Comparison of Canopy Architecture of Five Olive Cultivars in a High-Density Planting System in Sicily

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Abstract: In a young super-high-density (SHD) olive orchard located in Aidone (EN), in the Sicily Region, Italy, the architectural features of five olive cultivars were studied, specifically Arbequina, Arbosana, Oliana®, Giulia®, and FS-17®. Surveys were conducted in November 2019 considering biometric measurements for the whole tree, the canopy, and the primary and secondary branches. The "total branching frequency", the "sectorial branching frequency", the "total branching efficiency", the "sectorial branching efficiency", and the "total relative vigour" indexes were also calculated from the previous measurements. In addition, olive yield recorded for the years 2020, 2021, and 2022 (respectively, the third, fourth, and fifth years from planting) are shown in order to provide a more exhaustive description of the features of the cultivars. Giulia® and Oliana® resulted in being more similar to Arbequina and Arbosana, presenting a compact shape of the canopy and high and regular ramification of primary and secondary branches. FS-17® showed a higher expansion in canopy volume and higher vigour than the other cultivars, features that suggest it can be more susceptible to damage during mechanical harvest. Regarding the elaborated indexes, "total branching frequency" resulted in being not statistically different among the cultivars. "Sectorial branching frequency" resulted in being higher in the middle sector of the trunk height (51–100 cm) for all the tested cultivars. This study supplies helpful information about the different canopy and branch architectural characteristics of the five studied olive cultivars with respect to their suitability to high-density plantations.

Keywords: central leader; branching; Arbequina; Arbosana; Oliana®; Giulia®; FS-17®

1. Introduction

The olive tree is an iconic woody plant for the Mediterranean region that, together with wild olives, grapes, cereals, and bushy and herbaceous species, contributes to the definition of the most striking features of the agricultural territories [1] and of several natural landscapes. Since the 1990s, olive has been subjected to a progressive intensification of planting density (up to the super-high density olive orchards with more than 1000 trees per hectare) in order to increase mechanisation and reduce cultivation costs [2]. For the earliest super-high-density (SHD) olive orchards, a relatively limited number of cultivars, primarily Arbequina, Arbosana, and Koroneiki, have been utilised [3]. These cultivars are widely used thanks to their compact growth habit, limited vigour, abundant emission of fruit-bearing shoots and high ramification aptitude, early and consistent fruit bearing, and production of high-oil-quality fruits. In fact, it is well known that these characteristics are highly desired for the cultivars adaptation to the SHD plantation system [4,5].

Analysing the tree architecture is important for the understanding of the canopy growth, branching pattern, and yield, as well as for the development of crop models [6]. The architecture of a plant depends on the spatial arrangements of its parts and is based on morphological traits at the scale of a single shoot and at the scale of the branch complex [7]. The main architectural parameters typically studied include growth, branching, morphological differentiation of the axes, and the position of the reproductive structures (apical vs. lateral) [8–11]. Rosati et al. (2013) investigated different architectural traits among Arbequina, Arbosana, and other olive cultivars, mainly Italian ones, observing that high branching frequency and small diameter trunks are important characteristics that affect cultivar suitability for SHD orchards [6]. Tree architecture is affected by both endogenous (i.e., genetic) and exogenous (i.e., determined by environmental conditions) factors, which are well studied among species other than olive (e.g., apple and pear) [11]. Another factor affecting the tree architecture, tree size, and length of the period of juvenile traits is the propagation technique by which plantlets were obtained [12,13]. Rootstocks are widely used for the cultivation of fruit species [12], but it is not common in olive because of the necessity of having enough long one-year-old shoots for the abundant flowering and crop load [14]. Given the unavailability of the rootstock in olive cultivation, for the implementation of the SHD olive system, low-vigour cultivars are required in order to fit with the reduced planting pattern and ensure the mechanisation of the main cultivation practices (e.g., pruning and harvesting) [15]. Architectural traits of the canopies, such as the volume, branching pattern, and length and diameter of primary branches, provide useful information about the suitability of the cultivars to form a continuous hedgerow [4], as well as about the major or the lower susceptibility of the plants to damage induced by the mechanical harvester [16]. Other traits such as branching frequency along the central leader and the ability for secondary branching are important traits linked to the ability of the tree to fill the canopy of potential flowering/fruiting buds [2,6]. By the spreading of the SHD olive model, there are concerns about the loss of local germplasm and olive biodiversity [6,17]. On the other hand, this limitation represents a constraint for the diffusion of this model in Italy, given that several protected olive oil productions are obtained using locally spread or traditional germplasm. Research efforts are directed to enrich the range of olive cultivars suitable for SHD. Among regional olive cultivars, some of them (e.g., Maurino, Leccino, Moraiolo, and Piantone di Mogliano) presented suitable features for SHD plantation patterns [2,3,6,14,17,18] and for the mechanisation of the canopy management operation [14]. New cultivars were obtained by cross-breeding programs [19,20].

The suitability of the cultivars to a SHD plantation requires a highly detailed investigation, also considering the different Italian pedo-climatic conditions [21] and the specific cultural practices used [16].

The aim of the present work was to investigate the architectural traits of five olive cultivars (Arbequina, Arbosana, Giulia®, FS-17®, and Oliana®) in Sicily, in order to evaluate the suitability of the two Italian cultivars, Giulia® and FS-17®, and of the Spanish one, Oliana®, to the SHD planting system in comparison with two of the largely used Spanish cultivars, Arbequina and Arbosana.

2. Materials and Methods

The research was conducted in a young super-high-density (SHD) olive orchard planted at the "Beretta" farm in November 2017 and located in the Enna district (Lat. 37°22′12.9″ N, Long. 14°29′27.3″ E, Alt. 406 m a.s.l.) in the Sicily region (Southern Italy). Trees were arranged in North–South-oriented rows at a 4 × 2 m planting pattern (1250 trees per hectare). Self-rooted plantlets, obtained from the in vitro micro-propagation of five cultivars, were used: Arbequina, Arbosana, Oliana®, Giulia®, and FS-17®. Arbequina and Arbosana have been widespread cultivars since the plantation of the first SHD olive orchard [4]. The latter three evaluated cultivars were the results of Spanish and Italian breeding programs. In detail, FS-17®/Favolosa (patented CNR 1165nv), obtained in 1993 by free pollination of the Frantoio cultivar [22,23], and Giulia® (patented CNR 2358nv)

were obtained by Italian breeding programs; Oliana® (patented Agromillora) was obtained in 2012 from Arbequina × Arbosana controlled crosses [19]. At planting in November of 2017, plantlets were homogeneous. The measured height of the plantlets was on average 60 cm, and trunk calibre at 20 cm above the ground was 1–1.5 cm. Canopies were not subjected to a pruning operation and were trained while ensuring the presence of a central leader.

Climatic data for the area based on the last 30 years were supplied by the service CLIMATE-DATA.org (Figure 1). Precipitation was concentrated during autumn and winter months and was about 400 mm per year. Air temperature rarely decreased below 0 °C in the coolest months, while in summer, peaks above 40 °C were frequently recorded.
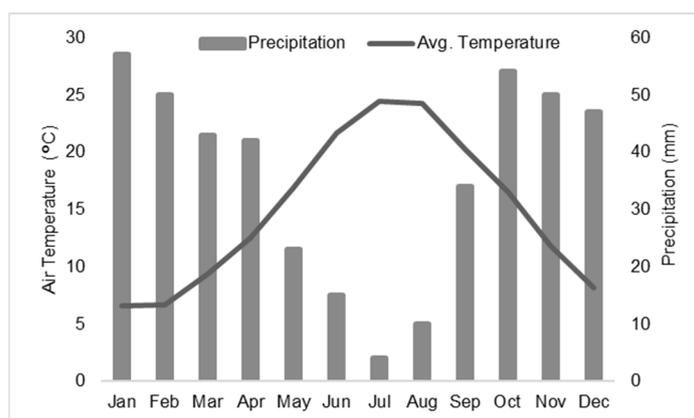

Figure 1. Trend of monthly mean air temperature and total rainfall for the Aidone (EN) climatic station based on the last 30 years. Meteorological data were provided by the CLIMATE-DATA.org service.

The soil analysis of the orchard is reported in Table 1. The soil analysis [24,25] indicated a clay texture and a neutral pH.

Table 1. Soil analysis of the olive orchard hosting the trial in the "Beretta" farm.

Mineral Nitrogen (‰)	pH	Electrical Conductivity (mS cm^{-1})	Total Dissolved Solids (g L^{-1})	Total Limestone (g kg^{-1})	Active Limestone (%)	Organic Matter (%)	Sand (%)	Lime (%)	Clay (%)
2.18	7.74	1.61	195.25	37.03	15.10	3.35	32.69	35.09	28.22

A drip fertigation system was positioned with a single line per row (Ø = 20 mm), and each dripper was positioned with an interval of 0.5 m with a flow rate of 1.5 lh^{-1}. Irrigation water was provided during the period of drought in summer. Trees were drip-irrigated early in the morning and three times per week, from June to September. Irrigation volume scheduling was based on the FAO-56 Penman–Monteith (P-M) approach, adjusted by the variable crop coefficient (kc) from 0. Trees were fully irrigated, corresponding to 95–98% of ET_c, for a total of 400–450 m^{3}ha^{-1}.

Weed control in the inter-row area was executed periodically with mechanical tillage, while along the row, chemical weeding was applied. Plantlets were grown, ensuring the central leader growing vertical by tiding it up to the support stake, and no pruning operations were executed until the harvest in 2021, when a remarkable fruit production was recorded for some of the tested cultivars. After the harvesting in 2021, only light pruning operations in the canopy were executed, mainly to remove the branchlets below a 0.6 m height from the ground and if plants required them. Surveys were mostly conducted in November of 2019, when ten homogeneous trees (as replicates) were selected for each of

the five cultivars. Trees were randomly distributed within the orchard. A choice was made, avoiding selecting contiguous trees. Biometric measurements regarded: calibres of the central leader at 20, 75, and 150 cm above the ground, in order to calculate the average trunk cross-sectional area (TCSA) (cm^2) and total tree and canopy heights (cm); transversal (inter-row cross) and longitudinal (along the row) canopy widths (cm) were used to calculate the volume of the canopies (m^3), calculated according to a cylinder shape [17]. The TCSA for each section was calculated, starting from the corresponding measured trunk calibres at 20, 75, and 150 cm, considered as diameters of the trunk cross-sections [21]. Measurements of the canopy volume were then noted as hectares (m^3 ha^{-1}). Canopy shape index was obtained as the ratio between the canopy height (CH) (cm) and the canopy transversal diameter (TD) (cm). If CH/TD > 1, canopy shape was attributed to a cylinder with an elliptical basis; if CH/TD < 1, canopy shape was attributed to an ellipsoidal shape [26].

Ten homogeneous trees were selected for each cultivar in order to describe the architectural structure, considering the number of the primary branches along the central leader and splitting them into the three belonging sectors, namely, 0–50 cm, 51–100 cm, and 101–150 cm, along the main axis. The calibre at the point of insertion and the total length of each branch were measured. The ratio between the total length of each branch and the calibre at the point of insertion was obtained for each cultivar, considered as the index of susceptibility to encounter damages at the passage of the mechanical harvester.

Moreover, for each tree, five uniform primary branches were chosen (which measured on average 80 cm in length), and the number of nodes where secondary branches were inserted and not inserted were counted. The ratio between branched and not branched nodes was then calculated; the density of ramification along the primary branches, calculated as the ratio between the number of branched nodes on the total branch length (cm), was also obtained. The length of the second-order branches and their calibres at the insertion point on the stem were also measured.

From the previous measurements, we obtained the following indexes: "total branching frequency" as the ratio between the number of total primary branches and tree height (cm); "sectorial branching frequency" as the ratio between the number of branches recorded along the different sectors of the central leader (0–50 cm, 51–100 cm, 101–150 cm) and corresponding length (cm) of each sector; "total branching efficiency" as the ratio between the number of primary branches and average TCSA (cm^2), obtained as means of TCSA at 20 cm, 75 cm, and 150 cm above the ground, along the central leader; "sectorial branching efficiency" as the ratio between the number of primary branches in each sector and the TCSA (cm^2) of the same sector; "total relative vigour", calculated as the ratio between the calibre at the insertion point of the primary branches; and the mean TCSA (cm^2) of the central leader, calculated as previously described.

In order to provide a better description of the features of the tested cultivars, the olive productions per hectare for each of tested cultivar were reported for the years 2020, 2021, and 2022, estimating them from olives collected by hand from the ten considered trees of each cultivar. Before 2020, no remarkable productions were recorded for any of the tested cultivars. The oil yield and the relative quality were investigated only in the year of 2020. For the determination of the yield in oil, fruits harvested separately from the trees belonging to each tested cultivar were gathered all together and milled at a local oil factory. No replies were considered. Olive production was around 6–8 kg per tree. The oil mill also provided information about the belonging product category of the extracted oil, according to EU Regulation 1308/2013 and its amendments [27].

Data were checked for normality and then subjected to ANOVA analysis with the JMP® 14.0 software (SAS Institute, Cary, NC, USA). Significantly different means were separated by the Tukey–Kramer HSD test at $p \leq 0.05$ or $p \leq 0.01$.

3. Results

3.1. Biometric Surveys on the Whole Tree

The cultivar Arbosana presented the highest value of trunk cross-sectional area (TCSA) at 20 cm above the ground (10.41 cm^2 ± 1.76) (Figure 2). The measured TCSA value at 20 cm above the ground of Arbequina (8.94 cm^2 ± 2.38) was similar to Arbosana, Giulia® (6.75 cm^2 ± 0.58), and Oliana® (6.05 cm^2 ± 0.89) for the Tukey–Kramer HSD test. FS-17® (5.44 cm^2 ± 1.54) had the most significantly thinnest TCSA measured at 20 cm above the ground.
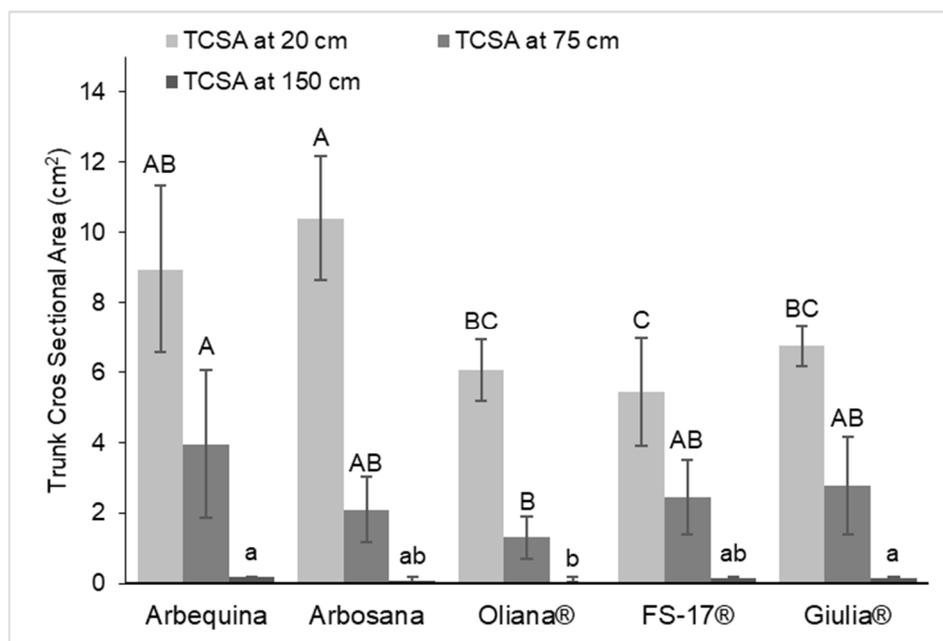
Figure 2. Trunk cross-sectional area of the central leader at 20, 75, and 150 cm above the ground. Bars indicate standard deviation. Different letters indicate significant differences for each considered height between cultivars (lowercase letters $p \leq 0.05$; uppercase letters $p \leq 0.001$) according to the Tukey–Kramer HSD test.

The TCSA value at 75 cm above the ground in Arbequina (3.96 cm^2 ± 2.08) was the highest among the studied cultivars. It was followed by Arbosana (2.09 cm^2 ± 0.93) that belonged to the same statistical population. Giulia® (2.79 cm^2 ± 1.39), FS-17® (2.46 cm^2 ± 1.05), and Oliana® (1.31 cm^2 ± 0.61) were similar each other for the Tukey–Kramer HSD test.

Significant differences in TCSA values measured at 150 cm above the ground were recorded between Arbequina and Oliana® (Figure 2).

Giulia® (180.10 cm ± 17.18) and FS-17® (179.90 ± 11.68) were the highest trees, and similarly, the canopies were statistically similar to those of the international cultivars Arbequina (179.10 cm ± 12.18) and Arbosana (172.60 ± 9.61). Oliana® (143.50 cm ± 11.72) resulted in the shortest tree.

No significant differences among cultivars were observed for the canopy width, measured along the row direction. The Italian cultivars, Giulia® and FS-17® had the greatest measured width along the row direction (134.70 cm ± 10.27 and 132.50 cm ± 11.06 cm, respectively), followed by Arbosana (131.90 cm ± 10.45), Arbequina (121.90 cm ± 12.49), and Oliana® (120.10 cm ± 16.48). The trees of all the considered cultivars closed the row at the end of the second year after planting, making a continuous hedgerow.

Referring to the canopy thickness (transversal to the row measurement), FS-17® reached values of 142.90 cm ± 15.56 at the end of the second year of growth. It was the highest value measured, followed by Arbosana (125.90 cm ± 9.39) and Giulia® (123.90 cm ± 7.52). Arbequina (110.30 cm ± 17.42) and Oliana® (104.50 cm ± 14.07) trees had the smallest thicknesses of their canopies (Figure 3).
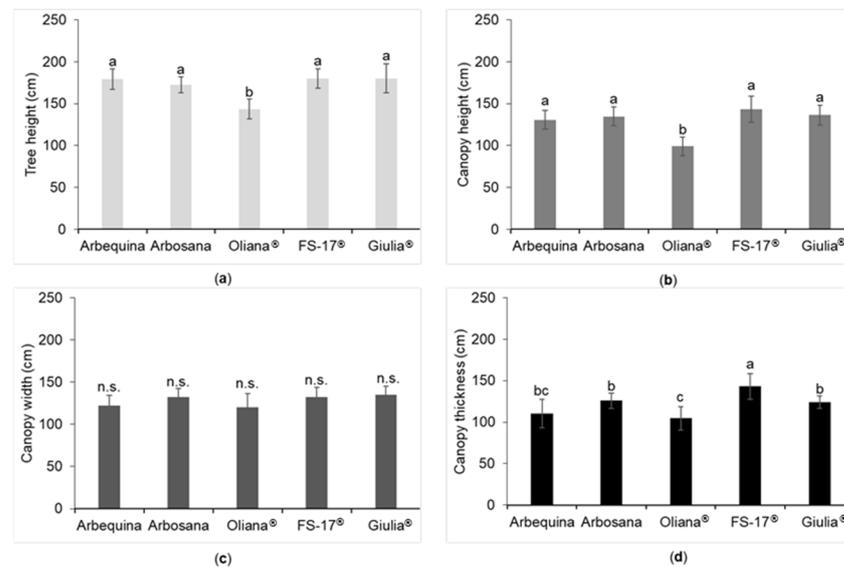
Figure 3. (**a**) Tree height; (**b**) canopy height; (**c**) canopy width (diameter along the row); (**d**) canopy thickness (diameter transverse to the row). Bars indicate standard deviation. For each parameter, different letters indicate significant differences between cultivars ($p \leq 0.05$; n.s.: non-significant difference) according to the Tukey–Kramer HSD test.

The canopy shape index of the studied cultivars was attributed to a cylinder with an elliptical base (CH/CT > 1). Arbequina had the highest value among the cultivars (CH/CT = 1.21 ± 0.23), but no significant differences emerged from statistical analysis. Oliana[®] tended towards an ellipsoidal shape (CH/CT = 0.96 ± 0.11), but the differences below the threshold value were very slight and not statistically relevant (for $p \leq 0.05$) (Figure 4).
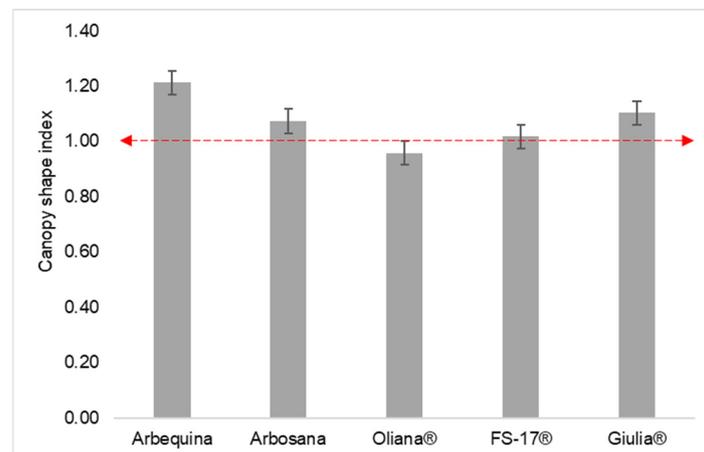

Figure 4. Canopy shape index calculated for the studied cultivars. The dashed line indicates the threshold value between the two identified canopy shapes. Bars indicate the standard deviation.

The FS-17[®] cultivar was the cultivar with the most expanded canopy (2.14 m³ ± 0.27), and it statistically differed from the other tested cultivars. The tree canopy volumes of Giulia[®] (1.79 m³ ± 0.24) and Arbosana (1.76 m³ ± 0.30) were slightly lower than FS-17[®]. Arbequina (1.41 m³ ± 0.37) and Oliana[®] (1.02 m³ ± 0.33) had the lowest canopy volume (Figure 5).
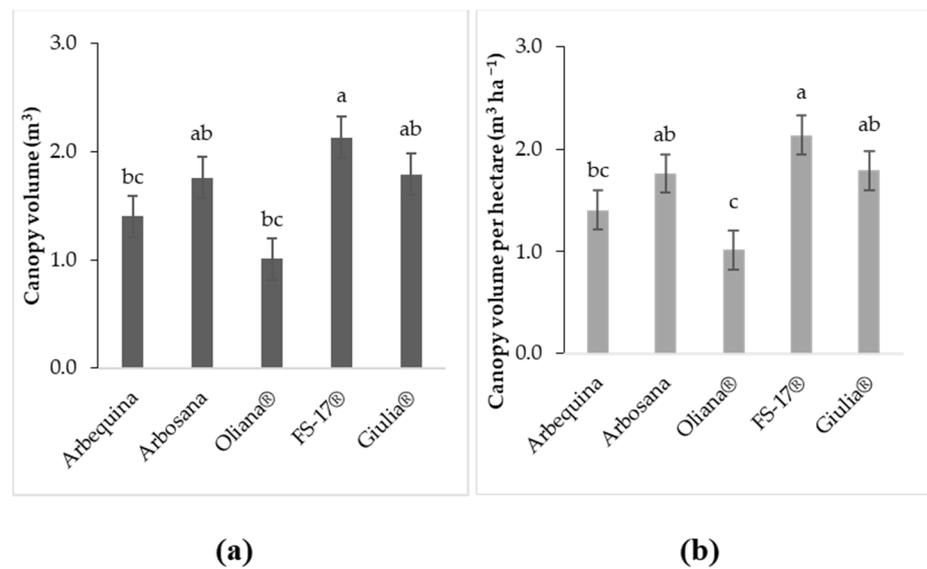
(a)　　　　　　　**(b)**

Figure 5. (**a**) Canopy volume; (**b**) canopy volume per hectare. Bars indicate standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test.

3.1.1. Biometric Survey on the Primary Branches

The highest number of primary branches along the central leader was observed for the cultivar Arbequina (12.40 ± 4.65). This cultivar, together with FS-17® (11.10 ± 3.28) and Arbosana (9.70 ± 2.11), belonged to the same statistical population. Giulia® (7.50 ± 2.07) showed intermediate values, and Oliana® (6.60 ± 1.26) had the lowest number of primary branches along the central leader (Figure 6).
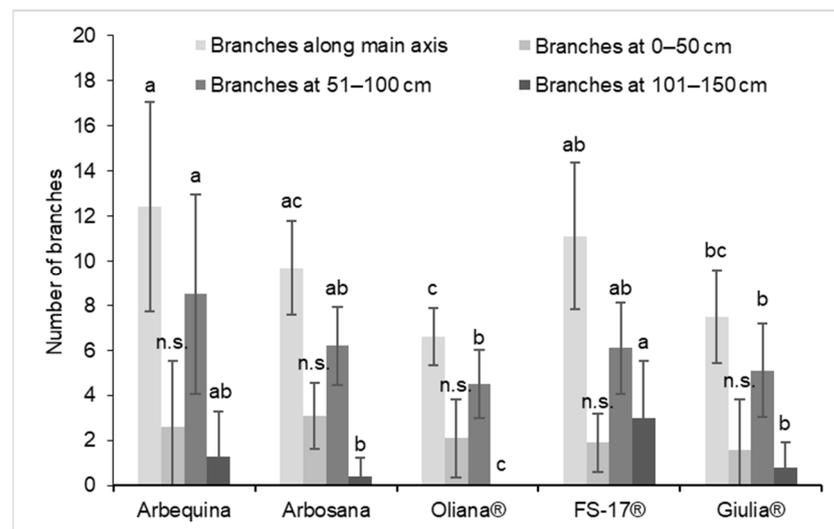

Figure 6. Number of primary branches along the main axis and number of branches along the central leader at 0–50 cm, 51–100 cm, and 101–150 cm height sectors. Bars indicate standard deviation. For each parameter, different letters indicate significant differences for each sector among cultivars ($p \leq 0.05$; n.s.: non-significant difference) according to the Tukey–Kramer HSD test.

When the number of primary branches per sector of the central leader (0–50 cm, 51–100 cm, and 101–150 cm) was considered, no significative differences among cultivars were observed within a 0–50 cm sector. Arbequina had the highest number of branches within a 51–100 cm sector (8.50 ± 4.45), followed by Arbosana (6.20 ± 1.75) and FS-17® (6.10 ± 2.02). Arbequina, Arbosana, and FS-17® belonged to the same statistical population.

Giulia® (5.10 ± 2.08) and Oliana® (4.50 ± 1.51) had the lowest number of primary branches within the 51–100 cm sector of the central leader, with no differences compared to Arbosana and FS-17® (Figure 6).

Referring to the 101–150 cm sector, FS-17® had the highest number of primary branches (3.00 ± 2.54) that resulted in being statistically similar only to Arbequina (1.30 ± 2.00). Giulia® (0.80 ± 1.14) and Arbosana (0.40 ± 0.84) did not statistically differ from Arbequina. Most of the trees of Oliana® (0.00) did not reach the considered height, and no branches were detected (Figure 6). As shown in Figure 6, within all considered sectors, there was a lot of variability among trees belonging to the same cultivar, as shown by the standard deviation bars.

Primary branches were placed mainly at the central portion of the leader, without there being significant differences among the studied cultivars (Figure 7). FS-17® showed a homogeneous distribution of the primary branches along the entire central leader and was the cultivar that presented the highest percentage of primary branches in the last sector (24.7%). Arbequina and Giulia® (68.11% vs. 69.8%), in a similar manner, showed a higher percentage of primary branches in correspondence of the central portion of the central leader to the detriment of the first sector and the last one. Arbosana and Oliana® showed the greatest number of primary branches in the 51–100 cm sector (63.95% vs. 69.72%), and only a few branches were placed in the 101–150 cm sector as a consequence of the lower size of trees.
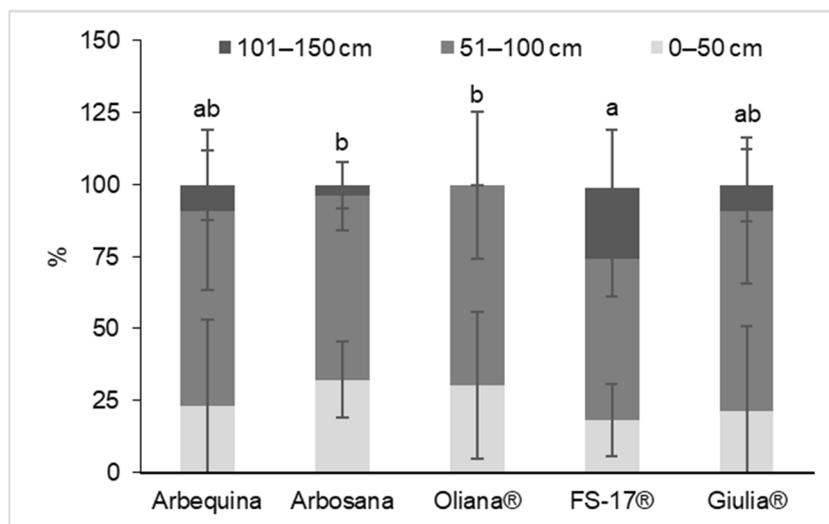

Figure 7. Percentage of distribution of the primary branches per sector along the central leader of the tree at 0–50, 51–100, and 101–150 cm height sectors. Bars indicate standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.05$) within the same sector according to the Tukey–Kramer HSD test.

In Arbosana, the primary branches were the longest (94.98 cm ± 8.38) and the thickest (12.86 mm ± 0.85). On the contrary, Oliana® had the shortest primary branches (79.54 cm ± 5.81), and the reduced length was balanced by the diameter of the branches in correspondence to the insertion at the central leader (12.52 mm ± 1.37). Arbequina (90.52 cm ± 12.94 and 11.08 mm ± 1.58), FS-17® (88.68 cm ± 7.12 and 10.8 mm ± 1.11), and Giulia® (84.76 cm ± 11.43 and 10.60 mm ± 2.51) showed an intermediate behaviour (Figure 8).
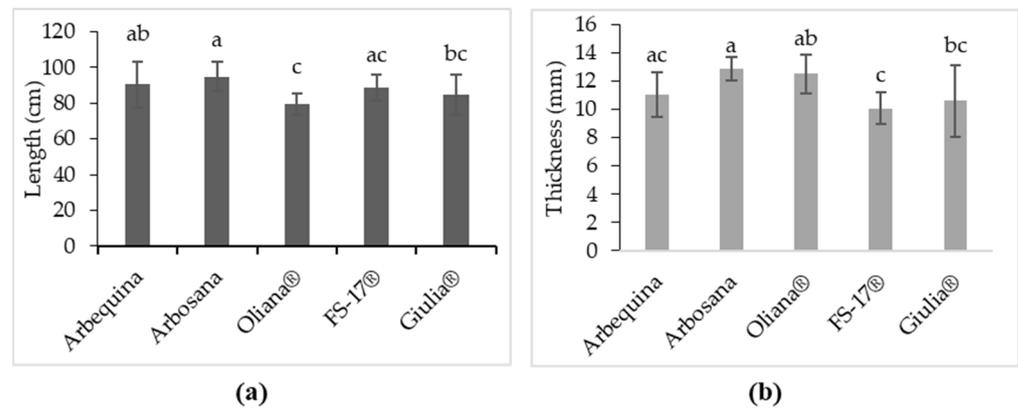
(a)　　　　　　　　　　　　　(b)

Figure 8. (**a**) Length of the primary branches; (**b**) calibre at the insertion point of the primary branches. Bars indicate standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test.

The aforementioned differences are highlighted in Figure 9, where the mean ratio between the length and the calibre at the insertion of the primary branches are reported.
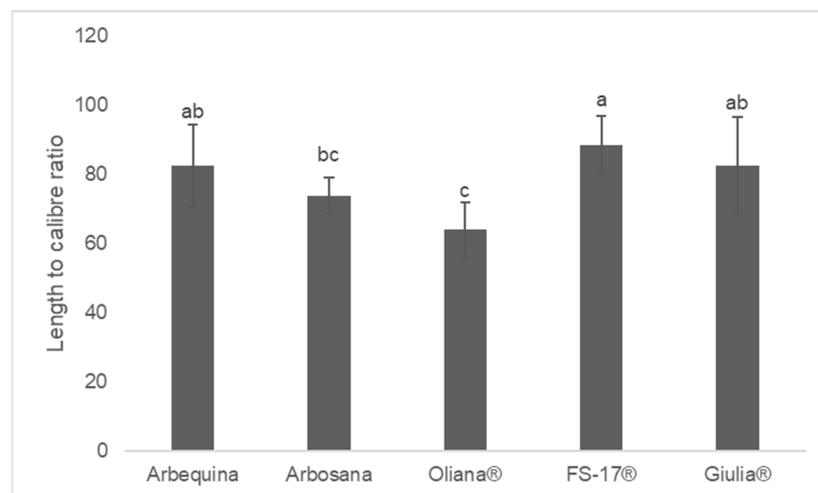

Figure 9. Length-to-calibre ratio of the primary branches. Bars indicate standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test.

FS-17® (88.6 ± 8.47) resulted in a significantly higher value of the calculated ratio than the other cultivars, followed by Giulia® (82.45 ± 14.04) and Arbequina (82.44 ± 11.86). Arbosana (73.90 ± 5.29) and Oliana® (64.11 ± 7.84) showed the lowest values for the length-to-calibre ratio of the primary branches.

When the architecture of the primary branches was considered, the number of branched and unbranched portions did not show significant differences among the studied cultivars (Figure 10).
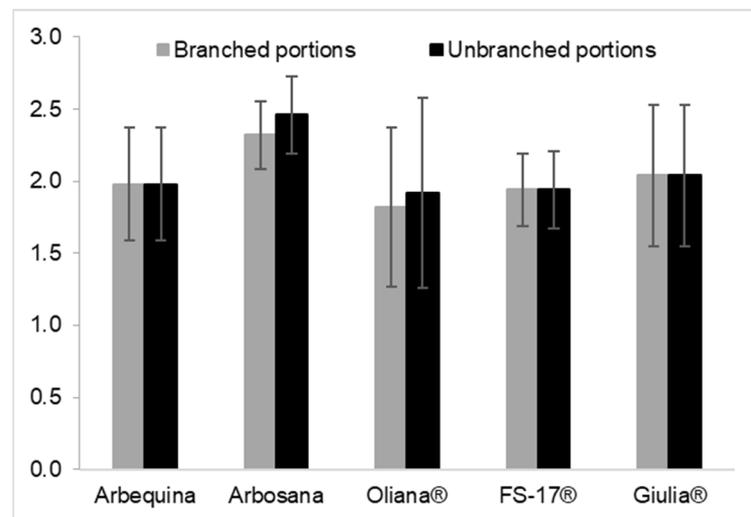
Figure 10. Number of branched and unbranched portions on the primary branches. The bars indicate the standard deviation.

All cultivars showed a good balance between the number of branched and unbranched portions along the axis of the primary branch (Figure 11a), showing a ratio near to 1.00 without significant differences among cultivars. The lowest value was recorded for Arbosana (0.94), showing a slight prevalence of unbranched portions. No significant differences were noticed for the density of secondary order branches per cm of primary branches among cultivars (Figure 11b).
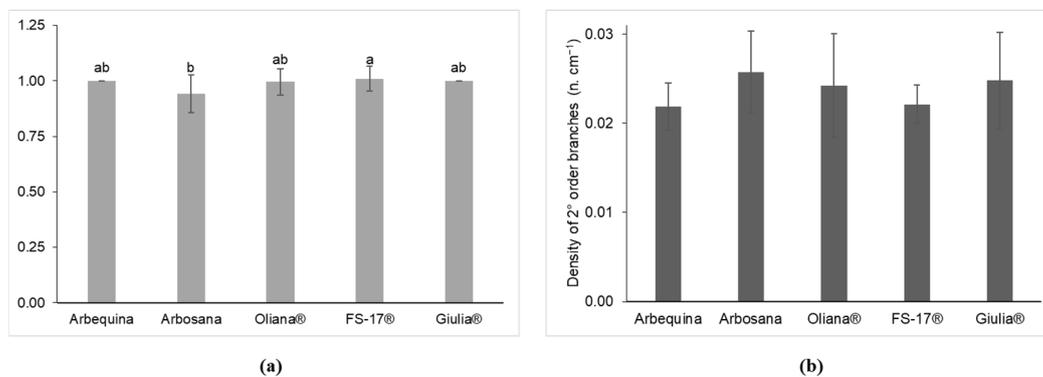

(a)

(b)

Figure 11. (**a**) Ratio of branched and unbranched portions on the axis of the primary branches; (**b**) density of second-order branches. Bars indicate the standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test.

The total length of the branched portions (as a sum of each part along the axis of the primary branch) exceeded the unbranched ones in all the compared cultivars (Figure 12a). Oliana® and Arbequina had similar branching patterns, with the total lengths of the branched portions being 31.57 cm ± 12.54 and 30.41 cm ± 6.01, respectively. The total lengths of the unbranched portions were 16.98 cm ± 4.39 and 16.00 cm ± 0.78 for Oliana® and Arbequina, respectively. The lowest values were found for Arbosana (21.82 cm ± 4.46 and 18.16 cm ± 2.01 for the total length of the branched and unbranched portions, respectively). Intermediate values were recorded for FS-17® (28.10 cm ± 5.62 for branched and 18.15 cm ± 2.01 for unbranched) and Giulia® (26.83 cm ± 12.16 for branched and 16.76 cm ± 3.57 for unbranched).

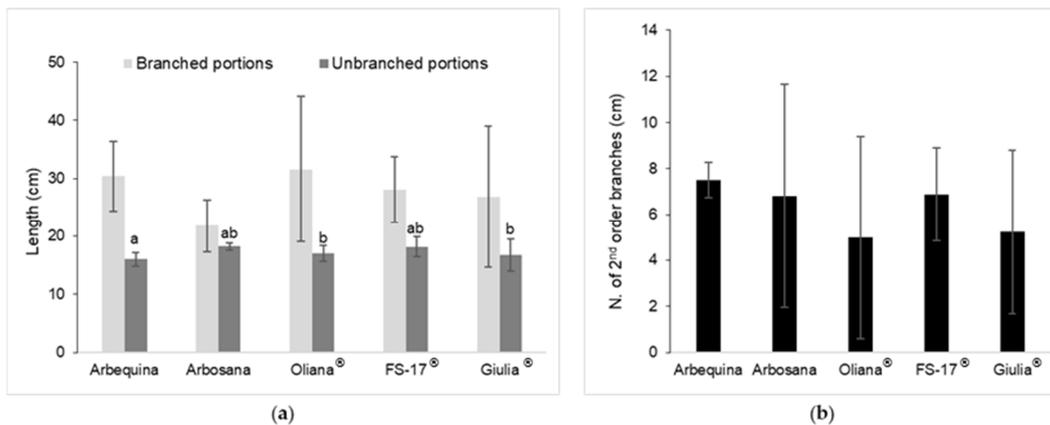**Figure 12.** (**a**) Total length of branched and not branched portions along the primary branch; (**b**) number of secondary order branches. Bars indicate the standard deviation. For unbranched portion length, different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test.

Along the primary branches of Arbequina, we recorded on average 7.49 ± 1.19 branches, followed by FS-17® (6.87 ± 1.70), Arbosana (6.80 ± 0.68), Giulia® (5.23 ± 2.81), and Oliana® (4.98 ± 1.40). No significant differences were observed among cultivars (Figure 12b).

The calibres of branched and unbranched portions showed significant differences among cultivars. In particular, the calibre of the branched portions was higher in most of the cases because it was near to the point of the insertion of the primary branch at the central leader. The largest calibres of the unbranched portions were found in Arbosana (8.77 mm ± 0.99), Arbequina (8.43 mm ± 1.28), and Giulia® (8.32 mm ± 1.17), which resulted in being statistically similar. The lowest calibres at the insertion point to the primary branch were measured for Oliana® (7.08 mm ± 0.96) and FS-17® (6.86 mm ± 0.82) (Figure 13).
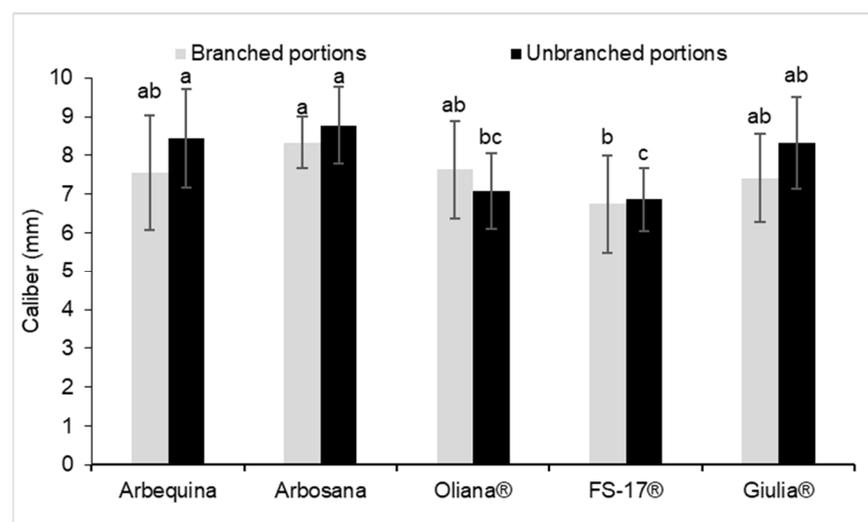

Figure 13. Calibre of branched and unbranched portions on primary branches. For each parameter, different letters indicate significant differences among cultivars ($p \leq 0.05$) according to the Tukey–Kramer HSD test. Bars indicate standard deviation.

3.1.2. Elaborated Indexes

The highest branching frequency index calculated along the central leader was observed for the cultivar Arbequina (0.07 ± 0.02). The index was lower than Arbequina along

the central leader of Arbosana (0.06 ± 0.01), FS-17® (0.06 ± 0.02), Oliana® (0.05 ± 0.01), and Giulia® (0.04 ± 0.01) (Figure 13).

Cultivars did not differ for the number of branches within the 0–50 cm sector. Some differences emerged within the 51–100 cm sector. The highest branching frequency within this sector was found for Arbequina (0.17 ± 0.09). Arbosana (0.13 ± 0.04) and FS-17® (0.04 ± 0.01) showed intermediate values. Giulia® (0.10 ± 0.04) and Oliana® (0.04 ± 0.01) had the lowest number of branches within the considered sector. Arbequina showed a strong ability towards branching in the median portion of the central leader. Almost two branches within 10 cm were observed in Arbequina, whereas only 1 branch per 10 cm was observed of the other studied cultivars.

FS-17® showed the highest branching frequency (0.06 ± 0.02) in the last one sector (101–150 cm). Arbequina (0.03 ± 0.01), Giulia® (0.02 ± 0.01), Arbosana (0.01 ± 0.01), and Oliana® (0.00) did not statistically differ. The FS-17® cultivar, in terms of the issue of branches at the top of the main axis, was shown to be able to keep a conical gradient over the years. Branching frequency observed in Arbequina and Giulia® suggested a rapid loss of the conical gradient with the prevalence of branching within the intermediate sector (51–100 cm) of the main axis. This feature was even more pronounced in Arbosana and Oliana® trees, in which canopies could start to lose functionality and efficiency already at one meter of height (Figure 14).
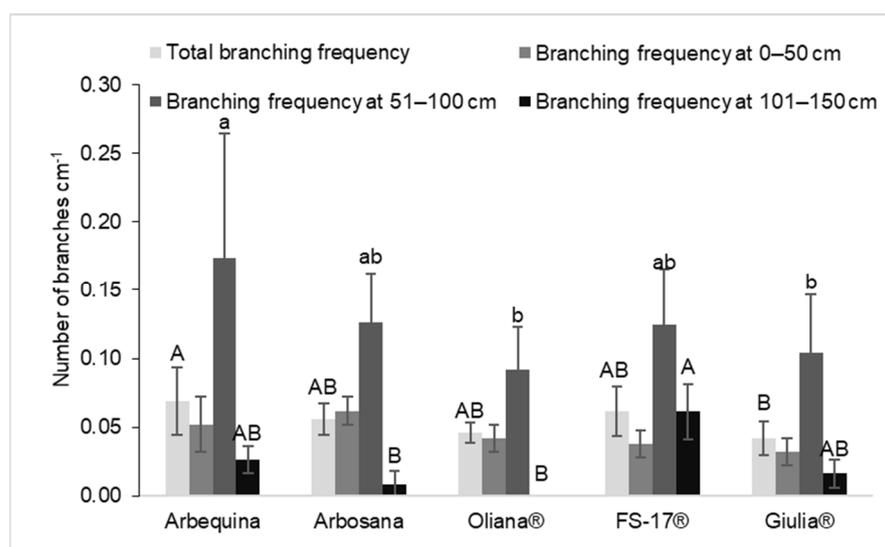

Figure 14. Total branching frequency and branching frequency per sector. Bars indicate standard deviation. Different letters indicate significant differences among cultivars for total branching frequency and for branching frequency index within each sector, separately considered (lower case letters $p \leq 0.05$; upper case letters $p \leq 0.001$), according to the Tukey–Kramer HSD test.

No significant differences were observed among the considered cultivars in terms of branching efficiency along the central leader and those calculated for the 0–50 cm sector.

In the 51–100 cm height sector along the central leader, the branching efficiency (number of branches cm^{-2}) was the highest in Oliana®, with almost 4.42 ± 3.65 branches per cm^2 measured above the mean of TCSAs at 20 cm, 75 cm, and 150 cm from the ground; Arbosana (3.84 ± 2.48) and FS-17® (3.56 ± 2.11) showed an intermediate behavior. Arbequina (2.41 ± 1.52) and Giulia® (2.11 ± 0.93) had the lowest branching efficiency for the considered section. The highest branching efficiency index for the third sector (101–150 cm) was found for FS-17® (17.84 branches per cm^2 ± 3.50) and Arbequina (8.69 branches per cm^2 ± 2.02). Arbequina was statistically similar to FS-17®, Arbosana (3.54 branches per cm^2), and Giulia® (3.62 branches per cm^2 ± 1.06). The branching efficiency of Oliana® within the third sector (101–150 cm) was near zero. These results confirm the behaviour of the cultivars, and in particular the Italian FS-17® tended to be more efficient in branching

at the top of the central leader, followed by Arbequina, Giulia®, and Arbosana. Oliana® showed a higher branching efficiency in the median part of the central leader (50–100 cm) that was very low at the top (Figure 15).
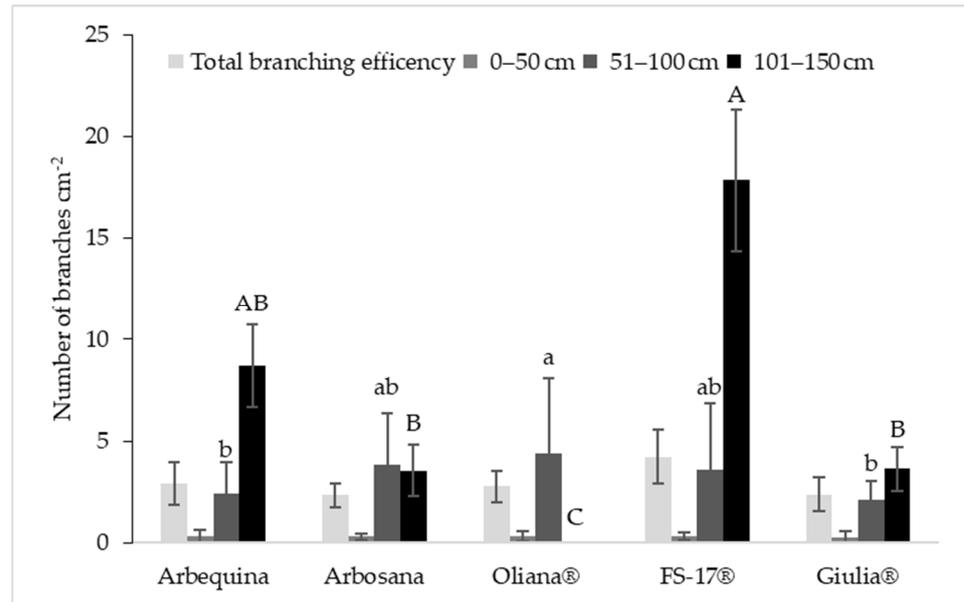

Figure 15. Total branching efficiency and branching efficiency per sector. The bars indicate the standard deviation. Different letters indicate significant differences among cultivars for total branching efficiency and branching efficiency within each sector, separately considered (lower case letters $p \leq 0.05$; upper case letters $p \leq 0.001$) according to the Tukey–Kramer HSD test.

The highest "total relative vigour" index was observed for the cultivar Oliana® (0.53 ± 0.12), followed by FS-17® (0.39 ± 0.07), Giulia® (0.34 ± 0.11), Arbosana (0.31 ± 0.04), and Arbequina (0.27 ± 0.06) (Figure 16).
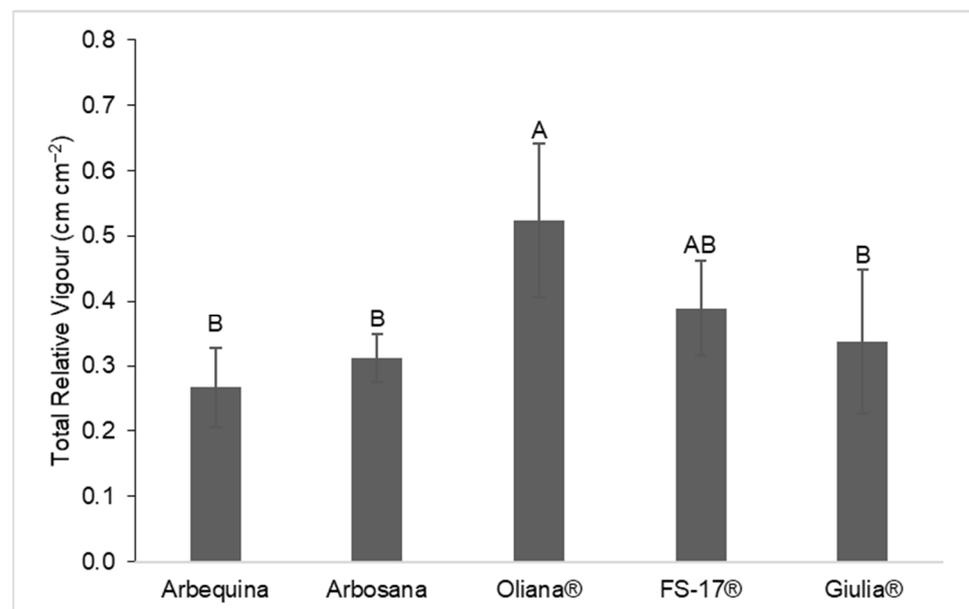

Figure 16. Total relative vigour. Bars indicate the standard deviation. Different letters indicate significant differences among cultivars ($p \leq 0.001$) according to the Tukey–Kramer HSD test.

3.1.3. Olive Productions

Figure 17 shows the fruit productions of the tested cultivars recorded in the olive orchard subject of the trial for the years 2020, 2021, and 2022. For all the considered cultivars, no significative fruit production was recorded before 2020.
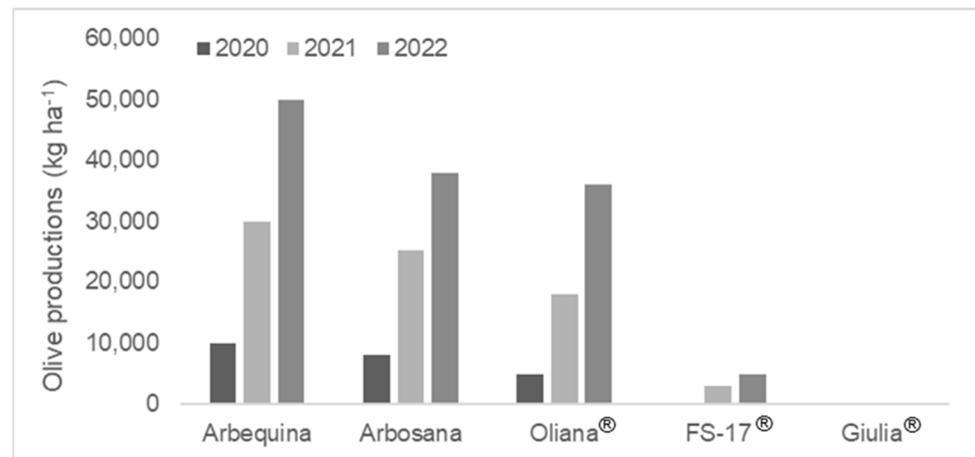

Figure 17. Olive productions (kg ha^{-1}) registered in 2020, 2021, and 2022 for the tested cultivars.

Arbequina, Arbosana, and Oliana$^{®}$ productions followed the same trend during the years. Olive productions were raised from the lower values registered in 2020 (10,000 kg ha^{-1}, 8000 kg ha^{-1}, and 5000 kg ha^{-1}, respectively) to the entry of full production registered in 2022, at 50,000 kg ha^{-1}, 38,000 kg ha^{-1}, and 36,000 kg ha^{-1} respectively. FS-17$^{®}$ and Giulia$^{®}$ showed a delay in the onset of the fruit production. After three years from planting, the latter two cultivars resulted in lower fruit productions than the previous ones.

Considering the oil yield and the quality of the extracted oil in 2020 (Table 2), interesting yield values and high-quality oil were found for the cultivars that showed the onset of fruit production in this year. This analysis was not repeated in the following years.

Table 2. Average oil yield (%) calculated as mean for the years 2020, 2021, and 2022 and relative oil quality.

Cultivar	Oil Yield (%)	Oil Quality
Arbequina	14	Extra-virgin
Arbosana	14	Extra-virgin
Oliana$^{®}$	14	Extra-virgin
FS-17$^{®}$	-	-
Giulia$^{®}$	-	-

4. Discussion

Beside the Spanish cultivars widely used for SHD olive orchards (Arbequina and Arbosana), other cultivars are being demonstrated to be suitable for an intensification of the planting systems [2,3,5,6]. Whole tree compact growth habit, high canopy density, slow canopy growth, and early and consistent fruit production were reported as the main cultivar features for their suitability to SHD olive plantation pattern [4]. Rosati et al. (2013) [6], in a detailed investigation about olive architecture traits, observed that Arbequina and Arbosana, considered as reference cultivars fitted to SHD plantation, presented reduced vigour, high branching frequency associated with smaller diameters of branches and shoots, and high branching efficiency index, expressed as nr. of branches per unit of TCSA. Further, Lodolini et al. [16] assessed the damages caused by the passage of an over-the-row harvester on different olive cultivars trained in SHD olive orchards. The authors highlighted how a high level of ramification of the branches, together with greater flexibility (reduced

thickness), might have resulted in a lower level of branch damages during the mechanical harvest. The higher values of the ratio reported in Figure 9 were associated with more flexibility of branches at the passage of the over-the-row harvester. FS-17[®] resulted in a significantly higher value of the length-to-calibre ratio of primary branches, suggesting more flexibility of branches at the passage of the over-the-row harvester. Giulia[®] and Arbequina showed intermediate values of the ratio, while Oliana[®] showed the shortest branches with the highest values in thickness at the insertion point. A separate mention is owed to Arbosana, which showed a length of primary branches similar to Arbequina and FS-17[®] (the highest ones) and at the same time a higher value in the thickness of primary branches at the insertion point. Such characteristics may represent a disadvantage, being more susceptible to damages during harvesting with an over-the-row machine.

Observing the "total relative vigour" index (Figure 16) in the complex of FS-17[®] and Giulia[®] resulted in the most vigorous cultivars among the tested ones, whereas Oliana[®] was the less vigorous one.

No differences were observed among cultivars when the canopy width (measured along the row) was considered. All the tested cultivars showed great growth and quick enclosing of the existing spaces among the trees along the row. These ones are recognised to be among the main characteristics of cultivars suitable for a SHD plantation pattern [2,4,17]. FS-17[®] showed the greatest canopy in thickness (measured transversally to the row direction). Arbequina and Oliana[®] showed the lowest values for canopy thickness.

FS-17[®] and Giulia[®] presented the most expanded canopies in volume (m^3) at the end of the second year after planting, followed by Arbosana, Arbequina, and Oliana[®] (Figure 5).

The existence of different vegetative habits among the tested cultivars was observed through analysing the biometric parameters. All tested cultivars presented a conical gradient at the end of the second year after planting. Arbequina and Arbosana were the earliest cultivars adopted for the realisation of a SHD olive orchard [2,4,18], and in our study, they demonstrated a great ability to form primary branches along the central leader (Figure 6), confirmed also with reference to the total branching frequency index (Figure 14). These results agreed with those of the previous studies in the literature [2,4,18,28]. FS-17[®] showed the same ability, registering values similar to Arbequina and Arbosana for the number of primary branches along the central leader. Giulia[®] and Oliana[®] showed a lower number of primary branches compared to the other cultivars (Figure 6) and low branching frequencies (Figure 14) [2,4,23].

The relative abundance of primary branches was higher in correspondence with the central portion of the central leader for all the tested cultivars. FS-17[®] showed a higher number of branches within the last considered sector (101–150 cm) compared to the other cultivars, with regard to the greater size of the plants. Giulia[®] and Arbequina were similar as well (Figure 7). This feature confirmed the greater vigour of these three cultivars and did not exclude negative consequences over the time, such as the tendency of the canopy towards strong vegetative growth in the upper portion if not properly managed with pruning. Concerning the length and the calibre of the primary branches, Arbequina, Arbosana, and FS-17[®] showed on average longer and thinner primary branches than Oliana[®] and Giulia[®]. These latter two had on average shorter but thicker branches (Figure 8). The reduced number of primary branches along the central leader of Giulia[®] and Oliana[®], together with the sparse relative distribution, suggest a better light penetration within the canopy and a greater canopy efficiency over the time, according to the results of a previous study [6].

The capacity for secondary branching is an important architectural characteristic to increase yield efficiency and influence the suitability of the cultivar to SHD cultivation system [2,14]. A high number of branches of an order higher than the first implies a great ability of the cultivar towards branching and producing potential productive shoots [2,4,6,29]. In our study, only slight differences were observed among the tested cultivars concerning the average number of secondary branches and the density of secondary branches in cm^{-1} of first-order branches (Figure 11b). The length of branched portions along the primary

branches resulted in being higher than the non-branched ones in all the tested cultivars, with the highest values recorded for Arbequina, followed by Oliana® (Figure 12).

Giulia® resulted the most similar to Arbequina and Arbosana in terms of vigour, canopy development, and branch architecture, with a high number of primary branches and an equilibrate branch distribution along the central leader.

FS-17® was the most vigorous cultivar among the tested ones, showing the greatest size of the canopy at the second year after plantation. FS-17® had a good attitude to branching, similar to Arbequina, Arbosana, and Giulia®. At the same time, the excess of the vigour of the FS-17® canopy (Figure 3) can be the cause of damage during mechanical harvest and be of detriment to the fruit yield of the orchard over the years, according to the results of a previous study [16], Arbequina was found to be averagely less damaged, whereas FS-17® showed more hurt and breakings after the harvesting with an over-the-row machine. Several pruning operations could be requested to contain the canopy vigour and remove the damaged branches in such planting conditions.

Oliana® resulted in being very similar to Arbequina in terms of vigour and branching aptitude, showing interesting characteristics for SHD plantations (Figure 16).

Early fruit bearing is an important feature for the olive cultivars cultivated in SHD systems, in order to promote a quick return of the initial investment [2,4]. In our study, we observed that among the tested cultivars, onset of fruit production was seen only since 2020 (three years after plantation). Arbequina, Arbosana, and Oliana® showed an increasing trend of fruit yield during the years (Figure 17), while Giulia® and FS-17®, the most vigorous cultivars, showed a delay in fruit production. For all the tested cultivars, good oil yields and excellent oil quality were observed (Table 2).

5. Conclusions

When planning a new high- or super-high-density olive orchard, the growth behaviour and the natural architectural characteristics of the cultivar must be carefully considered. The cultivars Oliana® and Giulia® were shown to be very similar to Arbequina and Arbosana, presenting a compact shape of the canopy and a high and regular ramification of primary and secondary branches. They were confirmed to have suitable characteristics for olive intensification according to hedgerow planting systems in the studied climatic conditions. On the contrary, FS-17® resulted in being less suitable for the hedgerow system, showing higher vigour, higher expansion, and a larger volume of the canopies.

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