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Two Almond Cultivars Trained in a Super-High Density Orchard Show Different Growth, Yield Efficiencies and Damages by Mechanical Harvesting

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Abstract: Modern almond growing travels on the tracks of super-high density (SHD). Born in 2010, it has already reached 6700 ha planted all over the world. This new cultivation system needs to define efficient agronomic techniques in order to identify it as a "Super-Efficient System". Among these, the choice of cultivar is a crucial technique and a key factor for sustainability. The purpose of this study was to compare different cultivars in terms of vegetative, productive, and efficiencies parameters in order to gain applicable relevant knowledge about the SHD almond cultivation technique. For this, 3 years of research was carried out during 2017–2019, on a young almond grove made in 2014 with row spacing of 3.80 m × 1.20 m (2190 trees/ha), to evaluate the agronomic behavior of the two most planted cultivars in Italy, Guara-Tuono and Lauranne® Avijor, grafted on the Rootpac®20 dwarfing rootstock. The main biometric, productive, yield, mechanical harvesting efficiencies, and almond quality parameters were evaluated. Cv Lauranne® showed greater vigor, greater fruit yield, and damaged axes by mechanical harvesting, while higher values of yield efficiencies were observed for cv Tuono. Harvesting efficiency was related to canopy size and tree age. On the contrary, almonds quality parameters were strongly related to the cultivar, confirming the good performance of Tuono as varietal characters. Then, this cultivar seems to be the most suitable for an efficient SHD planting system, in line with the objectives of modern sustainable fruit growing. The better performance of cv Tuono could be related to the positive influence of the *terroir* as well.

Keywords: Guara, Tuono; Lauranne®; Avijor; canopy size; mechanical harvest; damaged axes; shelling percentage; hull-tight nuts; double seed; *terroir*

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1. Introduction

The almond tree (*Prunus dulcis* Mill. = *Prunus amygdalus* Batsch) is the most important nut fruit produced and consumed throughout the world [1]. Almond acreage and production increased fairly consistently every year, recording +196% in the last decades [2]. Global almond market revenue was $10.5 billion and global almond production stood at 2.4 million tons in 2018, up 3.8% from the previous year [3]. In 2019/2020, 30% of global nut production and consumption consisted of almonds, with production increasing by 26% in the last 10 years [1]. Since 2013, a super high-density cropping system has been discovered, resulting in an increment of almond orchards worldwide to over 2.1 million hectares [2]. World production raised 1,684,395 tons in 2020, lead by USA and Spain occupying the second place [3–5]. Until now, the most used cultivation systems were the traditional low-density system and the medium-high system [6]. The traditional system is characterized by less than 350 trees per hectare, with tree spacings from 8 × 8 m to

6 × 6 m, the application of vigorous rootstocks; no mechanization and no irrigation [6,7]. The medium-high density system, instead, is characterized by 250 to 700 trees per hectare, with tree spacings from 6 × 4 m to 5 × 3.6 m medium to high levels of mechanization of the most important cultivation technique, like pruning and harvesting, using pruners and trunk shaker harvesters [6,7].

Even in Italy, where annual production has decreased linearly since 1960, an increment has been observed, making the country the fifth biggest almond producer in the world [1,2]. This new cropping system is based on the modern concept of agriculture, with a different "mindset" for almond cultivation. Mechanization and sustainability are the keys to improve efficiency and productivity and are the main guidelines for modern agriculture. They can significantly increase natural resources, use efficiency, reduce labor, and consequently reduce production costs [4,5]; moreover, they are replacing the traditional rain-fed almond cropping system based on a few large trees that do not allow mechanization and agronomic efficiency [8]. The new almond cropping system is based on the experience of the last 25 years in SHD olive orchards, which have already shown a high level of agronomic [9–13], economic [5,14], and environmental [15] sustainability. In the last decade, Agromillora Group started to develop super high-density almond orchards to solve the problems of traditional systems [16]. The first commercial SHD almond orchard was planted in Lleida in 2010 and within a very short time, all almond-producing countries started planting SHD orchards [17,18]. Currently, more than 6500 ha of super high-density almond trees are scattered all over the world: Spain, Portugal, Italy, USA, Morocco, Tunisia, Chile, and Turkey among others [5,16]. Super high-density almond orchards are characterized by a plantation using "Smarttree" plants, grafted on Rootpac-20 ® (Densipac; *P. besseyi* × *P. cerasifera*), a new vigor/size controlling rootstock developed by the genetic breeding programme carried out by the R&D department of Agromillora [19]; a wide range of cultivars, like Lauranne® Avijour and Guara Tuono; a tree spacing of 3–3.5 × 1–1.2 m, resulting in more than 2000 trees per hectare; early bearing, at the third year; fully mechanization of different operations, using pruners and straddle harvesters; increase in crop profitability and sustainability due to less inputs and production costs [6,16]. These new cropping systems are also called a 'Sustainable and Efficient System'/'Sustainable and Efficient Solutions', or SES, because they make better use of natural resources, such as soil and water, and agronomic inputs, such as fertilizers and phytosanitary treatments, than the open-center orchards [20,21]. The first almond SHD orchard in Italy was planted in Andria (Apulia, southern Italy) in 2013, followed by many Italian companies, which thus gave new life to almond cultivation [22].

Today, almond SHD orchards mainly use four cultivated varieties: 'Soleta', 'Lauranne® Avijor', 'Penta', and 'Guara-Tuono' [5]. In Italy, 48% and 39% of the total SHD almond areas are planted with 'Lauranne® Avijor' and 'Guara Tuono', respectively, without apparent scientific criteria (unpublished Agromillora data). Although the choice of Rootpac-20® (Densipac) as rootstock for SHD almond orchards is relevant to control the trees vigor, early production, and to improve adaptation to a particular soil [5,17,23], the cultivar's choice is a key factor, among the agronomical techniques, since it could influence the orchard performance.

Intensification in tree planting systems is now mandatory to achieve the sustainable food production targets set by 2050, also through the application of techniques that will lead to the so-called "sustainable intensification" of agricultural production [24–27]. For this reason, production efficiency is one of the key factors in modern agriculture, also evaluated in other important fruit orchards, such as sweet cherry [28] and apple [29–33]. In almond production, the adoption of the SHD cropping system, as the main component of SES seems promising [21]. Use efficiency of inputs and environmental sustainability are requirements established in the "From farm to fork strategy" of the "Green Deal" made in 2020 by the European Union [34], which can be easily achieved using this system.

In order to evaluate cropping system performances, a wide range of vegetative and productive parameters could be evaluated, as in modern medium to high-density almond orchards (HD; about 300 to 1000 trees/ha) did [7,35–41]. The percentage of fruit harvested related to the fruit set is the most correct method to estimate the harvesting efficiency, by calculating how much fruits remain both on the trees and on the ground after harvest [42]. In SHD olive orchards, fruit losses range from 2 to 10%, resulting in 90–98% of harvesting efficiency [12,13,42–45]. Sola-Guirado [46] reported that the vibration behavior of SHD olive groves, observed in time and frequency domains, showed that only the 62% of the calculated vibration time is used to detach fruits in the tunnel of the harvester, paying attention to fruit detachment force values. The highest efficiencies are found when the detachment index was around 2.7 cN g^{-1} [10].

In HD almond orchards, Loghavi et al. [47] determined the most appropriate shaking amplitude and frequency to achieve maximum fruit removal with minimal leaf fragmentation and branch damage. Results show that over-row contact shakers are efficient and cause little damage to trees, which has always been a problem with mechanical harvesting system [13]. The percentage of damaged axes ranges from 0 to 30% [47,48], but larger hedge dimensions lead to an increment of damaged axes [44,49]. No data are available for almond SHD.

As in other deciduous fruit species, such as in apple and peach [50,51], almond yield and quality are primarily genotype-dependent [52,53]. Hull-tight nuts' percentage has been widely studied, observing a major influence of environmental conditions on the expression of this trait [54]. The percentage of double seeds is a problem, as it can lead to a significant reduction in the value of harvested almonds [54,55]. This characteristic is strictly related to the cultivar [56], but environmental situations [57–59] or particular techniques [60] can lead to a deviation from the varietal values. Shelling percentage has been analysed in the past, with a specific range for each cultivar [7,38,41,54,61].

Due to the recent introduction of the SHD system on almond trees, few studies have been conducted on its performances up to now. Dias [62] studied the evaluation of biometric parameters of different cultivars. Iglesias [5,23] studied the effect of spacing on yield by increasing light interception and radiation absorption by optimizing the ratio between row spacing and border height to 1/1.1 under Spanish Mediterranean conditions. In north-south (N-S) oriented orchards, narrowing the inter-row SHD distances (from 4.0 to 3.5 and 3.0 m for V1, V2, and V3 versions, respectively) significantly increased yields by 31% and 65% compared to the first version and V1, respectively. Casanova-Gascon et al. [21] studied light interception in an SHD almond orchard compared to an open-center system, which may have problems with "sink leaves" and fruit yield in the SHD system. Maldera et al. [22] studied the effects of two different row orientations (N-S and E-W) and canopy position on LAI, PAR, biological, phenological, and agronomic parameters. However, no work has been published yet on the growth, yield, and mechanical efficiencies and quality parameters of different almond cultivars in the SHD system. Therefore, the purpose of this study was to compare the two most used cultivars in terms of vegetative, productive, and efficiencies parameters in order to provide applicable relevant knowledge about the SHD almond cultivation technique.

2. Materials and Methods

2.1. Site and Orchard

A 3-year study was carried out in an irrigated almond SHD orchard from 2017 to 2019, corresponding to the 4th, 5th, and 6th year after planting (YAP). Two cultivars were studied: Tuono (syn. Guara; [63,64]), an important self-compatible hard-shelled cultivar native of Apulia, and Lauranne® Avijor, a hard-shelled cultivar obtained by INRA-Avignon, from a cross ('Ferragnes' × 'Tuono'), made in 1978 and registered in 1991 [65,66]. The orchard (Figure 1) was planted in 2014 in Andria, southern Italy (41°09′47″ N, 16°13′29″ E; 260 m a.s.l.) with a tree spacing of 3.8 × 1.2 m apart (2190 trees ha^{-1}). Rootpac-20® (Densipac; *P. besseyi* × *P. cerasifera*), a new vigor/size controlling rootstock from Agromillora was used [5,6,16]. The climate of the region is typical Mediterranean, with an annual rainfall of 523 mm concentrated from autumn to spring; the lowest amount of monthly rainfall occurs in July (22 mm), in November the highest one (61 mm). The average temperature of the year is 15.3 °C, in which the hottest month is August (23.8 °C) and the coldest one is January (7.8 °C). The soil was a clay-loam, 40 cm depth with properly expanded roots. The orchards were managed using common practices diffused in the area; drip lines were used, and the controlled irrigation was applied, with a mean seasonal irrigation volume of 3000 m^3/ha. The plots were supplied annually with 80 kg/ha of N, 40 kg/ha of P, and 80 kg/ha of K. One-year-old trees were planted in July 2014 and trained in the first version (V1) of central axis [5,21,62]. First trimming was done by hand in the middle May 2015. Consecutives mechanical summer pruning were applied 2–3 times/season. During the first and second year, the trimming in between consecutive trees on the row was manual and preformed once a year. The objective was a multiplication of lateral branches to fill as soon as possible the space assigned to each tree. At the end of second year, the trees filled approximately the 70% of the edge volume. In 2016 and consecutive years, after and before harvesting, mechanical topping was made to size the tree canopy to the harvesting machine used, together with hedging and trimming. Two experimental plots were established, one for each cultivar. Each plot consisted of five rows, in which the three central rows were identified as the sampling area.

2.2. Climate Data

Monthly maximum, minimum, and mean temperature and rainfall were detected. Data were taken from the weather station located in Andria of the Apulia Region Civil Defense.

2.3. Sampling

All parameters were determined on 10 trees, divided into two blocks of five, randomly chosen in each experimental plot among the trees of the sampling area (three central rows).

2.4. Growth

Tree height (TH; cm), tree width (TW; cm), and trunk diameter (TD; cm) were measured at 39 BBCH Stage [61]. Tree cross-sectional area (TS; cm^2) was calculated as:

$$TS = \pi * (TD^2)/4. \quad (1)$$

Canopy volume (CV; m^3) was calculated considering a parallelepiped (Figure 2), in which 0.4 m in height was subtracted, representing the distance of the first branches from the ground, multiplied by TW and 1.2 m, representing the row distance between two adjacent trees:

$$CV = (TH - 0.4 \text{ m}) * TW * 1.2 \text{ m}. \quad (2)$$

(a)

Figure 1. *Cont.*

(**b**)

Figure 1. Guara Tuono (**a**) and Lauranne® Avijour (**b**) trees in the experimental plots.

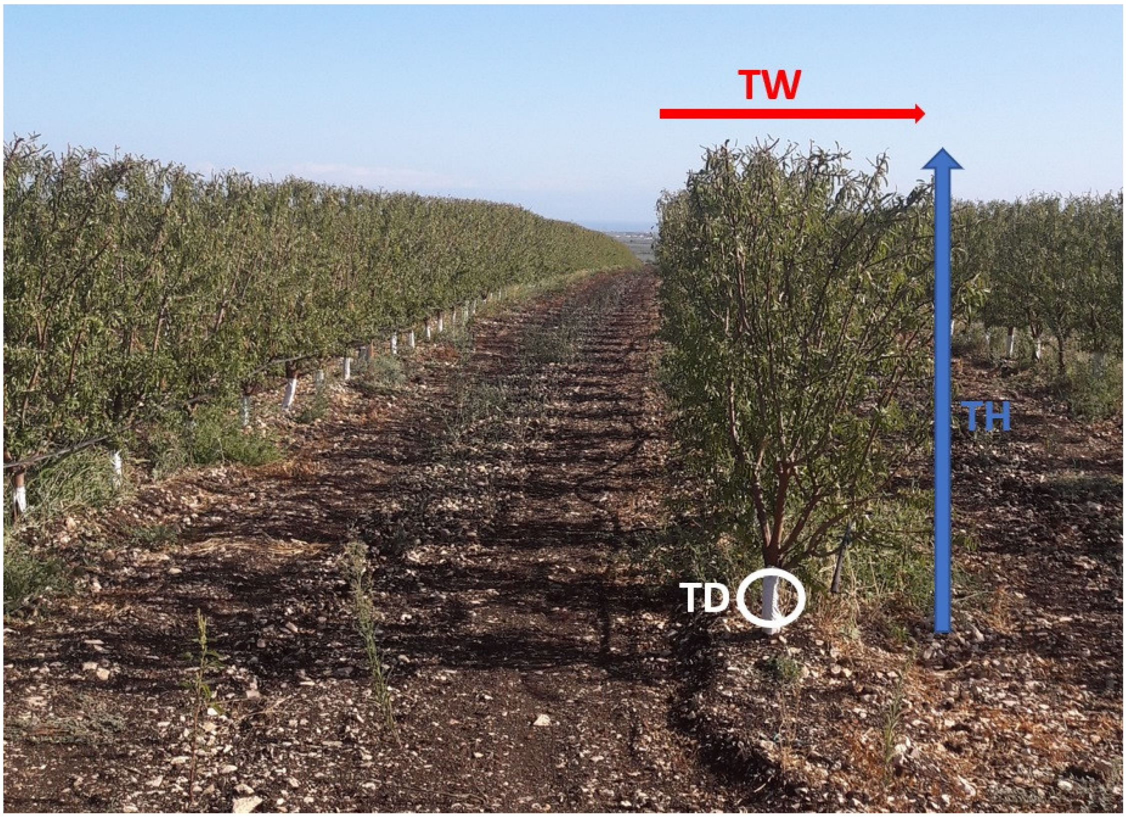

Figure 2. Canopy measurements carried out.

2.5. *Yield and Yield Efficiencies*

At harvesting time (85 BBCH stage [61]), all the fruits for each tree were manually collected to measure the in-shell fruit yield (FY; g or kg/tree). Yield efficiency on canopy volume (YV; kg/m^3) was calculated as:

$$YV = FY/CV, \quad (3)$$

while yield efficiency on trunk section (YT; g/cm^2) was calculated as:

$$YT = FY/CV, \quad (4)$$

2.6. Harvesting Efficiency and Damaged Axes

The straddle harvester Gregoire G167 was used. The fruits were harvested when >75% showed hull split. Harvesting efficiency (HE; %) was calculated by dividing the number of fruits still attached to the tree and those fallen to the ground by FY. The percentage of damaged axes (DA; %) was calculated by dividing the number of damaged axes by the total vegetative axes of each tree.

2.7. Fruits Quality Parameters

Three samples of 100 almonds for each cultivar were taken randomly from the total collected yield, to measure shelling percentage (SP; %), hull-tight nuts (HT; %) and double seed (DS; %).

2.8. Data Analysis

Field data collected were analyzed by one and two-way analysis of variance (ANOVA) followed by post hoc testing (SNK protected test) using the R 2.15.0 software (R Foundation for Statistical Computing); standard error (SE) was also calculated and shown in the figures.

2.9. Weather Data

Climate data are shown in Figures 3 and 4. Average monthly temperatures in 2017 and 2018 were quite similar to the normalized mean temperature. Average fluctuations of 1.5 °C were recorded compared to the thirty-year average, with peaks of 2.9 °C in April 2018 (16.7 compared to 13.8 °C) and June 2017 (25.1 compared to 22.2 °C). The year 2019 showed a different trend: March showed a higher mean value than the previous years. A major drop was recorded in May (15.9 °C), while all other means in the same month were above the 18 °C. In June, there was an increment of 10 degrees, recording the highest average monthly value (25.4 °C). Minimum and maximum temperatures followed the same trend of mean temperatures. The coldest year was 2017, the hottest was 2019. Highest annual rainfall was recorded for 2018 and 2019, while 2017 showed the lowest values. The normalized mean showed intermediate values, with a difference of 150 mm of rain from both higher and lower values. Monthly rainfall over 100 mm of precipitation was recorded in January for 2017, in March, June, and October for 2018 and in April for 2019.

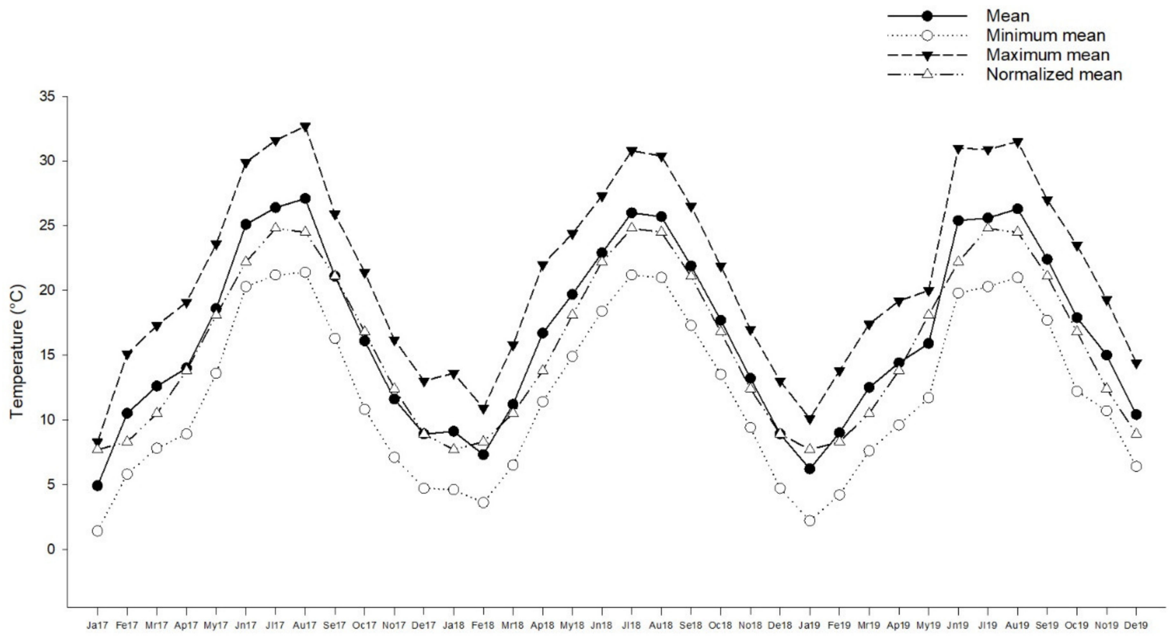

Figure 3. Average, minimum, and maximum monthly temperatures of 2017–2019 and the pluriannual mean (°C).

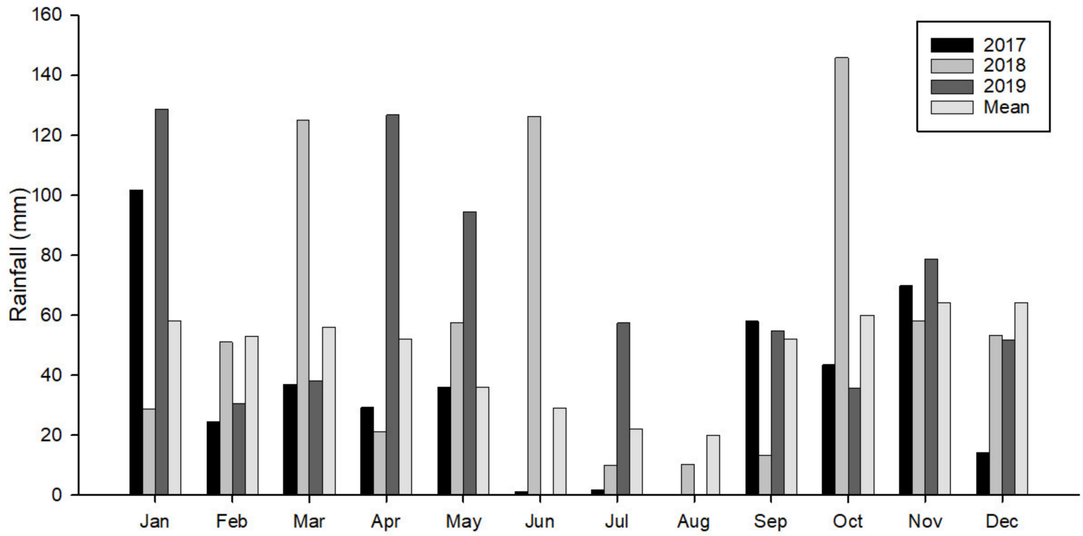

Figure 4. Monthly rainfall of the 2017–2019 and the pluriannual mean (mm).

3. Results

3.1. Growth

Tree height (TH) showed significant differences between the cultivars and among the years (Figure 5). Tuono showed an increasing growth from 2017 to 2019, when the highest values were reached (219.0 cm), below the threshold value of 270 cm. On the contrary, Lauranne nearly reached the maximum values in 2017 and exceeded it in 2019 (279.5 cm); for this reason, the trees were topped at the end of the first year Moreover, Lauranne presented significantly higher mean values than Tuono in 2017 and 2019 (249.8 and 279.5 cm, 171.6 and 219.0 cm, respectively). Finally, TH in 2018 showed no differences between the cultivars, due to the topping on Lauranne trees (203.0 cm).

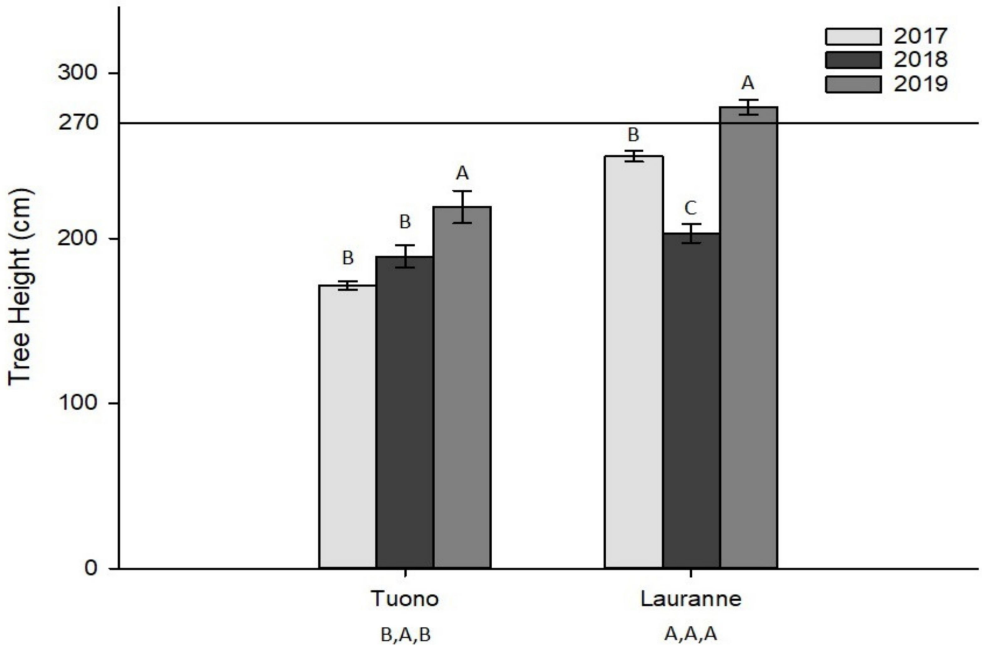

Figure 5. Tree height (cm) of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The letters on the bars denote statistical differences among the years for each cultivar; the letters on the x-axis denote statistical differences between cultivars for each year (SNK test). Letters denote statistical differences at $p = 0.01$. The horizontal line set at 270 cm indicates the threshold value.

A similar behavior was recorded for tree width (TW) (Figure 6). Tuono registered a steady growth from 2017 (93.0 cm) to 2019 (131.0 cm), when the threshold value of 120 cm was reached. Lauranne showed the significantly highest TW value in 2017 (158.9 cm), after that hedging was operated in order to restrain the canopy within the right size; no significant difference was observed between 2018 and 2019 (120.0 and 134.0 cm). Only in 2017, significant differences between the two cultivars were reported, with a higher average TW value for Lauranne (93.0 cm for Tuono and 158.9 cm for Lauranne). Both cultivars exceeded the maximum width in 2019.

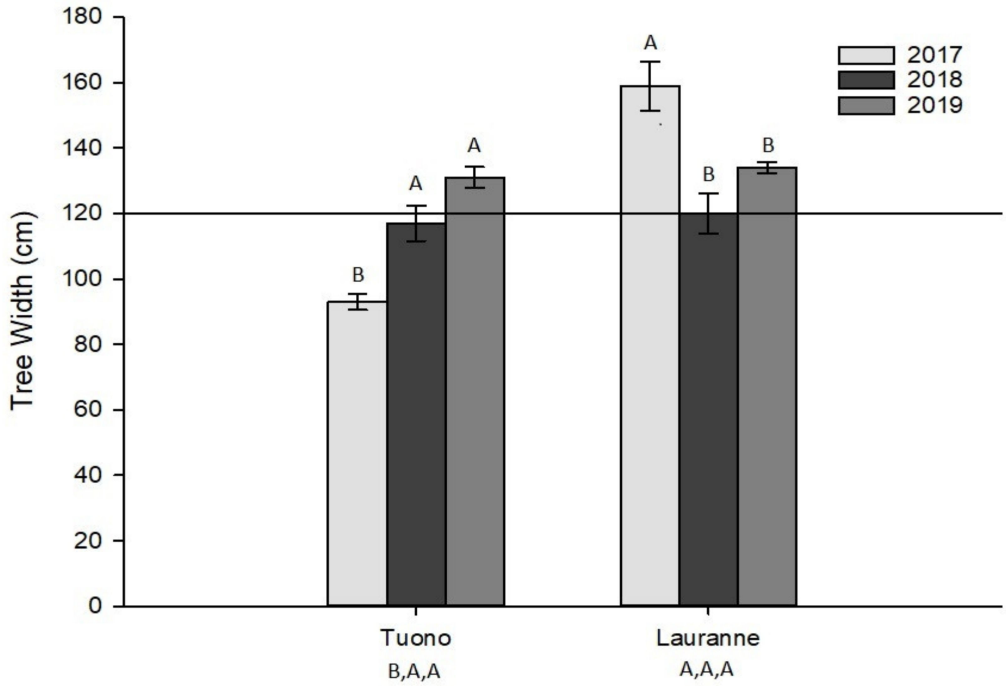

Figure 6. Tree Width of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The letters on the bars denote statistical differences among the years for each cultivar; the letters on the x-axis denote statistical differences between cultivars for each year (SNK test). Letters denote statistical differences at $p = 0.01$. The threshold values are also indicated.

3.2. Yield and Other Growth Parameters

Fruit yield (FY) showed significant differences between cultivars and among years (Table 1). Lauranne produced almost 0.5 kg/tree more than Tuono, leading to a slight statistical difference (2.47 and 2.02 kg, respectively). Tuono showed a significant growth from 2017 (1.44 kg/tree, 3.15 t/ha) to 2019 (2.41 kg/tree, 5.28 t/ha). Lauranne showed the highest FY mean value (3.45 kg/tree, 7.56 t/ha) in 2018 and an intermediate value in the subsequent year 2019 (2.46 kg/tree, 5.39 t/ha). Tuono yielded significantly less than Lauranne in 2018 only.

Trunk section (TS) showed a growth during years and between cultivars (Table 1). All TS mean values represented a statistical difference between the two cultivars, with higher values for Lauranne. For Tuono, the TS values recorded during 2018 and 2019 (26.6 cm^2 and 28.3 cm^2), almost equivalent, were statistically higher than the 2017 values (16.3 cm^2). Lauranne showed the highest TS mean value in 2019 (41.6 cm^2), statistically higher than 2017 and 2018 (24.5 and 32.5 cm^2, respectively).

The canopy volume (CV) showed important differences between cultivars and among years (Table 1). An average CV value was observed almost twice as high in Lauranne as in Tuono (3.41 and 2.13 m^3, respectively). For Tuono, CV raised constantly during the years, reaching the highest value in 2019 (2.81 m^3). Lauranne showed a significant decrement in 2018 (2.36 m^3), statistically lower than other years' value (4.0 and 3.85 m^3 for 2017 and 2019, respectively), due to a pruning applied to restrain the canopy size within the thresholds.

Lauranne showed higher mean values than Tuono in 2017 (4.0 and 1.46 m^3) and 2019 (3.85 and 2.81 m^3), while no statistical differences were found in 2018 (2.36 and 2.12 m^3).

Table 1. In-shell almond yield, trunk section, and canopy volume of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The first letters denote statistical differences between cultivars for each year; the second letters denote statistical differences among years for each cultivar. Lower case letters denote statistical differences at $p = 0.05$; capital letters denote statistical differences at $p = 0.01$. (SNK test).

Parameters	Tuono				Lauranne			
	2017	2018	2019	Mean	2017	2018	2019	Mean
Fruit Yield (kg tree^{-1})	1.44 A,B	2.22 b,A	2.41 A,A	2.02 b	1.52 A,B	3.45 a,A	2.46 A,AB	2.47 a
Fruit Yield (t ha^{-1})	3.15 A,B	4.86 b,A	5.28 A,A	4.42 b	3.33 A,B	7.56 a,A	5.39 A,AB	5.41 a
Trunk Section (cm^2)	16.3 b,B	26.6 b,A	28.3 B,A	-	24.5 a,B	32.5 a,B	41.6 A,A	-
Canopy Volume (m^3)	1.46 B,C	2.12 A,B	2.81 B,A	2.13 B	4.0 A,A	2.36 A,B	3.85 A,A	3.41 A

3.3. Yield Efficiencies

Statistical differences were found for the efficiency on trunk section (YT) between cultivars (Figure 7). No statistical differences were found among years for Tuono. Lauranne showed the highest value in 2018 (105.7 g cm^{-2}), while equal values were found in 2017 and 2019 (60.2 and 60.1 g cm^{-2}). In 2017, Tuono showed almost the double of Lauranne YT (118.1 and 60.2 g cm^{-2}, respectively). A similar situation was recorded in 2019, while 2018 mean values were statistically equal in both cultivars (81.7 and 105.7 g cm^{-2}).

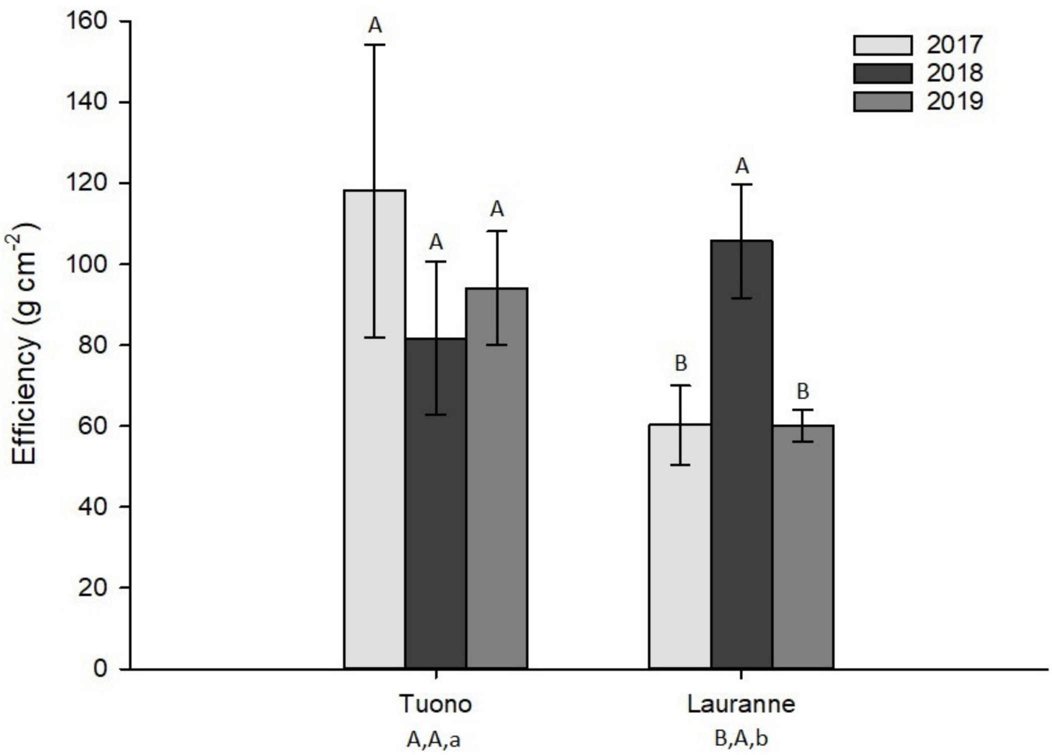

Figure 7. Efficiency on trunk section (g cm^{-2}) of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The letters on the bars denote statistical differences among years for each cultivar; the letters on the x-axis denote statistical differences between cultivars for each year (SNK test). Lower case letters denote statistical differences at $p = 0.05$; capital letters denote statistical differences at $p = 0.01$.

Similar results were observed for the efficiency on canopy volume (YV) (Figure 8). No statistical differences were found among years in Tuono. In 2018, Lauranne showed the highest YV mean value (1.43 kg m^{-3}), while 2017 and 2019 values were statistically the same

(0.38 and 0.63 kg m^{-3}, respectively). Tuono showed higher mean values than Lauranne in 2017 (0.95 and 0.38 kg m^{-3}) and 2019 (0.90 and 0.63 kg m^{-3}). An opposite situation was observed in 2018, in which Lauranne presented the highest value (1.43 kg m^{-3}).

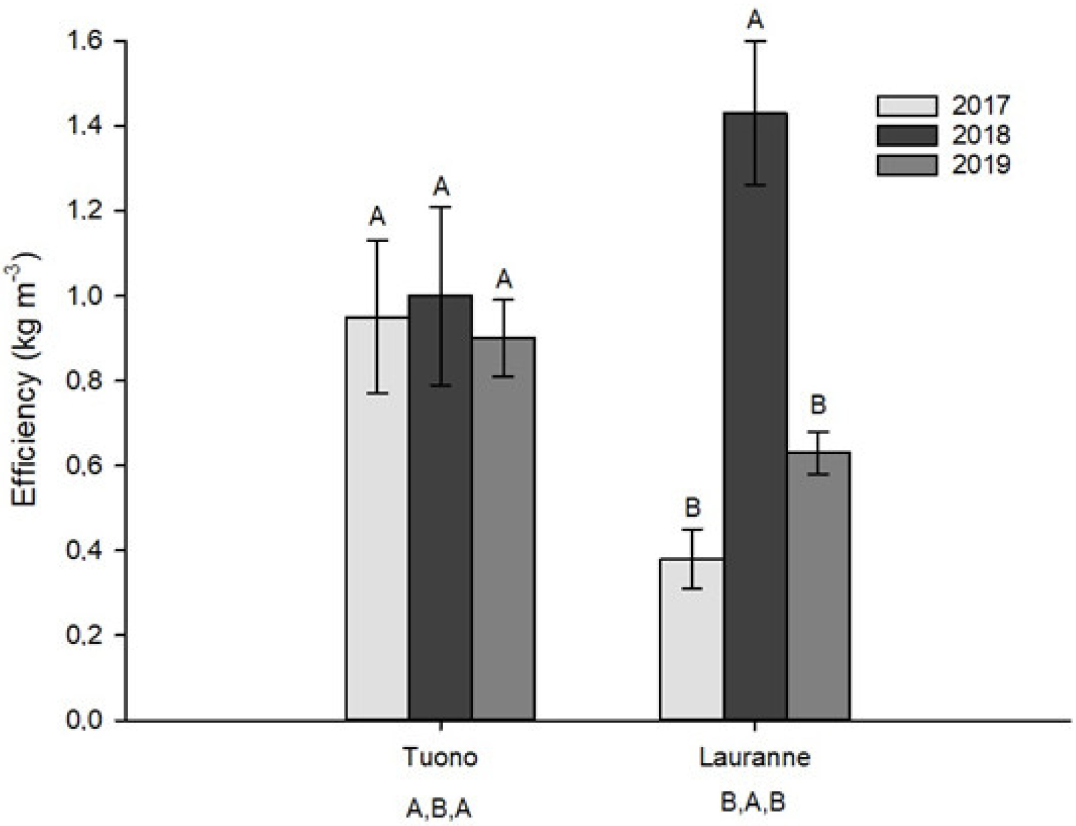

Figure 8. Efficiency on canopy volume (kgm^{-3}) of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The letters on the bars denote statistical differences among years for each cultivar; the letters on the x-axis denote statistical differences between cultivars for each year (SNK test). Lower case letters denote statistical differences at $p = 0.05$; capital letters denote statistical differences at $p = 0.01$.

3.4. Harvesting Efficiency and Damaged Axes

Because of the number of fruits still attached to the tree was neglectable for both cultivars and all years, the harvesting efficiency (HE) was calculated considering only the fruits fallen to the ground. Statistical differences were found between cultivars in 2019 (Table 2), when both cultivars showed the lowest values (71.1% for Tuono, 85.4% for Lauranne). Any other statistical difference was found.

Table 2. Harvested fruits and damaged axes of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The first letters denote statistical differences between cultivars for each year; the second letters denote statistical differences among years for each cultivar ($p = 0.05/0.01$; SNK test).

Parameters	Tuono				Lauranne			
	2017	2018	2019	Mean	2017	2018	2019	Mean
Harvested Fruits (%)	94.3 A,A	97.6 A,A	71.1 B,B	87.6 A	94.1 A,A	95.1 A,A	85.4 A,B	91.5 A
Damaged Axes (%)	3.33 B,B	5.98 A,A	6.73 b,A	5.35 b	6.74 A,b	5.06 A,b	9.06 a,a	6.94a

Damaged axes percentages (DA) varied during the years and between cultivars (Table 2). Lauranne showed the highest mean percentage of about 7% (6.94%), while Tuono stood at values close to 5% (5.35%). Cv Tuono showed in 2017 the lowest DA percentage (3.33%), while 2018 and 2019's values increased and remained unchanged (5.98% and

6.73%, respectively). In the same manner, DA of cv Lauranne increased from 2017 and 2018 to 2019 (6.74%, 5.06% and 9.06%, respectively). Only in 2018 the two cultivars presented the same DA percentage.

3.5. Quality Parameters

Lauranne showed slight but not significantly higher shelling percentage (SP) values than Tuono (38.2 and 35.7 % respectively) (Table 3). During the years, both cultivars did not show significant differences.

Table 3. Fruit quality parameters of cultivars Tuono and Lauranne in three subsequent years (2017–2019). The first letters denote statistical differences between cultivars for each year; the second letters denote statistical differences among different tree years for each cultivar ($p = 0.01$; SNK test).

Parameters	Tuono				Lauranne			
	2017	2018	2019	Mean	2017	2018	2019	Mean
Shelling (%)	35.8 A,A	34.9 A,A	36.3 A,A	35.7 A	36.7 A,A	40.7 A,A	37.2 A,A	38.2 A
Hull-Tight Nuts (%)	0.33 A,A	1.00 A,A	2.00 B,A	1.11 B	1.67 A,B	1.33 A,B	10.0 A,A	4.33 A
Double Seeds (%)	16.0 A,A	15.0 A,A	13.0 A,A	14.7 A	0.33 B,B	0.0 B,B	6.67 B,A	2.33 B

Hull-tight nuts (HT) mean values were substantially higher in Lauranne than in Tuono (4.33 and 1.11%) (Table 3). Tuono showed no significant differences through the years, while Lauranne presented the highest values in 2019 (10.0%); in this year, Lauranne presented a five times higher HT values than Tuono (2.00%). Any other statistical difference was found.

Double seeds' percentage (DS) was significantly higher for Tuono than for Lauranne (14.7 and 2.33%, respectively) (Table 3). No significant differences were found among the years for Tuono, while the highest DS mean value for Lauranne was observed in 2019 (6.67%).

4. Discussion

Due to a lack of studies on SHD almond orchards, we compared our results with what was reported for lower tree density almond plantations or for similar SHD olive cropping systems.

Tree height (TH) and tree width (TW) of cv Lauranne were 21% and 17% higher than cv Tuono (Figure 5 andFigure 6). In a younger SHD almond orchards, Dias et al. found a 25% higher TH mean values in Lauranne than in Tuono, while no differences were found for TW [62]. The growing environmental conditions may have influenced the growth of cultivars, as already observed for SHD olive orchards [9]. Trunk section (TS) and canopy volume (CV) values supported the idea that cv Lauranne is most vigorous than cv Tuono. Indeed, the former showed values of TS and CV 14% and 38% higher than the latter. In the previous study, 32% and 42% higher TS and CV values were found for Lauranne with respect to cv Tuono [62]. The medium-low vigour cultivars have been evaluated as suitable for SHD olive orchards, discarding all high and medium-high ones [12]. Indeed, cv Lauranne needed more intense pruning to keep tree size within the threshold values request by the SHD training system. Fruit yield (FY) was quite similar between the cultivars, with cv Lauranne showed 18% higher yield than cv Tuono (Table 1). The main difference was found at 5th YAP (2018), in which cv Lauranne yielded 1.30 kg/tree more than cv Tuono due to its higher canopy size. No comparison could be done with other studies since no one has evaluated this parameter in SHD almond orchards before.

Tuono showed 23% of yield efficiency on trunk section (YT) and 15% of yield efficiency on canopy volume (YV) values higher than Lauranne (Figure 7 andFigure 8); just at 5th YAP, cv Lauranne showed 30% of YV values higher than cv Tuono, due to a severe pruning made in the previous year. The only study that reports yield efficiencies of a SHD almond orchard is not comparable, because it is referred to different cultivar older than our study [21]. Yield efficiency is an important key-factor in modern agriculture. In the past, for almond cultivation, it seemed that the intensification, by using narrower tree spacings, could cause a decrement in efficiency [67]. On the contrary, a recent study showed higher yield efficiency levels for SHD training systems concerning the traditional ones, obtaining the best use of resources and productive inputs [21].

Both cultivars showed around 90% of fruits harvested, with a trend to decreasing the values with age and canopy size, particularly in cv Lauranne. In 2019, Lauranne showed higher detachment force than Tuono (6 N and 5 N, respectively, data not shown). For SHD olive orchards, studies have been carried out to maximize the percentage of fruits harvested and to minimize the percentage of vegetative axes damaged [13,41–45]. Harvesting efficiency was studied far and wide, showing acceptable values over 90%, with a very slight percentage of not harvested fruits [12,13,41–45]. In our study, the harvesting machine detached 100% of fruits set, this means that HE depends only on fruits fallen to the ground. The lower percentages of HE in 2019 could be related to two factors: (a) lower branches could lead to an inadequate closure of the catcher trays of collectors; (b) lower detachment forces could cause a premature fall of the fruits, before the tree was shaken. In olive, detachment forces lower than 2.7 N g^{-1} could lead to this situation [10,46]. Branch damages caused by the harvesters are an important issue for all mechanized orchards, so it is important to prevent them [44]. In SHD olive orchards, pruning has been studied in order to maintain the right canopy dimension for a chosen harvester because the branches removed are those that get stuck within the tunnel of the harvester machine [11]. Yet, no evidence has been found since now on SHD almond orchards for both the parameters. However, cv Lauranne showed higher damages percentages and it tended to increasing axes damages more than cv Tuono, related to its higher vigour (Tables 1 and 2). Shelling percentage was strictly related to the cultivar. Both cultivars showed mean values in line with varietal standards [22]. Cv Tuono's average values stood at around 36%, within the genetic range of 30–40% [7,38,41,54,60]. Cv Lauranne mean values ranged around 38%, in line with other studies [7,41,54]. The SHD training system did not influence this varietal's characteristics. Moreover, hull-tight nuts and double seed percentages seemed to be closely linked to the genetic standard of the cultivar as well [52,53], especially for cv Tuono. Nevertheless, cv Lauranne hardly got worse for both these quality parameters at 6th YAP (Table 3). According to other studies, hull-tight nuts and double seed percentages are complex genetic parameters, in which environmental conditions play a key role [53,59,68,69]. In particular, double seeds percentage could be affected by lower temperatures before or during blooming [57–59], but in our study, the mean temperatures before and during blooming were in line with the pluriannual values (Figure 3). On the other hand, a strong thermal excursion of 10 °C of the mean temperatures was observed between May and June during pit hardening: this may be the cause of higher DS. Anyway, double seed percentage mean values always ranged in the varietal standard interval [7,36,41].

5. Conclusions

The choice of cultivar is confirmed as a key factor for the achievement of the almond SHD cropping system goals. Cv Lauranne showed a better response in terms of yield and fruit quality parameters, trees were more vigorous, with a higher percentage of damaged axes observed during the harvest. On the contrary, cv Tuono seemed to be more efficient and better suitable to the SHD planting system in terms of tree architecture, but yield was lower than cv Lauranne. Adjusting spacing and first year's summer pruning to tree vigor, is required to optimize yields of cv Tuono. It should also consider the positive influence of the *terroir*, since Tuono is a native cultivar in production areas where the study was set up. Harvesting efficiencies depended on the size of the tree's canopy, and so, to the tree age as well. Finally, fruit quality is confirmed as strictly related to the cultivar.

These results provide important scientific evidence in support of a better management of SHD systems; they can contribute to improve the sustainability of SHD almond orchards based on a better efficiency of the inputs, which could lead to the spread SES and support an agricultural revolution based on sustainable intensification. Long-term research is needed in the suitability of other cultivars with different vigor. Further insights concerning optimal spacing, light interception, and canopy architecture are necessary, to constantly improve the production of almonds through increasingly efficient and sustainable cultivation techniques.

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