC: 446 µS/cm), and a sandy-loam texture (57.37% sand, 25.32% loam, and 12% clay) (Polat, 2022).

One-year-old 'Hafif Çukurgöbek' loquat trees, budded onto BA-29, Quince-A, and Quince-C rootstocks, were planted in January 2017 at a spacing of 1.0×0.5 m (corresponding to 20,000 trees per hectare) (Figure 1). Drip irrigation and standard horticultural practices were applied throughout the study period (Demir, 1987; Polat, 2023). During the experimental years, trees were trained to a Goble system. However, as the tree canopies began to fill the inter-row spaces, a Tatura Trellis training system was adopted in the following years. Branching was directed along the rows to maintain open inter-row spaces. Vegetative growth of the trees was effectively controlled through pruning and regulated deficit irrigation, which ensured that no orchard management difficulties occurred during the first three years of the experiment. In subsequent years, however, if canopy closure will occur across the inter-row spaces, a stepwise tree thinning strategy will be adopted. Initially, within-row thinning will be performed, adjusting the planting density to 1×1 m (10,000 trees ha^{-1}). At later stages, inter-row and within-row tree thinning will be implemented, ultimately establishing a spacing of 2×2 m (2,500 trees ha^{-1}).

The rootstocks BA-29, Quince-C, and Quince-A used in the experiment were originally selected at the East Malling Research Station, United Kingdom. 'Hafif Çukurgöbek' is an early-maturing loquat cultivar selected in Türkiye (Demir, 1987). It produces medium-sized, orange-colored fruits that are very appreciated by consumers for their taste and sweetness. The cultivar is self-fertile and resistant to black spot disease caused by *Spilocaea eriobotryae*.

2.2. Experimental design

The experiment was conducted in a factorial arrangement based on a randomized complete block design (RCBD). Each rootstock treatment consisted of 30 trees, with six trees per replicate, and five replicates.

2.3. Inflorescence Characteristics, Flowering, and Fruit Set Rate

For each rootstock, ten trees were selected, and four shoots per tree were used for the following measurements: number of peduncles per cluster, number of flower buds per cluster, and number of flowers per cluster. In accordance with the methodology described by Polat (2007, 2015) and Akkuş and Polat (2022), these observations were conducted at approximately 3-day intervals starting when the clusters first became visible on the shoots.

The flowering rate (%), initial fruit set (%), and small and final fruit set ratios (%) were calculated according to the methods proposed by Westwood (1995) and Polat (2007, 2015). To determine fruit set rate, four branches were selected randomly (one in each cardinal direction) and were tagged. Approximately 250-300 flower buds were counted at the pre-blossom phase on each of the selected branches. Thus, ca. 1000-1200 flower buds were selected on each tree. The flowers of each tagged branch were counted and blossom rate was calculated as the proportion of the flower to bud number. At the end of blossoming, the number of initial fruits was counted and initial fruit set percentage was calculated dividing this value by the flower number. Final fruit set percentage was determined by calculating the proportion of the number of harvested fruits to the number of flowers.

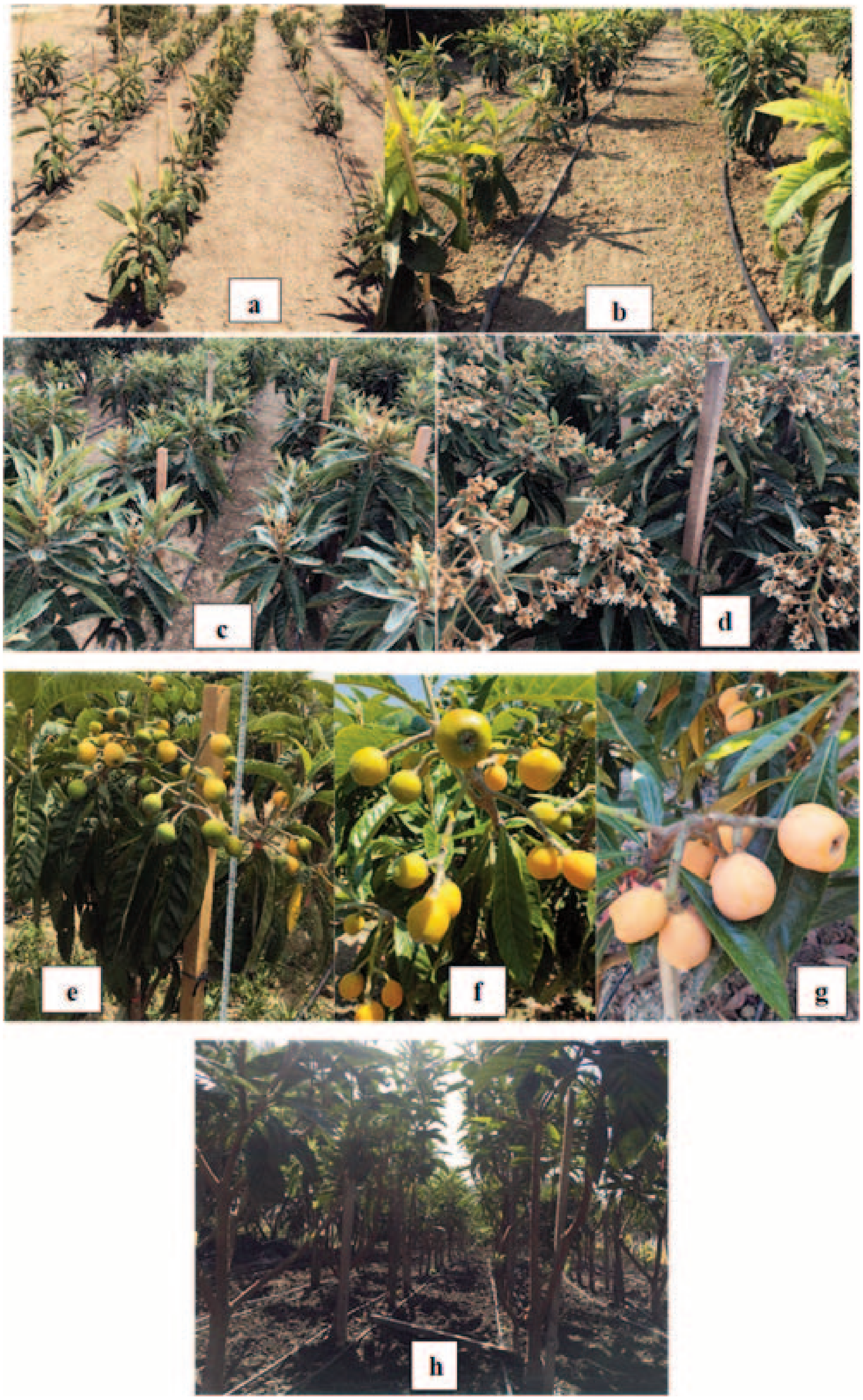

Figure 1. Successive development stages of the experimental high-density orchard of 'Hafif Çukurgöbek' loquat: (a) Planting; (b) Irrigation and soil tillage; (c) Elongation of flower cluster branches; (d) Full bloom; (e-g) Fruit maturation stages; (h) Current orchard condition.

2.4. Measurements of Pomological Characteristics and Fruit Composition at harvest

At harvest, fifty fully ripe fruits exhibiting cultivar-specific fruit color (100% orange skin color) were randomly selected from each cultivar/rootstock combination (10 fruits per replicate). These fruits were then randomly divided into five groups of ten fruits each, and the following physical and chemical measurements were performed according to Polat et al. (2010) and Durgaç et al. (2006). Each fruit was weighed with a digital scale (BJ 2200C, Precisa Gravimetrics AG, Dietikon, Switzerland). Fruit width and length were measured with a digital caliper (Mitutoyo, Kawasaki, Japan) with 0.01 mm sensitivity. The data were used to calculate the fruit width to length ratio. Then, seeds were removed, counted, and their fresh weight was measured separately with a digital scale (BJ 2200C, Precisa Gravimetrics AG, Dietikon, Switzerland). The fruit pulp to seed weight ratio was calculated according to the equation: (mean fruit fresh weight - mean seed fresh weight)/ mean seed fresh weight). Fruit juice was obtained by blending fruit pulps (after removing the seeds). Soluble solids were measured with a hand-held refractometer (NOW 507-1, Nippon Optical Works. Co. Ltd., Tokyo, Japan), with a brix scale of 0-32, wheras fruit juice pH was measured with a digital pH meter (HI 8521, Hanna Instruments, Woonsocket, RI, USA). Fruit juice acidity (expressed as % malic acid) was determined by titration adding a 0.1 N NaOH solution to an endpoint of pH 8.10.

2.5. Vegetative Growth Measurements

Tree vegetative growth was assessed at three-month intervals beginning in February 2018, measuring the following parameters:

- Annual shoot length (cm): The length of four shoots per tree (one for each cardinal direction) was measured with a 5-meter measuring tape.
- Trunk diameter (mm): Trunk diameters of both the scion and rootstock (5 cm above and below the graft union) were measured with a digital caliper (Mitutoyo, Kawasaki, Japan) with 0.01 mm sensitivity.
- Crown height (cm): The vertical distance between the first branching point of the scion (or tree trunk) and the trees apex was measured with a 5-meter measuring tape.
- Tree height (cm): The vertical distance between the bud union and the tree apex was measured with a 5-meter measuring tape.

2.6. Yield Measurements

Total fruit yield of each tree (kg/tree) was separately determined by weighing the harvested fruits with a digital scale (JCS-B, Ningbo Develo Precision Mac Co., Ltd, Beilun, Ningbo, China). To calculate fruit yield per trunk cross-sectional area (g fruit per mm^2 trunk cross-sectional area, TCSA), the total fruit yield per tree was divided by TCSA measured 5 cm above the graft union at harvest time (in May) of each year. Fruit yield per hectare was calculated multiplying fruit yield per tree by the number of trees per hectare.

2.7. Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using the RCBD model. When significant differences were detected, mean separations were performed with Tukey's Honestly Significant Difference (HSD) test at a probability level of 5% ($p < 0.05$) (Steel and Torrie, 1980). Percentage values were subjected to angular (arcsine) transformation prior to ANOVA. All statistical analyses were carried out using the SPSS software package (SPSS 23.0, IBM, Chicago, IL, USA).

3. Results and Discussion

3.1. Inflorescence Characteristics, Flowering, and Fruit Set Rate

3.1.1. Inflorescence Traits

The results presented in Table 1 show that the Year had significant effects on the number of peduncles per cluster, flower buds, and flowers per inflorescence. The lowest numbers of flower buds (108) and flowers (97) were observed in 2018, whereas the highest values were recorded in 2019. This pattern may be attributed to more favorable climatic conditions for flower differentiation in 2019; however, the climatic conditions of the previous year may also have contributed to enhance flower initiation and differentiation in 2019. The decline in the number of flower buds and flowers in 2020 can be attributed to the frost event recorded at –2.5 °C during the flowering period.

Trees on Quince-C produced significantly higher number of peduncles per cluster than BA-29 (Table 1). Although other parameters did not differ significantly among rootstocks, the effect of the Year × Rootstock interaction was significant for all three variables ($p < 0.01$), indicating that rootstock performance varied across years due to environmental fluctuations.

The number of studies evaluating comprehensively inflorescence characteristics, flowering behavior, and fruit set rates for trees grafted onto the rootstocks used in our research is fairly limited. Akkuş and Polat (2022) and Polat and Sezer (2022) reported that, in trees grafted onto the Quince-A rootstock, the number of peduncles per cluster ranged between 12.8 and 17.7, the number of flower buds per cluster ranged between 172.2 and 128.0, and the number of open flowers ranged between 150.3 and 102.5. In the same studies, these parameters were reported to be, respectively, 10.5-19.5, 133.2-156.5, and 124.8-143.8 for trees on Quince-C rootstock, and 10.8-16.7, 131.8-143.2, and 119.4-132.6 for trees on BA-29 rootstock. In an earlier study, the numbers of peduncles, flower buds, and open flowers were reported to be, respectively, 9.0, 123.3, and 115.3 in trees grafted onto hawthorn rootstock, and 10.3, 156.9, and 139.6 in trees grafted onto loquat seedling rootstock (Polat, 2023). These values are substantially similar to those obtained in the present study.

3.1.2. Flowering Rate (%)

The effect of the Year on flowering rate was not significant. Nevertheless, mean flowering rates were slightly higher in 2018 (91.0%) and 2020 (90.4%) compared to 2019 (86.4%) (Table 1). Rootstock effect on this parameter was highly significant ($p < 0.01$) with trees on Quince-C (91.9%) and BA-29 (93.1%) exhibiting higher flowering rates than those on Quince-A (82.9%). This suggests that Quince-A restricted vegetative growth and partially reduced flowering potential. Polat and Sezer (2022) reported flowering rates of 91.6%, 93.5%, and 90.7% for trees grafted onto Quince-A, Quince-C, and BA-29 rootstocks, respectively, while Akkuş and Polat (2022) found, for trees grafted onto same rootstocks, values of 80.1%, 91.9%, and 92.7%, respectively. In another study, the flowering rate was 93.5% in plants grafted onto hawthorn rootstock and 89.0% in those grafted onto loquat seedling rootstock (Polat, 2023). The findings obtained in our study are consistent with these reported values.

3.1.3. Initial Fruit Set (%)

Initial fruit set showed significant differences among years and was affected by the Year × Rootstock interaction (Table 1). The highest fruit set (14.02%) was observed in 2018, whereas this parameter decreased to around 9.8-9.6% in 2019 and 2020. This reduction might be due to increased vegetative growth in later years, which may have affected negatively the flower-to-fruit conversion rate (Webster et al., 2000; Reyes et al., 2016; Albarracín et al., 2017). Although differences among rootstocks were not statistically significant ($p > 0.05$), trees on Quince-A displayed slightly higher initial fruit set than BA-29 and Quince-C. Previous studies have reported that the initial fruit set rate ranged between 8.4% and 13.8% in trees on Quince-A rootstock, between 9.8% and 11.0% in trees on Quince-C, and between 10.5% and 10.9% in trees on BA-29 (Akkuş and Polat, 2022; Polat and Sezer, 2022). In another study, this parameter was found to be 11.2% in trees grafted onto hawthorn rootstock, and 10.0% in those grafted onto loquat seedling rootstock (Polat, 2023). The findings obtained in our study are consistent with these previous reports.

3.1.4. Percent of Small Fruit (%)

The proportion of small fruits varied significantly among years and was affected by the Year × Rootstock interaction (Table 1). The highest percentage was found in 2018 (8.7%), while in 2019 and 2020 values were significantly lower (5% and 5.3%, respectively). Although differences between rootstocks in this parameter were not statistically significant, trees on Quince-A tended to have higher percentage of small fruit, suggesting possible limitations in resources allocation to fruit. Akkuş and Polat (2022) and Polat and Sezer (2022) reported small fruit ratios ranging between 4.5% and 8.0% for trees on Quince-A, between 5.3% and 6.3% for trees on Quince-C, and between 6.1% and 6.2% for trees on BA-29 rootstocks. Polat (2023) found that the small fruit ratio was 7.9% and 5.6% in trees on hawthorn rootstock and loquat seedling rootstock, respectively.

Table 1. The effects of rootstocks on the inflorescences properties, blossoming and fruit set rates of 'Hafif Çukurgöbek' loquat cultivar (2018-2020).

Source of variation	No. of peduncle per cluster	No. of flower buds per cluster	No. of flowers per cluster	Flowering Rate (%)	Initial fruit set (%)	Small fruit (%)	Final fruit (%)
Year							
2018	12. 7 b[x]	108.2 c	97.6 c	91.0	14.0 a	8.7 a	4.1
2019	23.2 a	177.0 a	155.0 a	86.4	9.8 b	5.0 b	3.9
2020	11.1 c	145.7 b	131.5 b	90.4	9.6 b	5.3 b	3.8
Significance	**	**	**	NS[y]	**	**	NS
Rootstock							
Quince-A	15.8 ab	142.7	118. 5	82.9 b	12.0	6.9	2.5 b
Quince-C	16.5 a	148.8	137.5	91.9 a	10.6	6.0	4.6 a
BA-29	14.7 b	139.4	128.2	93.1 a	10.8	6.2	4.8 a
Significance	**	NS	NS	**	NS	NS	**
Year × Rootstock							
2018-Quince-A	12.7 a	114.9 a	98.6 b	86.3 b	20.2 a	12.3 a	1.6 b
2018-Quince-C	12.8 a	106.1 b	91.5 c	87.4 b	12.2 b	7.7 b	5.8 a
2018-BA-29	12.4 a	103.6 c	102.8 a	99.3 a	9.7 c	6.2 b	4.9 a
2019-Quince-A	22.6 b	141.1 c	106.5 c	75.2 b	7.4 c	3.7 b	2.8 b
2019-Quince-C	26.1 a	207.0 a	196.2 a	94.9 a	9.8 b	5.0 ab	4.3 a
2019-BA-29	20.9 b	182.8 b	162.5 b	89.2 a	12.1 a	6.1 a	4.5 a
2020-Quince-A	12.1 a	172.2 a	150.3 a	87.1 a	8.4 b	4.5 b	3.0 c
2020-Quince-C	10.5 a	133.2 b	124.8 a	93.5 a	9.8 ab	5.3 ab	3.7 bc
2020-BA-29	10.8 a	131.8 b	119.4 a	90.7 a	10.5 a	6.1 a	4.9 a
Significance	**	**	**	*	**	**	**

[x] Means within each column followed by different letters are significantly different according to Tukey's HSD test at $p < 0.05$. [y] NS: Not significant.

3.1.5. Final Fruit Set (%)

The final fruit set rate was significantly affected by The Rootstock and the Year × Rootstock interaction ($p < 0.01$), while the effect of the Year on this parameter was not significant. Trees on BA-29 (4.8%) and Quince-C (4.6%) exhibited higher fruit retention compared to those on Quince-A (2.5%), suggesting that trees on Quince-A, despite a relatively high flowering rate, were more prone to fruit drop. Previous studies (Akkuş and Polat, 2022; Polat and Sezer, 2022) reported that the final fruit set (fruit harvested) rates were 2.2–3.0%, 3.7–5.2%, and 4.7–4.9% for trees on Quince-A, Quince-C, and BA-29 rootstocks, respectively. Polat (2023) found that the final fruit set rates was 6.3% in plants grafted onto hawthorn rootstock, and 4.2% in those grafted onto loquat seedling rootstock.

Overall, Quince-C and BA-29 rootstocks induced the highest overall performance in terms of flowering and fruit set, confirming that these rootstocks are more suitable for the 'Hafif Çukurgöbek' loquat cultivar. These findings are consistent with previous studies by Polat et al. (2004), Durgaç et al. (2006), Polat (2018), Akkuş and Polat (2022), and Polat and Sezer (2022), who reported significant effects of quince rootstocks on loquat flowering intensity and fruit set.

3.2. Fruit quality

Significant differences were found among years for fruit weight, width, and length, with 2019 and 2020 showing larger fruit size than 2018 (Table 2). This increase likely reflects an improvement of tree maturity and productivity over time. Seed weight reached its maximum in 2019 and its minimum in 2020, probably due to a higher number of seeds per fruit in 2020 (5.8). The flesh-to-seed ratio was lowest in 2018 and higher in the subsequent years, indicating improved flesh development.

Total soluble solids (TSS) content was highest in 2018 (12.9%) and lowest in 2020 (10.1%) (Table 2), possibly due to differences among years in the weather conditions during fruit ripening. Titratable acidity was highest in 2019 and lowest in 2020, while pH showed the opposite trend, remaining higher in 2018 and 2019, and lower in 2020.

Rootstock effect was significant on most fruit quality parameters (Table 2). The highest fruit weight was obtained in trees grafted onto the Quince-C (22.9 g) and BA-29 (21.8 g) rootstocks, while the lowest values were recorded in trees on Quince-A (19.8 g). Fruit size (width and length) was significantly greater in trees on Quince-C and BA-29 compared to Quince-A (Table 2).

In loquat cultivation, various factors such as cultivar, soil characteristics, climatic conditions, and harvest time can influence fruit physical and chemical properties (Toker et al., 2010). Previous studies have reported that fruit weight of 'Hafif Çukurgöbek' on loquat seedlings ranged between 20.5 g and 39.7 g (Paydaş et al., 1992; Polat et al., 2004, 2005, 2010; Polat and Çalışkan, 2011). Durgac et al. (2006) reported that fruit weights of four loquat cultivars was between 22.6 g and 25.7 g. The fruit weights determined in the present study are generally lower than those reported in previous research except for the data by Durgac et al. (2006). This discrepancy may be attributed to the difference in tree age among the studies (younger trees in our experiment) and/or to the negative effect of very high planting densities on fruit quality. Fruit size is a critical parameter that can vary depending on tree age and fruit set (Durgac et al., 2006). Previous studies reported fruit width ranged between 36.8 and 40.1 mm and fruit length between 37.3 and 42.4 mm (Polat et al., 2005, 2010; Polat and Çalışkan, 2011). Durgac et al. (2006) found fruit widths between 32.8 and 36.5 mm and fruit lengths between 33.8 and 44.4 mm. The fruit widths obtained in the present study are comparable to those reported by Durgac et al. (2006), but differ from those of other studies, while fruit lengths are partially consistent with previous findings (Polat et al., 2005, 2010; Polat and Çalışkan, 2011).

Similarly, trees on both Quince-C and BA-29 rootstocks produced higher seed weight (5.2 and 4.9 g, respectively) and seed number (4.4 and 4.4, respectively) compared to Quince-A (4.3 g and 4.1 seeds, respectively) (Table 2). In terms of seed weight and seed number, the differences among the rootstocks were statistically significant, whereas differences in flesh/seed ratio were not. Seed weights in our study ranged between 4.9 g and 5.2 g, being generally lower than those reported in earlier research, which reported that this parameter varied between 4.00 g and 7.7 g (Polat et al., 2004, 2005; Durgac et al., 2006; Polat et al., 2010; Polat and Çalışkan, 2011), whereas they differ from the seed weights reported by Durgac et al. (2006) and Polat and Çalışkan (2011). Seed number per fruit was found to range between 3.6 and 3.9, that is consistent with previous reports (Polat et al., 2004, 2005, 2010; Durgac et al., 2006; Polat and Çalışkan, 2011).

In this study, flesh-to-seed ratio, an important indicator of fruit quality, ranged between 3 and 3.1 (Table 2), which is lower than the 3.4-5.4 range reported in earlier studies (Paydaş et al., 1992; Polat et al., 2004, 2005, 2010; Durgac et al., 2006).

Table 2. Effects of quince rootstocks on fruit quality parameters of the 'Hafif Çukurgöbek' loquat cultivar (2018-2020).

Source of variation	Fruit weight (g)	Fruit width (mm)	Fruit length (mm)	Seed weight (g)	Seed number per fruit	Flesh/seed ratio	Soluble solids (%)	Acidity (%)	pH
Year									
2018	18.9 b[x]	27.0 c	29.2 b	4.9 b	3.8 b	2.8 b	12.9 a	0.6 b	3.6 a
2019	22.1 a	33.73 b	37.7 a	5.4 a	3.4 c	3.2 a	11.0 b	0.8 a	3.6 a
2020	23.5 a	34.75 a	36.7 a	4.1 c	5.8 a	3.1 a	10.1 c	0.4 c	3.4 b
Significance	**	**	**	**	**	**	**	**	**
Rootstock									
Quince-A	19.8 b	27.8 b	30.5 b	4.3 b	4.1 c	3.1	11.9 a	0.5 b	3.7 a
Quince-C	22.9 a	34.1 a	36.5 a	5.2 a	4.4 a	3.0	10.3 b	0.6 a	3.5 b
BA-29	21.8 a	33.7 a	36.5 a	4.9 a	4.4 ab	3.0	11.8 a	0.7 a	3.4 b
Significance	**	**	**	**	*	NS[y]	**	**	**
Year × Rootstock									
2018-Quince-A	13.3 c	14.4 b	15.0 b	3.9 b	3.5 b	2.4 a	15.5 a	0.3 b	4.0 a
2018-Quince-C	23.7 a	34.6 a	37.0 a	5.6 a	4.0 a	3.2 a	11.5 b	0.8 a	3.3 b
2018-BA-29	19.8 b	32.0 a	35.6 a	5.2 a	3.9 ab	2.8 a	11.8 b	0.8 a	3.3 b
2019-Quince-A	22.6 a	34.0 a	39.1 a	5.1 b	3.2 b	3.6 a	10.8 b	1.0 a	3.6 b
2019-Quince-C	22.9 a	33.8 a	37.5 b	5.8 a	3.6 a	3.0 b	9.1 c	0.6 b	3.8 a
2019-BA-29	20.7 b	33.4 a	36.4 b	5.3 ab	3.3 ab	2.9 b	13.0 a	0.7 b	3.5 b
2020-Quince-A	23.6 a	34.9 a	37.4 a	5.6 a	4.1 a	3.2 a	9.2 b	0.4 b	3.5 a
2020-Quince-C	22.1 ab	33.8 ab	35.0 ab	5.7 a	4.0 a	2.9 ab	10.2 ab	0.5 a	3.3 a
2020-BA-29	24.8 a	35.6 a	37.7 a	6.1 a	4.2 a	3.1 ab	10.8 a	0.5 a	3.4 a
Significance	**	**	**	**	NS	**	**	**	**

(x) Means within each column followed by different letters are significantly different according to Tukey's HSD test at $p < 0.05$. (y) NS: Not significant.

TSS was highest in trees on Quince-A (11.9 %) and BA-29 (11.8%) and lowest in trees on Quince-C (10.3%) (Table 2). Acidity was higher in trees on Quince-C and BA-29, whereas pH was highest in trees on Quince-A (3.7) and lowest in trees on BA-29 (3.4). Trees on BA-29 rootstock exhibited higher TSS than the other rootstocks. Previous studies have reported that TSS values ranged between 8.1% and 12.8%, being generally consistent with those obtained in this study.

Titratable acidity was found to range between 0.6% and 0.7%, and pH values varied from 3.4 to 3.7. In comparison, prior studies reported acidity values between 0.6% and 9.9% and pH values from between 3.3 and 4.5 (Polat et al., 2004, 2005; Durgac et al., 2006; Polat et al., 2010; Polat and Çalışkan, 2011). Fruit juice acidity and pH values obtained in our study are lower than those reported by Polat et al. (2010), but higher than those of Polat et al. (2005). TSS, acidity, and pH are influenced by factors such as harvest time, climatic conditions, and cultivar (Pinillos et al., 2011; Baseda et al., 2011; Sortino et al., 2022; Shah et al., 2023; Parrado Muñoz et al., 2024). The Year × Rootstock interaction was also found to have a significant effect on most fruit quality traits (Table 2). This suggests that the effects of rootstocks on fruit quality traits vary depending on the year. These results suggest that rootstock choice should be aligned with production goals: Quince-C and BA-29 are preferable for higher yield and larger fruits, whereas Quince-A is advantageous for better fruit taste.

3.3. Vegetative growth

Table 3 shows that both the Rootstock and the Year had significant effects on all vegetative growth parameters measured, including annual shoot length, scion and rootstock trunk diameter, canopy height, and tree height. The effect of the Year × Rootstock interaction was generally not significant, suggesting consistent rootstock effects across years. The lowest growth was recorded in 2018, while in 2020 most vegetative parameters showed the highest values, reflecting continued vegetative development over time.

Table 3. Effects of rootstocks on vegetative growth parameters of the 'Hafif Çukurgöbek' loquat cultivar (2018–2020).

Source of variation	Annual shoot length (cm)	Scion trunk diameter (mm)	Rootstock trunk diameter (mm)	Crown height (cm)	Tree height (cm)
Year					
2018	45.8 b[x]	20.6 c	25.1 c	55.9 c	76.0 c
2019	72.5 a	27.3 b	33.0 b	91.7 b	115.7 b
2020	49.2 b	33.5 a	39.3 a	144.6 a	170.7 a
Significance	**	**	**	**	**
Rootstock					
Quince-A	42.3 b	21.5 b	27.1 b	76.3 b	103.5 b
Quince-C	65.8 a	31.6 a	35.4 a	109.7 a	129.2 a
BA-29	59.3 a	28.4 a	34.9 a	106.2 a	129.8 a
Significance	**	**	**	**	**
Year × Rootstock					
2018-Quince-A	28.5 c	16.3	20.6	42.7	63.0
2018-Quince-C	58.1 a	24.5	28.5	68.1	86.1
2018-BA-29	50.7 b	21.1	26.2	56.8	78.9
2019-Quince-A	50.8 c	21.3	26.3	66.3	95.6
2019-Quince-C	90.2 a	31.6	37.1	107.3	126.3
2019-BA-29	76.6 b	29.1	35.6	101.4	125.1
2020-Quince-A	47.7 b	27.0	34.4	119.9	151.7
2020-Quince-C	49.2 a	38.6	40.7	153.7	175.2
2020-BA-29	50.7 a	35.0	42.8	160.3	185.2
Significance	*	NS[y]	NS	NS	NS

(x) Means within each column followed by different letters are significantly different according to Tukey's HSD test at $p < 0.05$. (y) NS: Not significant.

Among the rootstocks examined, Quince-C the strongest vegetative growth as indicated by effects of this rootstock on all measured parameters, followed by BA-29. Quince-A yielded significantly lower vegetative growth (Table 3). Trees grafted onto Quince-C produced the longest annual shoots, thickest trunks, and largest crown volumes, indicating that this rootstock induces moderately vigorous growth in the scion. Trees on BA-29 exhibited a similar growth habit. In contrast, Quince-A induced a significant dwarfing effect in terms of shoot length and crown size. These differences between rootstocks could be related to their root vigor and degree of compatibility with the loquat scion. Quince-C and BA-29 exhibit strong graft compatibility with loquat, which facilitates more efficient water and nutrient transport, whereas Quince-A may restrict growth due to relatively weak root development and reduced nutrient uptake. Indeed, Basile and DeJong (2018) indicated that scion–rootstock semi-incompatibility is one of the possible mechanisms potentially involved in many scion–rootstock combinations and capable of inducing various physiological responses. Furthermore, substantial evidence suggests that alterations in water relations are associated with dwarfing responses in several species, supporting the view that compatibility-related hydraulic limitations may contribute to the reduced vigor observed in trees on Quince-A. However, the dwarfing physiological mechanisms are still not fully understood, because different physiological mechanisms may play a major role in the dwarfing effect depending on the species (Basile and DeJong, 2018). These include modifications in flowering genes, scion/rootstock vascular tissue anatomy and morphology, carbohydrate allocation, nutrient/water distribution, and hormonal regulation. These genetic and physiological factors affect tree architecture and function, providing the basis for orchard design and training systems that improve fruit quality (Anthony and Musacchi, 2021).

From an orchard management perspective, the moderate scion growth vigor induced by Quince-C and BA-29 rootstocks may be advantageous in orchards with wider spacing than present experimental orchard. Conversely, the dwarfing effect induced by Quince-A may be preferred in high-density planting systems, because it facilitates crown management, pruning, and harvesting, while also improving light distribution and uniformity of fruit color. However, the strong dwarfing effect of Quince-A may contribute to the reduced yield and fruit size, as it limits leaf surface area and overall photosynthetic capacity.

The generally consistent vegetative growth trends across years indicate that the studied rootstocks demonstrates reliable performance under differing weather conditions, including in the year when the frost and heat stress events occurred in our study. The Year × Rootstock interaction was found to have a significant effect only on annual shoot growth, indicating that this parameter may be more sensitive to annual weather fluctuations (differences in air temperature and rainfall).

In our study tree growth was initially rapid, but crop load and pruning management appeared to regulate tree height and canopy volume. Currently, most trees have an average height ranging between 1.03 and 1.30 m, and trunk diameters between 21.5 mm and 31.5 mm. These results are consistent with those reported by Hueso et al. (2007) for ‘Magdal’ cultivar grafted onto Quince-C rootstock. In previous studies, Polat and Kaşka (1992a) reported an average shoot growth of 23.4 cm for plants grafted onto the Quince-A rootstock. Polat (1995) measured, in loquat (‘Akko-XIII’ and ‘Armut Şekilli’ cultivars) grafted onto Quince-A rootstocks, scion trunk diameters of 18.2, 30.2, and 36.4 mm, and seedling heights of 74.3 cm, 120.2 cm, and 124.4 cm in 1993, 1994, and 1995, respectively. The vegetative growth results obtained in the present study are consistent with those reported by Polat and Kaşka (1992a) and Polat (1995).

3.4. Fruit Yield

Significant effects of the Year, Rootstock, and their interaction ($p < 0.01$) were found for fruit yield parameters (Table 4). The highest yield per tree (3.12 kg tree^{-1}) was obtained in 2019, substantially exceeding 2018 and 2020 yields (0.80 and 0.74 kg tree^{-1}, respectively). Similar patterns were observed for fruit yield per unit trunk cross-sectional area and yield per hectare. The severe yield reduction in 2020 can be attributed to environmental stresses, including frost (–2.5 °C) during flowering and fruit set and extreme heat (42 °C) prior to harvest.

Among rootstocks, significant differences were detected in fruit yield. Trees on Quince-A exhibited the lowest fruit yield in all parameters, while trees on Quince-C produced the highest total yield per tree (2.15 kg/tree) and per hectare (42.94 ton/ha). Conversely, trees on BA-29 had the highest fruit yield per unit trunk cross-sectional area (3.45 g mm^{-2}). The Year × Rootstock interaction was also found to have a significant effect on fruit yield and this indicates that the effect of the rootstock on this parameter varied among years. Indeed, in 2018 and 2019, trees on Quince-C and BA-29 had 4-5 times higher yields than trees on Quince-A. In 2020, fruit yield decreased for all rootstocks, but trees on BA-29 maintained relatively higher yields compared to the other rootstocks.

Overall, Quince-C and BA-29 rootstocks demonstrated to induce superior fruit yield and quality for the ‘Hafif Çukurgöbek’ loquat cultivar. Although Quince-A enhanced sweetness and flavor (higher TSS and pH), trees grafted on this rootstock were less productive. These findings align with earlier reports (Polat et al., 2004; Durgaç et al., 2006; Polat, 2018) emphasizing the substantial influence of quince rootstocks on loquat productivity and fruit quality.

Table 4. The effects of rootstocks on fruit yield parameters of 'Hafif Çukurgöbek' loquat cultivar (2018-2020).

Source of variation	Yield (kg tree^{-1})	Yield per unit trunk cross-sectional area (g mm^{-2})	Yield per hectare (ton ha^{-1})
Year			
2018	0.80 b^{x}	2.26 b	16.07 b
2019	3.12 a	4.81 a	62.34 a
2020	0.74 b	0.88 c	14.72 b
Significance	**	**	**
Rootstock			
Quince-A	0.50 c	1.29 b	10.08 c
Quince-C	2.15 a	3.21 a	42.94 a
BA-29	2.01 b	3.45 a	40.11 b
Significance	**	**	**
Year × Rootstock			
2018-Quince-A	0.1 c	0.4 c	1.5 c
2018-Quince-C	1.5 a	3.6 a	30.3 a
2018-BA-29	0.8 b	2.8 b	16.4 b
2019-Quince-A	0.9 c	2.5 c	17.0 b
2019-Quince-C	4.3 a	5.5 b	85.3 a
2019-BA-29	4.2 b	6.5 a	84.8 a
2020-Quince-A	0.6 b	1.0 a	11.8 c
2020-Quince-C	0.7 b	0.6 b	13.3 b
2020-BA-29	1.0 a	1.1 a	19.1 a
Significance	**	**	**

$^{(x)}$Means within each column followed by different letters are significantly different according to Tukey's HSD test at $p < 0.05$.

Based on our preliminary results, BA-29 and Quince-C rootstocks appear more suitable for high-density orchards due to their higher yield performance. However, if in subsequent years (3rd-4th growing seasons after planting) canopy closure will occur in the intra- and inter-row spaces, a gradual thinning strategy should be adopted. This will consider firstly an intra-row thinning to reduce the planting density to 1 × 1 m (10,000 trees ha^{-1}) and in later stages, an inter-row and intra-row thinning to reach a final spacing of 2 × 2 m (2,500 trees ha^{-1}).

Only a limited number of studies on high-density loquat orchards are available in the literature. Insero et al. (2004) evaluated ten loquat cultivars grafted onto BA-29 quince rootstocks planted at a spacing of 4 × 2 m, reporting an average cumulative yield of approximately 45 ton/ha from the 4th to the 8th growing season. Polat et al. (2004) compared 'Hafif Çukurgöbek' (HÇG), 'Sayda', and 'Golden Nugget' cultivars grafted onto loquat seedlings with a spacing of 3 × 3 m, reporting a mean productivity of 7,2 ton/ha during the first three harvests. In this latter study, the cumulative yield per hectare was found to increase to 9.3 ton/ha after two years (Polat et al., 2005) and to 30.3 ton/ha three years later (Polat and Caliskan, 2011). Hueso et al. (2007) established an orchard of the 'Magdal' cultivar grafted onto Quince-C rootstocks with a spacing of 2.5 × 1.7 m (2,353 trees/ha) to evaluate the suitability of loquat for extreme intensification. The authors reported that first harvest occurred in 2004 yielding an average of 2.8 kg/tree, and that fruit yield increased to 10.8 kg/tree (25 t/ha) and 13.0 kg/tree (30 t/ha) in 2005 and 2006, respectively.

4. Conclusions

High production costs remain a major constraint for loquat cultivation. The expansion of loquat cultivation in Türkiye depends on cost reduction, increased productivity, and the supply of early and profitable products. High-density orchards using dwarf or semi-dwarf rootstocks offer a potential solution to this constraint. However, studies on dwarfed loquat trees grafted onto quince rootstocks are limited in loquat producer countries. Rootstock choice markedly influenced fruit yield and quality, and vegetative growth of the 'Hafif Çukurgöbek' loquat cultivar. Our preliminary findings indicate that dwarfing quince rootstocks are suitable for establishing high-density loquat plantings. Among the rootstocks tested, BA-29 and Quince-C outperformed Quince-A. Considering both yield and fruit quality, particularly total soluble solids content, BA-29 appears to be the most suitable rootstock for high-density 'Hafif Çukurgöbek' loquat orchards.

It can be inferred that the very high densities tested in our study does not pose major problems during the first four years after orchard establishment. However, these elevated planting densities are expected to complicate orchard management in later years. Therefore, in commercial loquat cultivation, an extremely dense spacing such as 1 × 0.5 m (20,000 trees ha^{-1}) is not considered suitable. Instead, planting distances of 3 × 1.5 m or 2 × 2 m (approximately 2,200-2,500 trees ha^{-1}) appear to be more appropriate for maintaining manageable tree architecture and sustainable orchard performance.

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