Fruiting, Morphology, and Architecture of 'Arbequina' and 'Calatina' Olive Branches

Alessandro Carella [ID], Roberto Massenti, Giuseppe Milazzo, Tiziano Caruso [ID] and Riccardo Lo Bianco *[ID]

Department of Agricultural, Food and Forest Sciences, University of Palermo, 90128 Palermo, Italy;
alessandro.carella@unipa.it (A.C.); r.massenti@gmail.com (R.M.); giumila100@gmail.com (G.M.);
tiziano.caruso@unipa.it (T.C.)
* Correspondence: riccardo.lobianco@unipa.it; Tel.: +39-091-23896097

Abstract: Two different olive cultivars grown under a high-density hedgerow system were studied to compare their fruiting and branch architecture features and to determine the possibility to use 'Calatina' olive trees for intensive plantings, as a local alternative to the international reference 'Arbequina'. Weights of two-year-old branches, fruits and leaves were recorded to estimate the growth partitioning. Growth and architectural parameters, such as shoot length, vector and diameter, branching angle, branch total length, height, width, area, and branching frequency, were determined by digital image analysis. Digital images of the fruits were also used to estimate fruit maturation by peel color analysis. Whole branch and fruit crop weights were similar in the 'Arbequina' and 'Calatina', while the latter had a greater fruit/leaf ratio, showing a higher production efficiency than 'Arbequina'. Fruits were fewer but bigger in 'Calatina' than in 'Arbequina', suggesting an advantage for both trunk-shaking and straddle machine harvesting in the Sicilian cultivar. Leaf/wood ratio, branching frequency and branching angle were similar in the two cultivars. 'Calatina' shoots exhibited a greater bending degree than those of 'Arbequina' and this trait particularly favors straddle harvesting. In addition to many similarities between the two cultivars, the present study indicates that 'Calatina' is more efficient in terms of yield and harvesting than 'Arbequina'. This qualifies 'Calatina' as a superior, yield-efficient olive cultivar suitable for intensive hedgerow plantings to be harvested with straddle or side-by-side trunk shaker machines.

Keywords: branching pattern; canopy growth; digital image analysis; biomass partitioning; fruit bearing habit; fruit peel color; *Olea europaea*

1. Introduction

In recent decades, plant architectural analysis has led to the development of new approaches ranging from gaining knowledge about tree development to the investigation of intra-species variation in related characters and, in more applied cases, to improving plant management at the orchard level [1]. The architecture of a plant depends on the spatial and temporal arrangements of its parts, and is based on morphological traits at the shoot and branch scale [2]. Studying plant architecture is important for understanding tree growth, branching pattern, productivity, and for developing cultural models. The main architectural parameters typically studied include growth, branching, morphological differentiation of the axes, and position of the reproductive structures (apical vs. lateral) [3–6]. Several studies showed that branching density, branching frequency, and frequency of flowering on one-year-old branches are traits that vary depending on the cultivar, although they can be influenced by environmental factors [2,7–9].

Commonly, another factor that influences plant architecture is the rootstock. The use of dwarfing rootstocks allows control of tree size and shape and to obtain a higher planting density [2]. As an example, Arenas et al. [10] used dwarfing rootstocks to develop a super-high density system to permit mechanical harvesting of sweet orange trees for industrial

use. However, in olive (*Olea europaea* L.), dwarfing rootstocks are not very promising because olive flowering and fruiting occur mainly on relatively long one- or two-year-old branches. Therefore, reducing tree vigor generally decreases fruiting potential [11]. Instead of using dwarfing rootstocks, an increase in olive planting density has been achieved by selecting low-vigor cultivars suitable for high-density conditions [12].

Olive is traditionally grown in regions with a Mediterranean climate, where in some areas, scarce natural precipitation is a limiting factor, with densities varying from 100 to about 300 plants/ha, mostly arranged in squares and poorly mechanized [13–15]. In traditional systems, generally, the canopies of nearby plants never touch each other, so the fruiting is well distributed at the upper and peripheral zone of the canopy [16]. The main problem in this type of planting system is the marked alternate bearing, favored by the age and size of the plant and the decay of the wood, the lack of irrigation, and severe pruning every 3–5 years [17,18]. Mechanical or mechanized harvesting is difficult due to the size of the trees [19–21], the location of the orchard (areas unfavorable to reach), and the layout of the land (high slopes) [22]. Therefore, because of low profitability, most of these traditional, extensive olive orchards were abandoned in the last years, causing dangerous losses of genetic resources and a reduction in chemical and sensory diversification of the oils available in the market [23].

Nowadays, in modern olive orchards for the production of olive oil there is a tendency to use increasingly high-density planting systems, which can be classified as intensive plantings and super-intensive (or super-high density, SHD) plantings. Intensive plantings have a density of 300–1000 trees/ha, with trees arranged in squares or rectangles [24]. This wide range of variation in planting densities depends also on the availability of water at the site. In irrigated olive orchards, it is preferable to increase the planting density up to about 1000 plants/ha, especially if the cultivars used are characterized by modest vigor and early and abundant fruiting [13]. Mechanical harvesting is performed with self-propelled or hauled trunk shakers [25].

Initially, SHD planting systems were based on densities of about 1600 plants/ha, drip irrigation, and using mostly the Spanish cultivars Arbequina and Arbosana. Recently, new varieties have been selected, including Oliana and Lecciana, that allow to further increase planting density up to 2500 trees/ha [26]. A great advantage of SHD systems is the possibility of harvesting with a totally mechanized continuous system. In particular, straddle machines (similar to those used in viticulture) modified for the olive tree are utilized [27,28]. Cultivars suitable for SHD systems are characterized by slow vegetative growth, early fruiting, low alternate bearing, self-fertility, clustered fruiting (3–5 fruits/cob), and, above all, low vigor [13]. Cultivars bearing fruit in the distal part of one-year or current-year branches, which are thinner and less lignified than standard bearing branches, are quite suitable for mechanized harvest [29]. In addition, these cultivars have branches that are more flexible than standard branches [30]. The production capacity of trees depends on the possibility of keeping their canopy within the allotted space, a condition that is achieved through annual pruning, based on both thinning and return cuts. Branches that have exceeded a diameter of more than 3 cm must be eliminated in order not to compromise the efficiency of the straddle machine [29,31]. In the formation of SHD hedgerows, the leaf area density or porosity of the canopy is also an important parameter [32] as it determines the ability of light to reach the canopy inner portions, thus influencing the overall photosynthetic rate, aeration, and the effectiveness of the disease control treatments. Therefore, this system shows high levels of profitability due to both decreasing production costs (mechanical harvesting, pruning, and disease control) and increasing yield/ha through high light interception by relatively small tree canopies [33,34].

Generally, the most popular cultivars used worldwide for SHD olive orchards are Arbequina and Arbosana [35]. Nowadays, the research aims at selecting other cultivars suitable for intensive and SHD systems, with higher adaptability to local environments and markets. Several of the tested cultivars are giving very interesting results, and among those, Calatina, an old Sicilian cultivar originally selected in the south-eastern part of the

island [36], was recently rediscovered and fully characterized [37,38]. It features low vigor and high yield efficiency, showing good potential for intensive hedgerow plantings [23,39].

Recently, significant progress has been made in the development of mathematical models, analytical software, and image analysis tools to make the complexity of perennial plant architecture more comprehensible [1,40]. However, these methods for evaluating the architectural variability may be limited by the need for a significant sample size. Tree architecture can be estimated using qualitative visual criteria based on morphological and botanical concepts [41–43]. Nevertheless, the robustness of qualitative data often has been questioned, and their subsequent analysis is difficult [44]. In addition, the vague or very complicated definitions in the description of complex plant morphological traits contribute to increase the error and reduce the reliability of the collected data [45]. To solve this problem, the development of analytical models as similar as possible to real plant structures has been adopted. Research can be done with 3D computer models, which are often expensive or destructive or even difficult to apply, because of the very long life cycle of trees [46].

In this study, an attempt was made to analyze olive tree architecture using digital images. The use of digital cameras for monitoring natural vegetation and agricultural ecosystems is particularly attractive because it does not require expensive equipment or detailed expertise. In particular, we tested the use of digital images to generate 2D plant reconstructions for the recovery of the main architectural features using specific software.

In order to characterize vegetative and reproductive growth of 'Calatina' olive trees and fine-tune its canopy management, we decided to carry out a detailed study on the growth, architecture, and fruiting traits of 'Calatina' olive canopies, using 'Arbequina' olive as a reference. Specifically, different methods of image analysis were applied for the detailed and localized study of the canopy growth, architecture, and bearing habit at the two-year-old branch level. The results will provide further insight into the suitability of 'Calatina' olive for hedgerow training and continuous mechanical harvest.

2. Materials and Methods

The trial was carried out in an experimental field of the Department of Agricultural, Food and Forest Sciences, University of Palermo, located in Sciacca (AG). A total of 24 two-year-old branches were collected from 12 trees of the olive (*Olea europaea* L.) cultivar Calatina and 12 trees of the cultivar Arbequina three times in two consecutive years, on 27 October 2020 and 29 October 2021, at veraison (right before harvest), and on 16 April 2021, during bloom. Trees were six years old, spaced at 2 × 5 m, and trained to hedgerows. The branches included two-year-old and one-year-old wood and current season shoots.

Samples were labeled, brought to the lab, and weighed with an electronic scale. Each branch was photographed with a digital camera against a white background and under standard light conditions.

Pictures were taken with a ruler placed near the sample as a size reference, to convert image pixels into cm. Three pictures of each branch with their respective weights were taken: branches with leaves and fruits (Figure 1A; front and side views), defoliated branches (Figure 1B), and bare branches (Figure 1C). Photographs of the defoliated branches with fruit were used to determine the fruit percentages in the top, middle, and basal portions of the bearing shoot. Leaves and fruits of each branch were also photographed for leaf area and fruit peel color determinations (Figure 2), respectively.

The EZ-Rhizo II [47] and RhizoVision Explorer [48] software were adapted from the root to branch analysis and used for the study of the architectural and growth traits of the individual samples. The EZ-Rhizo II software was used to determine the length, vector, and branching angle of each shoot in the branches. The ratio between the shoot length and vector was used to calculate the shoot bending degree. The Rhizo Vision Explorer software was used to quantify the branch total length, height, width and area, shoot diameter, and branching frequency in the analyzed samples. Branch area from the frontal views and

average thickness from the side views were used to calculate the branch volume. The ratio between branch total length and volume was used to calculate the branch density. After calibration (pixels into cm), a thresholding step was initially used in both software to separate the woody structures of the branch from the background and binarize (0 = black; 255 = white) the color images (Figure 3).
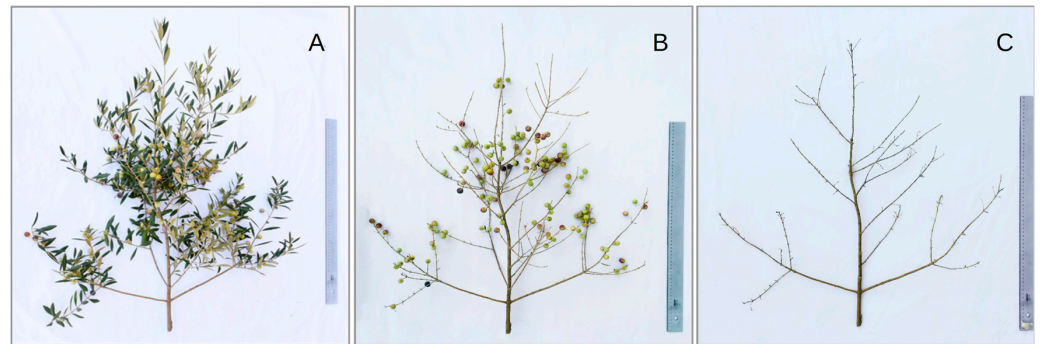

Figure 1. Example of a two-year-old bearing branch with leaves and fruits (**A**), defoliated (**B**), and bare frame **(C)** from 'Arbequina' olive trees.
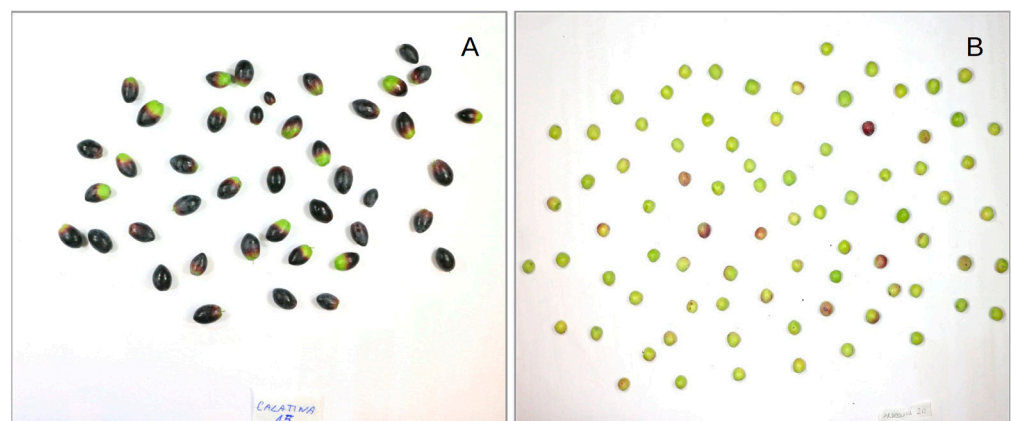

Figure 2. Examples of fruits from two-year-old branches of 'Calatina' (**A**) and 'Arbequina' (**B**) olive trees photographed for peel color analysis.
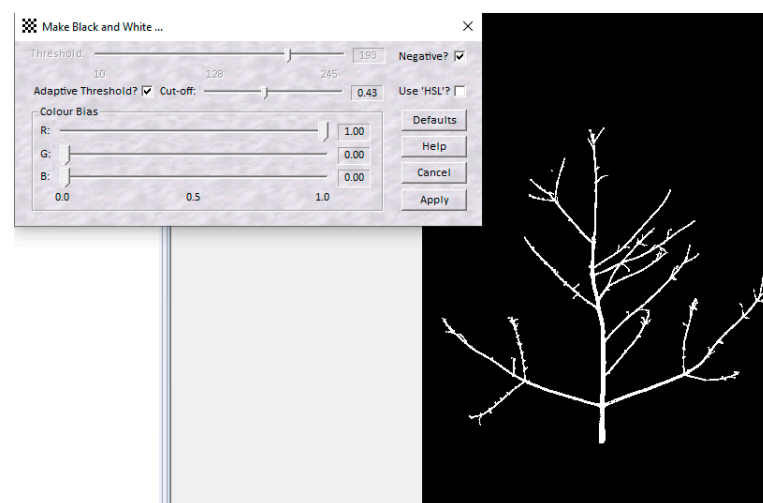

Figure 3. Example of a two-year-old branch from 'Arbequina' olive trees after binarization with the thresholding function of the EZ Rhizo II software.

Weights of the leaves, wood, and fruit were used to describe the growth partitioning, while fruit load (weight), leaf area or weight, and wood weight were used to calculate sink-to-source ratios.

Fruit maturation was estimated only in October 2021 by peel color analysis during the veraison period; i.e., partial peel pigmentation with no flesh pigmentation. Digital images containing all fruits from each branch were analyzed using an algorithm that converts images from the RGB to CIE 1976 L*a*b format, extracts the fruits from the image (removing the image background), and quantifies the color characteristics as the weighted distance of each pixel in the image from a reference sample (dark-purple-colored area interactively chosen from a ripe fruit). A green-red threshold step was used to separate the dark-purple and green regions of the fruit peel. The percentage of dark-purple pixels over the total number of pixels in the fruit was used as the degree of veraison, which is directly related to the degree of fruit maturation.

Data were analyzed by two-factor analysis of variance (ANOVA; cultivar and sampling time) using procedures of the software Jamovi 1.8.4 (The Jamovi project, 2021). Sampling time was used in the ANOVA model as a random replicate factor. Data of growth partitioning and fruit distribution along the shoot were analyzed by two-factor (cultivar and branch organ or shoot portion) ANOVA. When appropriate, Tukey's test ($p < 0.05$) was used to separate means. Data of the degree of veraison were analyzed by *t*-test ($p < 0.05$).

3. Results and Discussion

Branches of 'Arbequina' and 'Calatina' olive had a similar total weight (Table 1). The exact same trend was observed for the fruit load (weight of all fruits in each branch). On the contrary, leaf and wood weights were greater in 'Arbequina' than in 'Calatina' (Table 1). Overall, fruit load was the primary determinant of branch weight.

Table 1. Weight of two-year-old bearing branches and its components from 'Arbequina' and 'Calatina' olive trees.

	Arbequina	Calatina	*p*-Value [z]
Branch weight (g)	177 ± 17.9	162 ± 14.6	0.496
Leaf weight (g)	54.3 ± 4.96	39.0 ± 2.95	0.003
Weight of fruits (g)	109 ± 12.6	127 ± 11.2	0.220
Wood weight (g)	45.1 ± 3.97	35.6 ± 3.26	0.047

[z] Level of significance for the cultivar factor from the analysis of variance.

'Arbequina' partitioned more fresh matter into leaf than 'Calatina', while the latter partitioned more fresh matter into fruits than 'Arbequina'; partitioning to wood was similar in the two cultivars (Figure 4). Similarly, the fruit/leaf ratio was in favor of 'Calatina', confirming a greater production efficiency in the Sicilian cultivar than in 'Arbequina' (Table 2). Both leaf area and number of fruits were greater in 'Arbequina' than in 'Calatina', while the average fruit weight was significantly greater in 'Calatina' (Table 2). Basically, the large fruit size of 'Calatina', which is for the most part a genetic trait and did not depend on crop load or more advanced maturation, totally offset the lower number of fruits, leading to a similar fruit load per branch in the two cultivars. The presence of fewer but larger fruits favors fruit detachment at harvest, indicating a higher efficiency of trunk-shaking and straddle machines in 'Calatina'.

In terms of vegetative growth, the two cultivars were equally efficient, showing a similar leaf/wood ratio (Table 2). This is an important parameter also for continuous harvesting with straddle machines. Cultivars with a low leaf/wood ratio may expand lignified structures away from the main frame, thus interfering with the shakers of the straddle machine and suffering major limb damages [49]. In this case, the similar leaf/wood ratio suggests that 'Calatina' is suitable to straddle harvesting as much as 'Arbequina' is.

Despite the non-significant differences in branch length and width between the two cultivars, branches of 'Calatina' exhibited a significantly different shape (shorter and slightly wider) than those of 'Arbequina' (Table 3). Branch volume was similar in the

two cultivars, while total shoot length was greater in 'Arbequina' than in 'Calatina' reflecting data of fresh weight. The result of this combination of branch shape, volume, and total shoot length was a greater branch density in 'Arbequina' than in 'Calatina'. This suggests a better light penetration and wind flow (less humidity) within canopies of 'Calatina'. No significant difference between the two cultivars was observed in terms of branching frequency (level of dichotomy) and branching angle, posing the two cultivars at the same level in terms of harvest efficiency by trunk shakers.
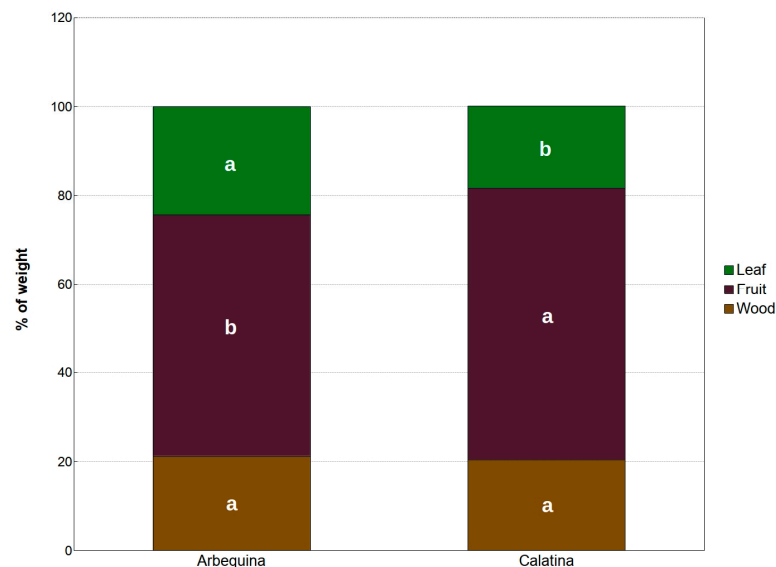

Figure 4. Percentage of leaf, fruit, and wood in two-year-old bearing branches from 'Arbequina' and 'Calatina' olive trees. Different letters indicate significant differences between cultivars for each branch component (Tukey's test, $p < 0.05$).

Table 2. Leaf area, number of fruits, average fruit weight, and source–sink ratios in two-year-old bearing branches from 'Arbequina' and 'Calatina' olive trees.

	Arbequina	Calatina	*p*-Value [z]
Leaf area (dm^2)	12.5 ± 1.22	9.08 ± 0.70	0.006
Number of fruits	85.1 ± 9.83	39.0 ± 3.85	<0.001
Fruit weight (g)	0.90 ± 0.15	2.25 ± 0.38	<0.001
Fruit/leaf (g/cm^2)	2.42 ± 0.19	3.76 ± 0.32	<0.001
Leaf/wood (cm^2/g)	1.21 ± 0.04	1.19 ± 0.06	0.883

[z] Level of significance for the cultivar factor from the analysis of variance.

Table 3. Branch and shoot size and architecture in two-year-old bearing branches from 'Arbequina' and 'Calatina' olive trees.

	Arbequina	Calatina	*p*-Value [z]
Length (cm)	60.2 ± 2.26	54.9 ± 2.20	0.081
Width (cm)	47.7 ± 2.25	50.5 ± 2.69	0.431
Width:Height	0.82 ± 0.04	0.96 ± 0.06	0.033
Volume (dm^3)	78.1 ± 15.0	62.7 ± 8.18	0.377
Total length (m)	3.39 ± 0.23	2.63 ± 0.17	0.002
Density (m m^{-3})	78.3 ± 7.73	54.9 ± 4.52	0.004
Branching frequency (n. branching/m)	25.8 ± 3.54	28.4 ± 3.65	0.281
Branching angle (°)	45.8 ± 1.14	45.2 ± 1.59	0.430
Shoot length (cm)	21.0 ± 0.64	22.5 ± 0.92	0.276
Shoot diameter (mm)	3.32 ± 0.06	3.27 ± 0.09	0.546
Shoot bending degree	1.10 ± 0.003	1.12 ± 0.005	<0.001

[z] Level of significance for the cultivar factor from the analysis of variance.

Average shoot length and diameter were similar in the two cultivars, while branches of 'Calatina' tended to have shoots with a greater ability to bend than those of 'Arbequina' (Table 3). Flexible and bending shoots are features that favor straddle harvesting [29,30,50], providing further evidence of the suitability of 'Calatina' for this harvesting method.

Fruit distribution along the bearing shoot was different in the two cultivars. Specifically, the two cultivars had similar percentages of fruit in the middle and basal portions, while 'Arbequina' bore more fruit than 'Calatina' in the top portion of the shoot (Figure 5). This small difference between the two cultivars may slightly favor 'Arbequina' in terms of straddle harvesting as fruits in the terminal portion of the shoot are generally detached more effectively [29].
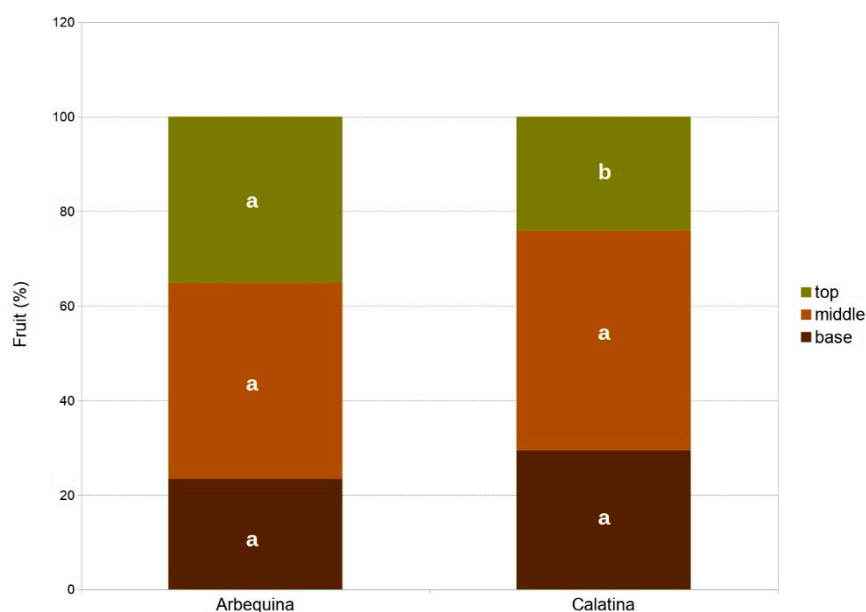

Figure 5. Percentage fruit in the top, middle, and base portions of the bearing shoots from 'Arbequina' and 'Calatina' olive trees. Different letters indicate significant differences between cultivars for each shoot portion (Tukey's test, $p < 0.05$).

Fruit maturation was definitely more advanced in 'Calatina' than in 'Arbequina', as shown by the significantly ($p < 0.001$) higher percentage of purple-black peel color in the former (69%) than in the latter (1%). Such a big difference in maturation degree did not depend on the ON-year fruit load (number of fruits is the average of two consecutive seasons) and suggests the significant advantage of 'Calatina' as an early harvest allows for taking fruit to the mill in a non-congested period; this in turn means a shorter waiting time before milling and higher olive oil quality. It also lowers the chance of adverse weather conditions in the Mediterranean regions and significant attacks from the olive fly. Indeed, late-maturing olives may have a greater chance to be harvested and taken to the mill over a long period of time (adverse weather), as well as to suffer attacks from the olive fly, with significant losses due to fruit drop and/or a low-quality olive oil.

4. Conclusions

The results of the present trial show that the Sicilian olive cultivar Calatina is similar to the international reference cultivar Arbequina in several architectural traits. This indicates that 'Calatina' has great potential for both intensive and SHD olive plantings trained to hedgerows. 'Calatina' also showed to be superior to 'Arbequina' for specific traits such as shoot bending degree (higher) and branch density (lower), which should qualify the Sicilian cultivar for high-efficiency straddle harvesting and intensive hedgerow systems, respectively. Last but not least, the Sicilian cultivar allocated more growth into fruit than vegetative organs, bearing fewer but larger early maturing fruits than 'Arbequina'.

This, along with the already documented low tree vigor and high yield efficiency [23], further qualifies 'Calatina' as a superior, yield-efficient olive cultivar potentially suitable for intensive hedgerow plantings to be harvested with straddle or side-by-side trunk-shaker machines in the warm and dry Mediterranean areas of southern Sicily.

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