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Flowering Phenograms and Genetic Sterilities of Ten Olive Cultivars Grown in a Super-High-Density Orchard

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Abstract

The introduction of Super-High-Density (SHD) olive orchards represents a crucial innovation in modern olive growing, enhancing sustainability. However, the long-term success of these planting systems depends strongly on cultivar selection, combining suitable vegetative and reproductive traits. This three-year field study investigated key floral biology parameters—flowering phenograms, gynosterility, and self-compatibility—of ten olive cultivars grown under irrigated conditions in southern Italy: 'Arbequina', 'Arbosana', 'Cima di Bitonto', 'Coratina', 'Don Carlo', 'Frantoio', 'Favolosa' (='Fs-17'), 'I-77', 'Koroneiki', and 'Urano' ('Tosca'). Flowering phenograms varied significantly across years and cultivars, showing temporal shifts related to chilling accumulation and yield of the previous year. Early blooming cultivars ('Arbequina', 'Arbosana', and 'Coratina') exhibited partial flowering overlap with mid-season ones, enhancing cross-pollination opportunities. Quantitative analysis of flowering overlap revealed that most cultivar combinations exceeded the 70% threshold required for effective pollination, although specific genotypes ('Coratina', 'Fs-17', and especially 'I-77') showed critical mismatches, while 'Frantoio' and 'Arbequina' emerged as the most reliable pollinizers. Gynosterility exhibited statistical differences among cultivars and canopy positions: 'I-77' showed the highest values (71.4%), while 'Coratina' and 'Cima di Bitonto' showed the lowest ones (7.3 and 8.4%, respectively). The median portions of the canopies generally displayed a greater number of sterile flowers (29.4%), reflecting the combined effect of genetic and environmental factors such as light exposure. In the inflorescence, the majority of gynosterile flowers were concentrated in the lower part, for all canopy portions (modal value). Self-compatibility tests were performed considering a fruit set of 1% as a threshold to discriminate. For open pollination, the fruit set was highly variable among cultivars, ranging from 0.5% in 'I-77' to 4.7% in 'Arbosana'. Apart from 'I77', all varieties achieved a fruit set greater than 1%. Instead, for the self-pollination, only 'Arbequina', 'Koroneiki', 'Frantoio', and 'Cima di Bitonto' could be identified as pseudo-self-compatible, whereas 'Coratina', 'Fs-17', and the others were clearly self-incompatible and therefore unsuitable for monovarietal orchards in areas with limited availability of pollen. By integrating self-compatibility and gynosterility data, the cultivars were ranked according to reproductive aptitude, identifying 'Cima di Bitonto' and 'Frantoio' as the most fertile genotypes, whereas 'Don Carlo' and particularly 'I-77'

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Academic Editors: Nicola Cinosi and Luca Regni

Received: 12 December 2025
Revised: 14 January 2026
Accepted: 15 January 2026
Published: 19 January 2026

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showed severe genetic sterility constraints. The findings underline the critical role of floral biology in defining reproductive efficiency and varietal adaptability in SHD systems. This research provides valuable insights for optimizing cultivar selection, orchard design, and management practices, contributing to the development of sustainable, climate-resilient olive production models for Mediterranean environments.

Keywords: floral biology; gynosterility; self-incompatibility; chilling accumulation; climate change

1. Introduction

Nowadays super high-density orchards (SHD) have become the most important innovation for modern sustainable olive growing, exceeding 500,000 hectares in the world and 5000 hectares in Italy [1–4]. This choice is firstly related to the hard reduction in labor costs, thanks to full mechanization of harvesting and pruning [5–8], achieving even better profitability compared to traditional growing systems [9–11]. SHD can refine the application of regulated deficit irrigation for water saving and gaining phytosanitary status [12,13]; moreover, they can also reduce key pest infestation [14,15] and parasitic nematodes [16].

In SHD orchards, the key factor for olive sustainability is cultivar selection [17–20]. The ideotype of the suitable cultivar for SHD should exhibit both vegetative and productive parameters, such as low vigor, early bearing, high fertility, and adaptation to mechanical pruning and harvesting [20–22]. First-generation cultivars adapted to SHD olive systems were 'Arbequina', 'Arbosana', and 'Koroneiki' [8,11,20]. After these, international breeding programs have been started, leading to new cultivars like 'Lecciana', 'Coriana', 'Oliana', and 'Sultana' [4,23–25]. In order to enlarge this varietal platform, also considering the traditional cultivars, research are still ongoing on widespread cultivars such as 'Coratina' and 'Frantoio' and other of recent introduction like 'Don Carlo', 'Favolosa' (='Fs-17'), 'I/77', and 'Urano' ('Tosca') [8,26].

Understanding the floral biology of different cultivars under SHD conditions could lead to serious implications for new olive orchards. In particular, blooming phenograms and genetic sterilities are of main relevance to understand their suitability for different growing areas [27,28]. The lack of overlap between flowering phenograms could lead to serious issues in fruit set; however, assessing them is a complex process influenced by various factors, including genetics and climatic conditions, such as unsatisfied chilling requirements [28–32].

On the other hand, genetic sterilities, such as gynosterility and self-incompatibility, play a crucial role [33–35]. Generally, gynosterility (improperly known as 'pistil abortion') is influenced by the flower's position on the inflorescence and by the inflorescence's position on the tree; this is influenced by nitrogen availability and environmental factors such as air temperature and sun exposure, which could depend on canopy height, row orientation, and tree spacing [36–39]. Gynosterility could cause a substantial drop in fruit yield when over 50% [40–42].

In general, self-incompatibility effectively promotes genetic variability and biodiversity by preventing self-fertilization [43]. In olive trees, a gametophytic self-incompatibility system was once hypothesized, but research now indicates a sporophytic self-incompatibility (SSI) system [42,44,45]. This genetic system is primarily characterized by a diallelic mechanism, dividing cultivars into two incompatibility groups, called G1 and G2, which cannot fertilize each other, necessitating cross-pollination for successful fruit production [28,46–48]. A combination of hormones and a hemizygous supergene

controlling homomorphic diallelic SSI was demonstrated [47]. In other terms SSI system excluded self-compatibility in olive trees. So, self-compatibility is crucial for high yields in monovarietal systems [49–51]. Despite the presence of a functional SSI system, recent studies suggested that some olive varieties exhibit pseudo-self-compatibility (PSC), allowing them to set seeds following self-fertilization; this phenomenon likely results from the degradation of S-determinants in the pollen tube, enabling some pollen tubes to bypass the SSI response in relation to specific S-allele composition of each variety [46,52]. The threshold index for self-compatibility is set at 1% fruit set, meaning cultivars with a higher self-pollination fruit set are defined as self-compatible, while those below this threshold are self-incompatible. This threshold reflects the average fruit set in olive cultivars, which ranges between 1% and 5% [34,53,54]. In multivarietal orchards, intercompatibility between cultivars is equally vital to maximize productivity [55–57]. Indeed, to overcome SSI in olives, selection of a suitable pollinator whose blooming phenograms overlap by at least 70% with the intercompatible cultivar is fundamental [58–60].

Olive floral biology has already been widely investigated, mainly on traditional crop cultivation systems [27,29,30], but no research has been performed on SHD orchards. Moreover, flowering phenology, gynosterility, and self-incompatibility have often been examined separately, leaving their combined influence on reproductive performance in modern systems still not understood.

Therefore, the aim of this three-year field research was to investigate the floral biology of ten olive cultivars grown in an adult SHD olive orchard, focusing on flowering phenograms and genetic sterilities.

2. Materials and Methods

2.1. Experimental Orchard

This three-year research (2010–2012) was carried out in an SHD olive orchard of the University of Bari at the "Centro Didattico-Sperimentale P. Martucci" located in Valenzano (BA-Apulia region; 41°01′ N; 16°54′ E; 110 m a.s.l.; Figure 1), planted in 2006 on a sandy clay soil (sand, 630 g kg^{-1}; silt, 160 g kg^{-1}; clay, 210 g kg^{-1}) classified as a Typic Haploxeralf (USDA) or Chromi-Cutanic Luvisol (FAO), and with pH of 7.2, EC of 0.2 dS m^{-1}, total organic content of 12.8 g kg^{-1}, total nitrogen of 1.1 g kg^{-1}, available phosphorus of 4.6 mg kg^{-1}, and available potassium of 141.7 mg kg^{-1}.



Figure 1. Focus on the experimental orchard of the University of Bari Aldo Moro, Valenzano (BA, Italy).

The experimental orchard consisted of 24 rows, including 15 olive cultivars. Among them, the study focused on ten olive oil cultivars: 'Arbequina', 'Arbosana', 'Cima di Bitonto', 'Coratina', 'Don Carlo', 'Frantoio', 'Favolosa' (='Fs-17'), 'I/77', 'Koroneiki', and 'Urano' ('Tosca'); the trees were spaced 4.0 m × 1.5 m (1660 trees ha^{-1}), with a North–South row orientation. A central leader training form was used with props. A

complete randomized block was used as the experimental setup. Three rows per cultivar were randomly spread within the orchard; 40 self-rooted trees were planted in each row. Drip irrigation was managed by restoring the 100% of ETc, giving every year, on average, 2000 m^3 ha^{-1}. Nutrition, weed management, and disease control were implemented in the same manner for all cultivars following the best agricultural practices and the integrated pest management, as reported in previous research [13,15,20]. Mineral nutrition was provided through foliar and soil applications, while weed management was handled with chemical control in the rows and mowing between rows.

2.2. Weather Conditions

Agro-climatic data (Figure 2) was supplied by the Research Unit for Climatology and Meteorology Applied to Agriculture (Ministry of Agriculture) and recorded at the nearest station, a few kilometers from the experimental site. In 2010, the average temperature was 15.1 °C, 0.5 °C under the thirty-year average (15.6 °C). However, total rainfall was significantly higher (633 mm and 528 mm, respectively), mainly due to heavy rains in October (163 mm). For 2011, the average temperatures were slightly above the thirty-year average (15.8 °C compared to 15.6). Rainfall was 40 mm above the thirty-year average (568 mm and 528 mm, respectively), with heavy rains in March (96 mm) and November (131 mm). The 2012 average monthly temperatures were higher than the thirty-year average (16.6 °C). Total rainfall was slightly below the thirty-year average (518 mm and 528 mm, respectively), although there was heavy rain in February (153 mm).

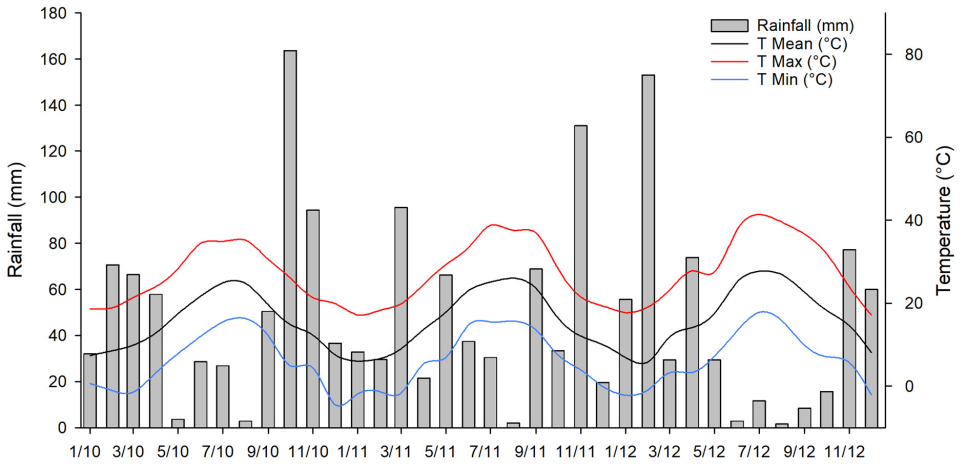


Figure 2. Thermo-pluviometric trend recorded in Valenzano (Bari) from 1 January 2010 to 31 December 2012.

Moreover, two widely used bioclimatic indices were applied to quantify temperature-driven phenological responses: Chilling Units (CU) and Chilling Portions (CP). These indices were computed from hourly and daily temperature data, following standard methodologies described in the literature. The Utah CU model quantifies winter chill accumulation by assigning hourly chill units according to specific temperature ranges [61]. No chill is accumulated below 1.4 °C, while temperatures between 1.5 and 2.4 °C and 9.2–12.4 °C contribute 0.5 units per hour. The most effective range, 2.5–9.1 °C, yields 1 unit per hour. Temperatures between 12.5 and 15.9 °C do not contribute, while higher values progressively subtract chill, with −0.5 units assigned between 16.0 and 17.9 °C and −1 unit above 18 °C. The Dynamic Model to calculate CP conceptualizes chilling as a two-step process [62]. Cold temperatures induce the formation of an intermediate product that can be negated by subsequent heat; once this product reaches a threshold, it is irreversibly converted into a chill portion. Chill portions accumulate progressively and cannot be destroyed by later warm periods. This approach, which accounts for the

sequence of temperature fluctuations, provides more consistent and biologically realistic estimates of dormancy release compared with the Utah model.

2.3. Data Collection

As illustrated below, gynosterility assessment involved a destructive sampling and open flower counting required frequent branch manipulation. Therefore, in order to avoid any effects due to flower load and man disturbance, different trees were randomly selected for each of the studied parameters.

2.3.1. Flowering Phenograms

For each cultivar, 9 trees (3 per row × 3 rows) were randomly selected. On each tree, two fruiting branches were identified and tagged, one on the east side and one on the west side, each bearing approximately 100 inflorescences. At regular two-day intervals, starting from the beginning of anthesis, the number of open flowers on the individual clusters of each branch was counted. Each phenogram was built considering: start, full, and end of flowering when 10%, 50%, and 90% of the flowers were open, respectively.

2.3.2. Gynosterility

When flowers were at the pre-anthesis stage, corresponding to 55–59 BBCH identification code [63], from each cultivar, 90 inflorescences (6 per tree × 5 trees per row × 3 rows) were collected from three different portions of the canopy: apical, median, and basal. The inflorescences were placed in paper bags and kept under controlled conditions to maintain the viability of the floral organs. Shortly after collecting, the corolla and stamens of each flower were removed. Sterile pistils (hypotrophic or atrophic) were identified, counted, and their position on the inflorescence was recorded. The total number of flowers, the number of gynosterile ones, and their positions on each inflorescence were determined.

2.3.3. Self-Incompatibility

Six trees per cultivar (2 per row × 3 rows) were randomly selected. Before anthesis, two fruit-bearing branches, each carrying approximately 100 inflorescences, were selected from the middle portion of the canopy on both the east and west sides of each tree. These branches were enclosed in fine-mesh bags made of non-woven fabric, impermeable to pollen but permeable to air (self-pollination). On the same trees, additional fruit-bearing branches carrying about 100 inflorescences were left to open pollination as controls. The bags were removed 4 weeks after full bloom. Fruit set (%) values were recorded just before harvest. The threshold for self-compatibility was set at >1% [53].

2.4. Statistical Analysis

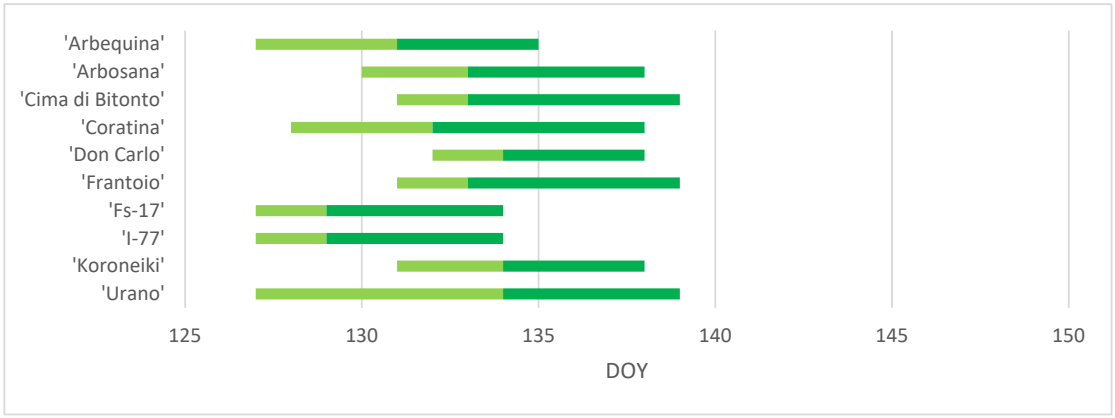
Analysis of Variance (ANOVA) was performed. Student-Newman-Keuls (SNK) post hoc test (p = 0.05) was applied following significant ANOVA results to separate group differences. The data were statistically analyzed using R 2.15.0 software (R Foundation for Statistical Computing); standard error (SE) was also reported. Modal values were graphically reported just for the effect of flower position within the inflorescence on gynosterility.

3. Results

3.1. Flowering Phenograms

Phenology during the three years revealed interesting trends and fluctuations in flowering timing across cultivars (Figure 3). In the first year (2010), flowering started and finished 7–9 days earlier than the other two following years (Figure 3a). Early flowering cultivars, such as ‘Arbequina’ and ‘Arbosana’, began around 8 May, finishing by 14 or 15 May. ‘Coratina’ followed a similar schedule, overlapping slightly with these two cultivars. Mid-season culti-

vars, like 'Koroneiki', bloomed between 10 May and 19 May. Among all, 'Urano' showed the longest flowering period, reaching full bloom only 10 days after the beginning. In the second year (2011), a shift was observed as flowering periods generally started later compared to the previous year. For instance, 'Arbequina', 'Arbosana', and 'Coratina', which began flowering around 8 May 2010, started closer to 16 May, while their flowering durations remained similar (Figure 3b). Mid-season cultivars followed a similar pattern, with a delay of 1–2 days. Other cultivars, such as 'Urano', 'Fs-17', and 'Don Carlo', started on 17 May, with 'Fs-17' showing the shortest flowering among all the cultivars (6 days).



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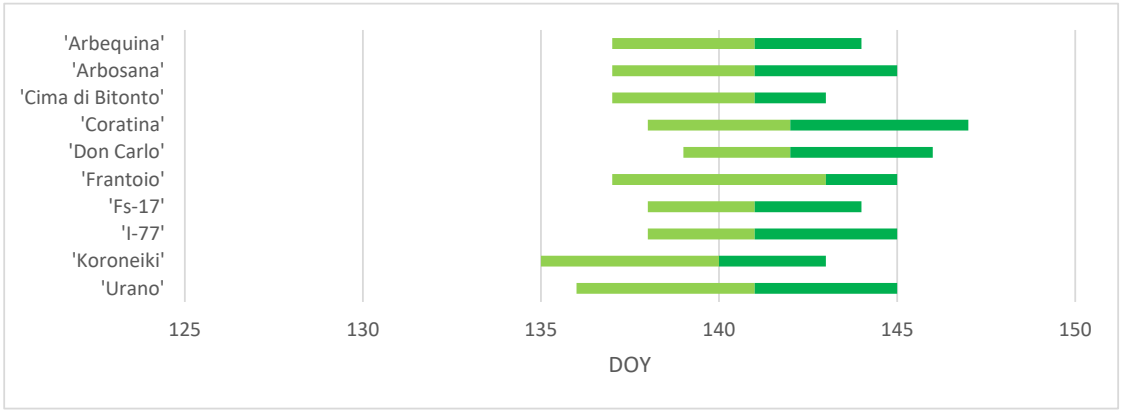

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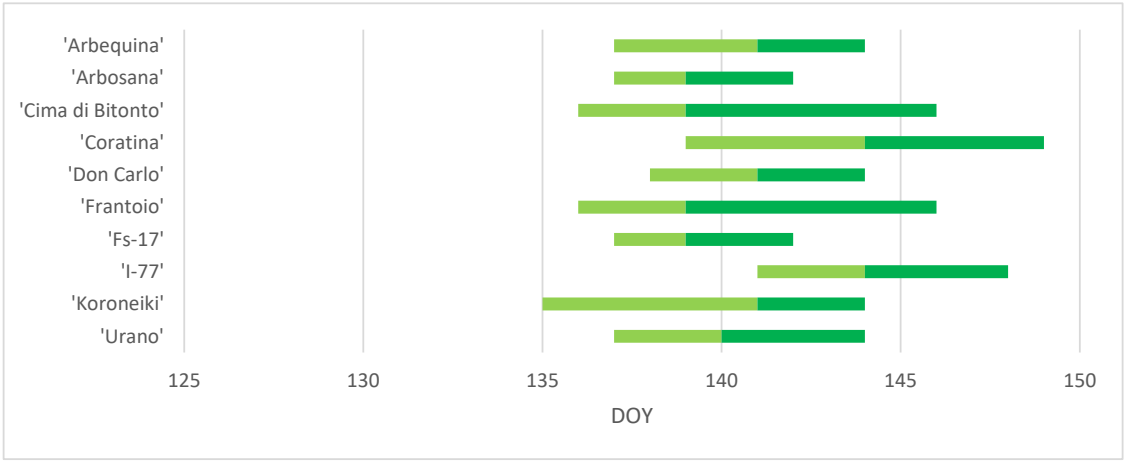


(**c**)

Figure 3. Flowering phenograms of ten olive cultivars on different days of year (DOY) in 2010 (**a**), 2011 (**b**), and 2012 (**c**). Light green bars refer to 10–50% interval of open flowers, while dark green bars refer to 51–90% interval of open flowers, for each cultivar.

In the third year (2012), flowering periods were in line with those observed in the previous year, showing only a slight advancement of about two days compared to the previous year (Figure 3c). Early cultivars such as 'Arbequina' and 'Arbosana' started blooming around 15 May. 'Coratina' mirrored its 2011 pattern, beginning around 15 May and finishing by 25 May, showing the longest period (10 days). 'Koroneiki' exhibited the same behavior, with flowering starting just a couple of days earlier, but ending later than in 2011. Even the late-flowering cultivars maintained their patterns from 2011, with only a minor two-day advancement.

3.2. Gynosterility

3.2.1. Effect of Inflorescence Position

In terms of mean number of flowers per inflorescence, 'I-77' and 'Fs-17' had the highest values (around 20) and 'Coratina' the lowest (11.9), while the remaining cultivars ranged from 13 to 18 flowers per inflorescence (Table 1). For the canopy portion, apical inflorescence showed a higher number of flowers than the median and basal ones (19.4, 15.6, and 13.1 flowers per inflorescence, respectively). The pattern was also confirmed in the different layers for each cultivar, in which the apical portion of the canopy showed a higher number of flowers than the lower ones. The median portions showed mostly the same number of flowers as the basal one. 'Urano' was the only cultivar to produce the same inflorescence in the whole canopy, with no statistical differences from the apical to the basal portions.

Table 1. Flowers per inflorescence (n) of the olive cultivars in different tree canopy portions (apical, median, and basal), as the mean of three years. Capital letters denote statistical differences among cultivars for the same portion; lowercase letters denote statistical differences among portions for the same cultivar (SNK test; $p = 0.05$).

Cultivar \ Canopy Portion	Apical	Median	Basal	Mean
'Arbequina'	20.6 ± 0.82 AB,a	16.0 ± 0.65 B,b	12.8 ± 0.56 BC,c	16.5 ± 0.52 B
'Arbosana'	18.4 ± 0.87 B,a	15.3 ± 0.82 BC,b	13.7 ± 0.93 BC,b	15.8 ± 0.54 BC
'Cima Di Bitonto'	18.7 ± 0.97 B,a	15.2 ± 0.89 BC,b	9.90 ± 0.73 D,c	14.6 ± 0.63 BC
'Coratina'	15.6 ± 0.76 BC,a	9.90 ± 0.49 D,b	10.2 ± 0.57 CD,b	11.9 ± 0.45 D
'Don Carlo'	18.3 ± 0.81 B,a	13.3 ± 0.54 C,b	11.6 ± 0.54 BC,b	14.4 ± 0.48 C
'Fs-17'	24.2 ± 0.99 A,a	18.2 ± 0.63 AB,b	18.4 ± 1.19 A,b	20.3 ± 0.63 A
'Frantoio'	17.6 ± 0.82 B,a	13.8 ± 0.52 C,b	14.1 ± 0.66 AB,b	15.2 ± 0.43 BC
'I-77'	24.2 ± 1.28 A,a	22.9 ± 1.45 A,a	15.5 ± 0.74 AB,b	20.9 ± 0.80 A
'Koroneiki'	23.1 ± 1.30 AB,a	18.4 ± 1.03 AB,b	12.0 ± 0.54 AB,c	17.8 ± 0.75 B
'Urano'	13.3 ± 0.80 C,a	13.3 ± 0.80 C,a	13.0 ± 0.74 BC,a	13.2 ± 0.45 CD
Mean	19.4 ± 0.36 a	15.60 ± 0.32 b	13.1 ± 0.27 c	

Gynosterility mean values varied significantly with cultivar and across the canopy portion of the inflorescences (Table 2). The average percentage of gynosterile flowers was low (around from 7 to 20%) for 'Coratina' (7.3 ± 1.3%), 'Cima di Bitonto' (8.4 ± 1.3%), 'Frantoio' (9.7 ± 1.6%), 'Arbequina' (15.0 ± 1.5%), and 'Urano' (17.5 ± 1.4%). Intermediate pistil sterility was observed in 'Don Carlo' (30.3 ± 3.2%), 'Arbosana' (21.8 ± 2.1%), and 'Fs-17' (20.5 ± 2.0%). Percentages were the highest in 'I-77' (71.4 ± 3.1%), followed by 'Koroneiki' (50.3 ± 3.7%). On average, the tree median portion exhibited the highest mean values of gynosterility (29.4 ± 1.9%), higher than both the apical (23.5 ± 1.6%) and basal (22.8 ± 1.5%) canopy portions.

Table 2. Gynosterility (%) of the olive cultivars in different tree canopy portions (apical, median, and basal), as the mean of three years. Capital letters denote statistical differences among cultivars for the same portion; lowercase letters denote statistical differences among portions for the same cultivar (SNK test; $p = 0.05$).

Cultivar \ Canopy Portion	Apical	Median	Basal	Mean
'Arbequina'	9.35 ± 2.4 C,b	13.77 ± 2.0 C,b	21.8 ± 2.8 B,a	15.0 ± 1.5 D
'Arbosana'	28.41 ± 3.8 B,a	16.20 ± 2.9 C,b	20.6 ± 3.7 B,b	21.8 ± 2.1 C
'Cima Di Bitonto'	7.85 ± 1.7 C,a	10.15 ± 2.8 C,a	7.2 ± 2.3 C,a	8.4 ± 1.3 E
'Coratina'	15.91 ± 2.5 C,a	2.99 ± 1.3 D,b	3.1 ± 1.6 C,b	7.3 ± 1.3 E
'Don Carlo'	19.30 ± 4.0 C,b	42.62 ± 6.9 B,a	29.1 ± 4.6 B,b	30.3 ± 3.2 C
'Fs-17'	16.32 ± 3.6 B,b	29.07 ± 3.4 B,a	16.1 ± 2.6 B,b	20.5 ± 2.0 C
'Frantoio'	5.25 ± 1.3 C,b	17.45 ± 4.0 C,a	6.3 ± 1.8 C,b	9.7 ± 1.6 E
'I-77'	92.21 ± 1.8 A,a	74.78 ± 5.1 A,a	47.2 ± 4.7 A,b	71.4 ± 3.1 A
'Koroneiki'	23.84 ± 3.0 B,c	70.93 ± 5.5 A,a	56.2 ± 6.7 A,b	50.3 ± 3.7 B
'Urano'	16.39 ± 2.2 C,a	16.39 ± 2.2 C,a	19.8 ± 3.0 B,a	17.5 ± 1.4 D
Mean	23.49 ± 1.6 b	29.43 ± 1.9 a	22.8 ± 1.5 b	

However, cultivar × canopy portions interaction effects were also observed. In 'Arbequina', gynosterility increased progressively from the apical (9.4 ± 2.4%) to the basal (21.8 ± 2.8%) portion, with the basal section exhibiting the highest sterility. 'Arbosana' showed significantly higher sterility in the apical portion (28.4 ± 3.8%) compared to the medial (16.2 ± 2.9%) and basal (20.6 ± 3.7%) layers. 'Don Carlo' and 'Fs-17' exhibited peak sterility in the medial portion (42.6 ± 6.9% and 29.1 ± 3.4%, respectively), while the apical and basal values were significantly lower and similar. In contrast, 'Cima di Bitonto' and 'Urano' displayed uniform sterility across all canopy portions. 'I-77' exhibited extreme sterility levels at all portions, reaching 92.2 ± 1.8% in the apical layer, the highest value recorded. 'Koroneiki' also displayed elevated sterility, particularly in the medial (70.9 ± 5.5%) and basal (56.2 ± 6.7%) portions. Meanwhile, 'Frantoio', 'Cima di Bitonto', and 'Coratina' had consistently low sterility values across all layers, with apical sterility levels of 5.3 ± 1.3%, 7.9 ± 1.7%, and 15.9 ± 2.5%, respectively.

3.2.2. Effect of Flower Position

The modal distributions of gynosterile flowers within each inflorescence for each canopy portion were shown for three different cultivars as the most representative (Figure 4). Gynosterility position data for all the other cultivars are available in the Supplementary Materials (Figure S1).

In 'Arbequina', gynosterile flowers were concentrated in the lower part of the inflorescence for all canopy portions. The highest number of gynosterile flowers was observed in the median portion, while the apical and basal portions showed the same number. The cultivars 'Arbosana', 'Cima di Bitonto', 'Coratina', 'Don Carlo', 'Frantoio', 'Fs-17', and 'Urano' followed the 'Arbequina' model. 'Koroneiki' performed differently: while in the apical portion, gynosterile flowers were concentrated in the lower part of the inflorescence, the basal portion also showed gynosterility in the middle and median portions of all the inflorescences, with the highest number of them (6). 'I-77' registered the highest levels of gynosterility in all portions of the canopy, with a gradient from basal to apical portions: while in the basal portion, 41% of the flowers were gynosterile, in the apical part, gynosterility reached almost 88%.

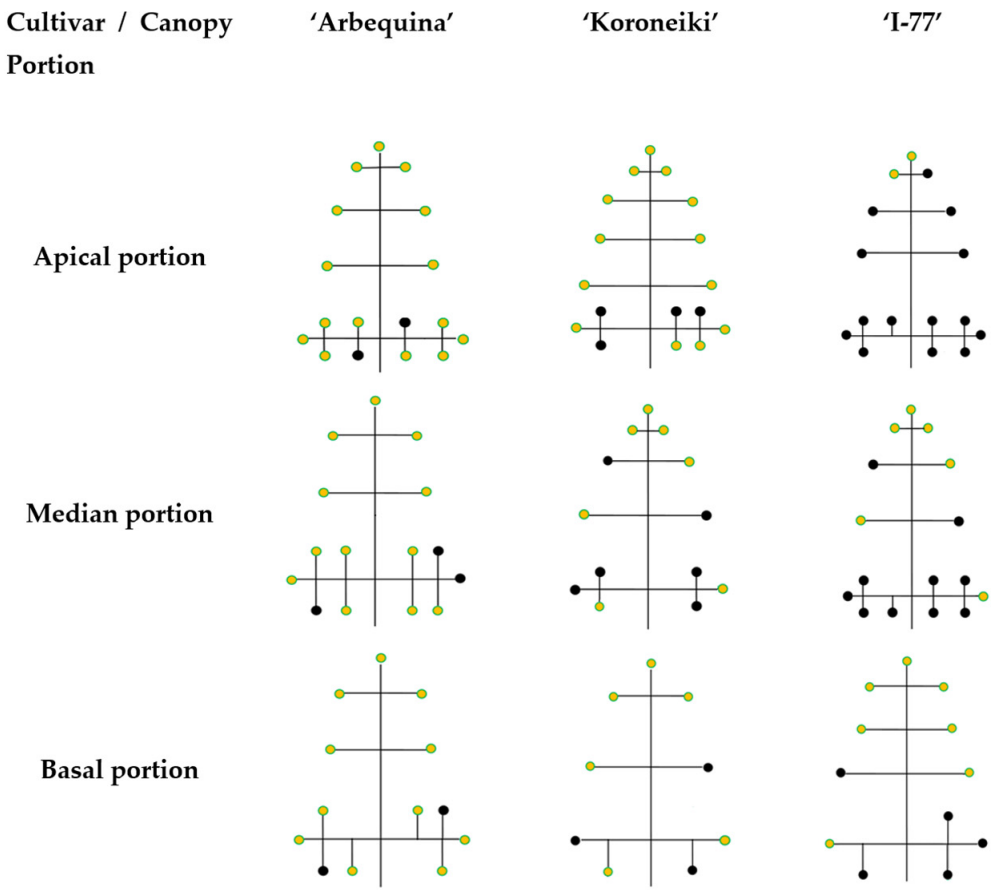
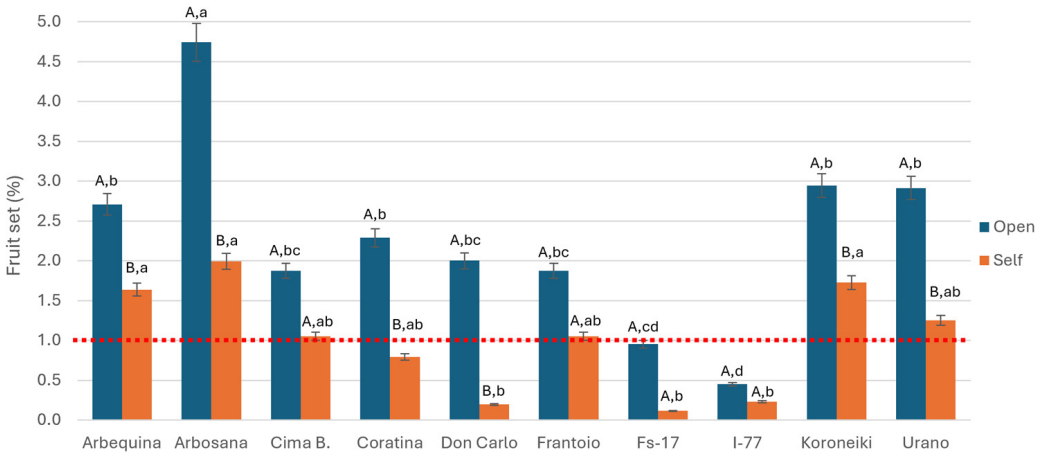


Figure 4. Three-year modal position of gynosterile (black circles) and perfect (yellow circles) flowers in cultivars 'Arbequina', 'Koroneiki', and 'I-77' coming from the apical (**upper row**), median (**central row**), and basal (**lower row**) tree canopy portion.

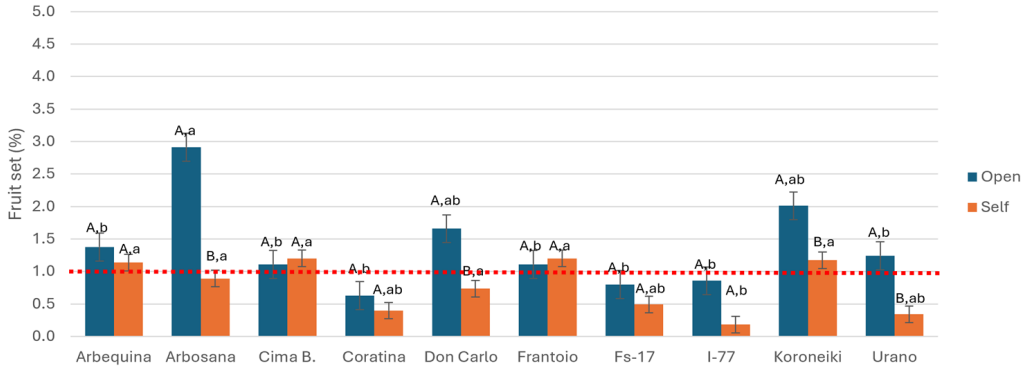
3.3. Self-Incompatibility

In 2010 'Arbequina', 'Arbosana', 'Cima di Bitonto', 'Frantoio', 'Koroneiki', and 'Urano' showed fruit set mean values beyond the 1% threshold in self-pollination conditions (Figure 5a). Conversely, 'Coratina', 'Don Carlo', 'Fs-17', and 'I-77' showed lower values. For the open pollination, fruit set was highly variable among cultivars, ranging from 0.5% in 'I-77' to 4.7% in 'Arbosana'. Apart from 'I77', all the varieties achieved a fruit set greater than 1%. 2011 data confirmed in part the findings of 2010 for these cultivars (Figure 5b). In fact, even with lower values, 'Arbequina', 'Cima di Bitonto', 'Frantoio', and 'Koroneiki' showed more than 1% of fruit set in self-pollinated flowers. 'Arbosana' showed a contrasting behavior in self-pollination: while it hit the 2% in 2010, in 2011 it only reached the 0.9% in 2011. On the other hand, lower values for every cultivar were observed also in open pollination, where the highest value recorded was in 'Arbosana', 38% lower than the previous year (2.9% and 4.7%, respectively).

To better ascertain the biological behavior of 'Arbosana', the test was repeated in 2012, together with four cultivars that showed a marked behavior in the two previous years as controls (Figure 6). Under self-pollination 'Arbosana' showed a fruit set value way less than 1%, while the other cultivars showed consistency with previous years. In open pollination 'Arbosana' confirmed the 2011 values, while the other four exceeded the previous fruit set.



(**a**)



(**b**)

Figure 5. Fruit set (%) from self-pollination (self) and open-pollination (open) of ten olive cultivars in 2010 (**a**) and 2011 (**b**). Uppercase letters denote statistical differences between pollination methods for the same cultivar. Lowercase letters denote statistical differences among cultivars for the same pollination method (SNK test; $p < 0.05$).

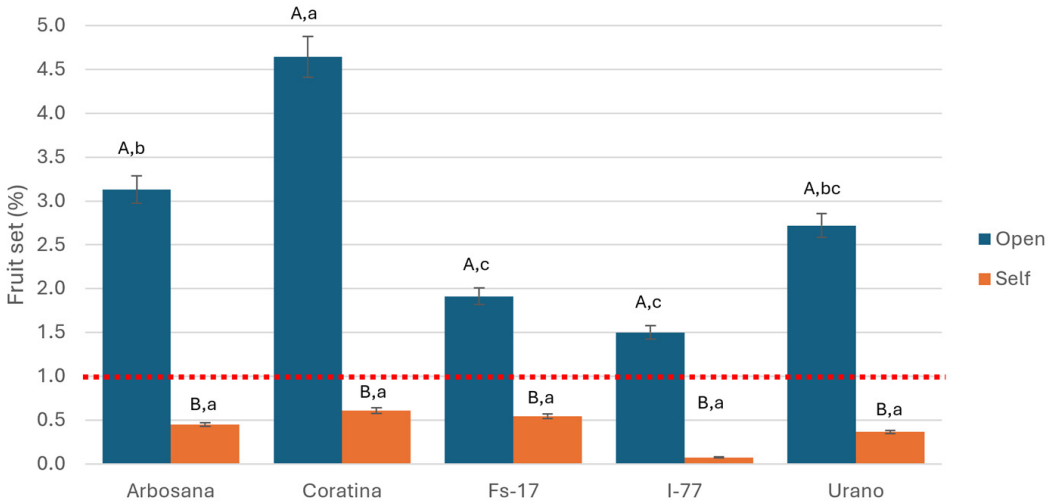


Figure 6. Fruit set (%) from self-pollination (self) and open pollination (open) of five olive cultivars in 2012. Uppercase letters denote statistical differences between pollination methods for the same cultivar. Lowercase letters denote statistical differences among cultivars for the same pollination method (SNK test; $p < 0.05$).

4. Discussion

4.1. Flowering Phenograms

The flowering phenology of the ten olive cultivars observed during three years showed distinct interannual variations and cultivar-specific behavior (Figure 3). This particular behavior could be related to different internal and external factors. Firstly, the influence of different climatic trends and olive reproductive biology played an important role in explaining blooming variability [64]. Different temperatures can radically influence blooming, causing it to either advance or delay [34], and increment or decrement its length. Garrido et al. [65] observed that in the northern part of Spain (Quiroga, Lugo), the Main Pollen Season (MPS) in 'Arbequina' also reached a 27-day flowering period, while Medina-Alonso et al. [66] observed a 14-day flowering period in southern Spain (Cordoba) and a 50-day flowering period in Tenerife. Mhanna et al. [67] observed for 'Coratina' a 9–15 flowering period, while Medina-Alonso et al. [66] recorded a variation from 12 to 40 days, depending on the area. On the other hand, other cultivars like 'Koroneiki' and 'Frantoio' showed quite the same length of blooming as the current study [27,66,68]. In general, different temperatures and different agro-climatic conditions could anticipate or delay flowering, but always considering, in Apulia, a period between the first days of May and the first days of June [69]. In this case no relevant differences were observed for either of the climatic conditions. To better understand this data, two bioclimatic indices have been calculated (Figure 7).

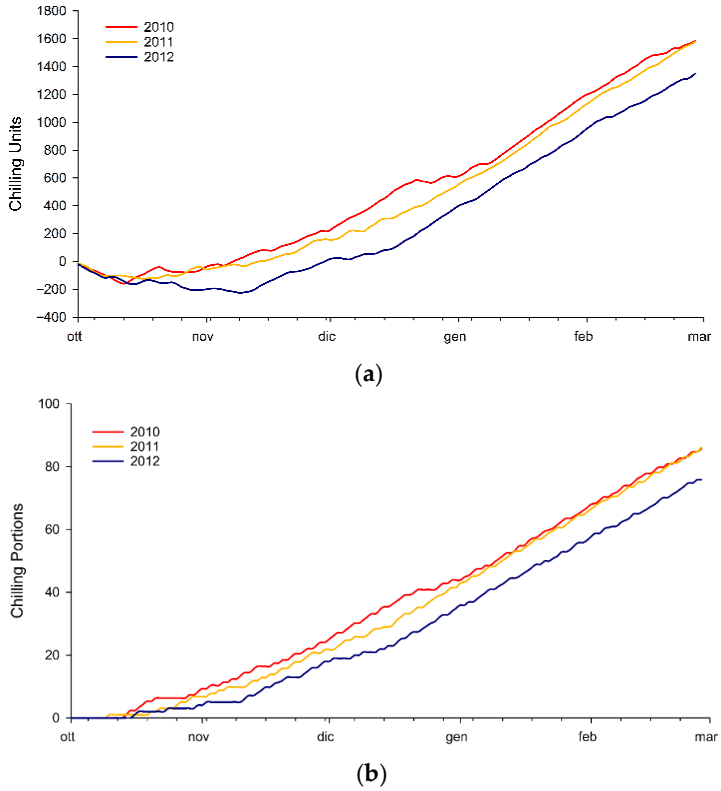


Figure 7. Annual accumulation of Chilling Units (CU, (**a**)) and Chilling Portions (CP, (**b**)) cumulated in 2010, 2011, and 2012.

The anticipation or delay of blooming could be related to both harvesting time and chill accumulation. In 2010 the same CU and CP of 2011 were accumulated (1584 and 1577.5 CU and 85.69 and 86.14 CP, respectively), higher than 2012 (1349 CU and 75.84 CP, respectively), but with a 7-day anticipation in blooming. In this case, harvesting time played an important role: the earlier ripening of 2009 (19 November 2009) could have anticipated blooming

in 2010. In particular, Haim et al. [70] observed that fruit presence generates relatively strong polar auxin transport in citrus and olive stems. By harvesting the fruits earlier, the indoleacetic acid (IAA) levels decreased and, consequently, an earlier flowering the next year was observed. The blooming of 2011 was influenced by a late harvest, performed on 14 December 2010. For 2012, despite the earliest harvesting (10 November 2011), a delayed blooming was observed. In this case, lower CU and CP accumulated could have delayed blooming. Chilling units are essential for the flower bud differentiation in olive trees: the accumulation of cold hours helps break bud dormancy [71]. In 2012, chill accumulation observed a delay in time and a decrement of 200 CU and 10 CP compared to the other years. Even if a variation in chill accumulation is observed among cultivars, a general reduction could lead to a delay in blooming [72].

Cultivar-specific phenograms were also analyzed. For 'Arbequina', flowering in 2010 happened in DOY 128 in Valenzano, while in Cordoba, it occurred around DOY 113 and DOY 95 in Tenerife, indicating up to 40-day advances in warmer climates [66]. Similar early blooming was observed in 2022–2023 [57]. In central Italy, blooming was recorded from DOY 132 to 146 [73], while studies in Spain showed comparable bloom dates to Valenzano [39]. In hotter environments like Pakistan, flowering was up to one month earlier due to 6 °C higher temperatures [74]. Similar temporal shifts were confirmed by other researchers [75–77], highlighting the cultivar's climatic sensitivity. 'Arbosana' showed similar plasticity, with earlier bloom in Cordoba in 2022 and April anticipation in 2023 [57], and up to 13-day advances in warmer sites [75]. 'Coratina' followed early cultivars but had an extended bloom in 2012. Compared to Valenzano, flowering occurred 20–35 days earlier in Cordoba and Tenerife, respectively [66]. A one-month anticipation was recorded in Egypt and Pakistan due to +8–10 °C differences [55,74]. 'Frantoio', a mid-season cultivar, bloomed later in Tuscany due to higher elevation [78], but matched flowering dates in Morocco [27]. In Asia, it showed earlier flowering by 10–30 days [74]. 'Koroneiki' displayed similar behavior: flowering was recorded between April 16–28 in Cordoba in 2023 [57], while in Tenerife it occurred up to 40 days earlier [66]. Flowering dates matched Italy and Spain depending on the year [39], with earlier flowering observed in Egypt and Pakistan due to warmer climates [55]. For 'Urano', no external comparative data was available, but it consistently exhibited the longest anthesis. Similarly, 'Cima di Bitonto', genetically related to 'Frantoio' [79], shared similar phenological behavior, and by inference, likely the same sensitivity to climatic shifts. No literature data were found for 'Don Carlo', while 'Fs-17' was reported to flower almost a month earlier in Pakistan due to higher pre-bloom temperatures [74].

To better address the best couples pollinizer–pollinated, flowering phenograms of the three years for all the cultivars were compared, and overlap percentages were calculated (Figure 8 and Figures S8–S10); a cultivar is considered a good pollinizer when its overlap percentage exceeds 70% [80].

Almost all the flowering phenograms overlapped for more than 70%, with only three cultivars that showed overlap issues. 'Coratina' showed values below 70% in combination with 'Arbequina', 'Arbosana', and 'Cima di Bitonto' (65.8, 66.1, and 68.5%, respectively). Similarly, 'Fs-17' did not sufficiently overlap with three other cultivars, 'Don Carlo', 'Koroneiki', and 'Urano' (68.8, 58.9, and 68.8, respectively). 'I-77' was the cultivar with the highest overlap issues; in fact, it underperformed with 'Arbosana', 'Cima di Bitonto', 'Don Carlo', 'Koroneiki', and 'Urano', while only with 'Coratina' it showed an overlap higher than 80% (95.8%). On the other hand, 'Frantoio' is the only cultivar that showed a good overlap for every combination, followed by 'Arbequina', which showed low overlap only with 'Coratina' (65.8%). To the best of the authors' knowledge, no research has been published on this data, so no comparison could be made with other research.

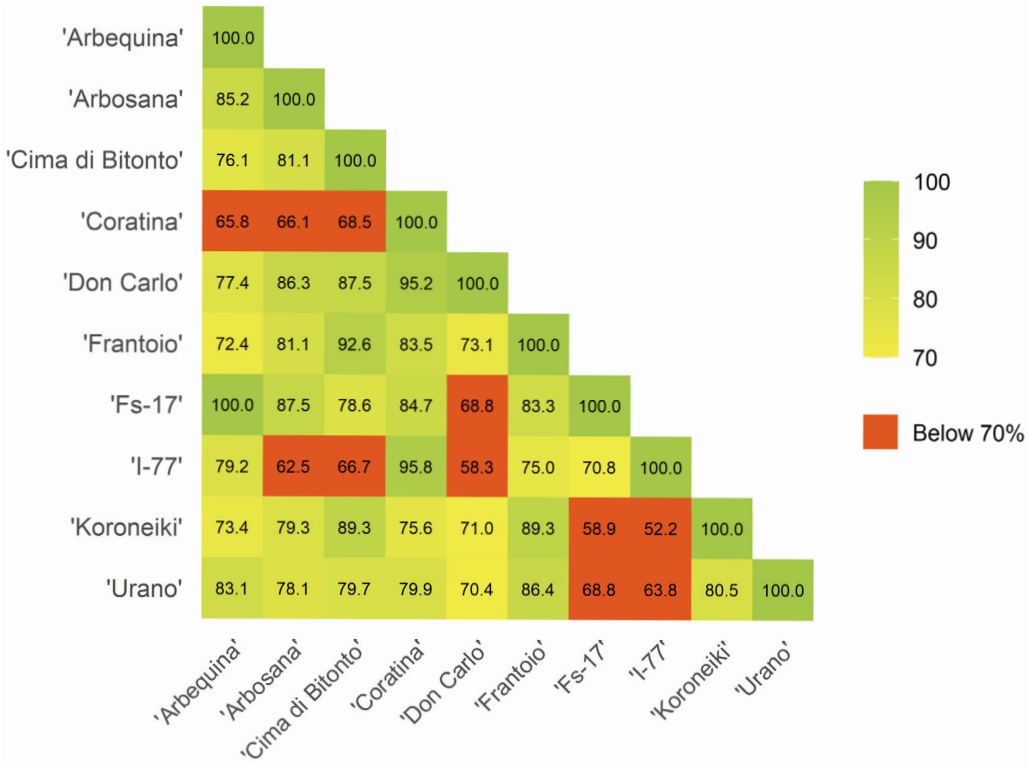


Figure 8. Average values of flowering overlap (%) of the ten olive cultivars in the 2010–2012 period.

4.2. Number of Flowers and Gynosterility

The number of flowers ranged from 9.9 in 'Coratina' and 'Cima di Bitonto' to 24.2 in 'Fs-17' and 'I-77' (Table 1). These results were consistent with previous research, in which a range of 9 to 25 flowers per inflorescence was observed [27,81,82]. Moreover, in almost all cultivars, a higher number of flowers was observed in the apical portions, with lower numbers in the basal portions. Apical inflorescences generally have more flowers than basal ones, consistent with the olive tree's tendency to bloom in sunlit areas of the canopy [34,81,83].

The proportion of gynosterile and perfect flowers revealed clear canopy positional patterns, which were cultivar-dependent (Table 2). In general, the apical and medial sections showed a higher proportion of perfect flowers, while gynosterile flowers were more frequent in the basal parts of the canopy. Exceptions were observed in 'Koroneiki', where sterility peaked in the median portion, and in 'I-77', which exhibited the highest overall sterility and a progressive increase from basal to apical portions. Mean gynosterility rates ranged widely, from 7.3% in 'Coratina' to 71.4% in 'I-77'. Rosati et al. [64] observed that pistil abortion varies largely with cultivar and year, but also among trees for the same cultivar and within a single tree, among branches and shoots, as well as among and within inflorescences, and cultivar-specific patterns confirmed this variability. 'Arbequina' and 'Arbosana' showed low-to-moderate gynosterility, while 'Don Carlo' and 'Fs-17' exhibited peak values in the medial. In contrast, 'Cima di Bitonto' and 'Urano' displayed uniform sterility across portions, indicating minimal spatial influence [34]. These trends could be linked to physiological processes that promote sterility in the central inflorescence. These cultivar-specific differences underscored the genetic factors influencing gynosterility, as well as the potential for selective breeding to optimize productivity [34,84].

As for the position of gynosterile flowers in the inflorescences, this appeared to be strictly cultivar-dependent (Figure 3). The majority of the cultivars showed the gynosterile flowers in the lower part, while 'I-77' exceeded the 87% of gynosterility, a unique cultivar. These behaviors are strictly related to genotype [84].

4.3. Self-Incompatibility

Self-incompatibility varied among cultivars and years (Figures 5 and 6). The results are in general consistent with previous findings [49,55–57]. SSI was found for 'Coratina' [49] and 'Arbosana' [57], while 'Koroneiki' was found self-compatible [56,85]. On the other hand, some discrepancies were highlighted. 'Arbequina', 'Cima di Bitonto', 'Frantoio', and 'Koroneiki' were reported as self-incompatible [34,52,56,86–88]. For 'Don Carlo', 'Fs-17', 'I-77', and 'Urano', no data are available in the literature about SSI. PSC could explain the highlighted discrepancies. Indeed, the expression of both SSI and PSC could vary depending on environmental factors such as soil and climate [49–51]. The present study was conducted along the Adriatic coast of Italy, on a sandy clay soil. In contrast, previous research has been carried out in markedly different pedoclimatic conditions, including the Ionian coastline, the Calabrian Apennines, and the desert environments of Israel [49–51]. Such pronounced climatic and environmental variability is likely to have modulated the floral biology of the olive tree in meaningful ways, potentially contributing to the divergent patterns reported across studies.

Based on self-compatibility and gynosterility levels less than 10% [89], the cultivars can be ranked according to their reproductive aptitude and potential reliability under different orchard conditions. Among self-fertile cultivars, 'Cima di Bitonto' and 'Frantoio' exhibited low gynosterility. Conversely, among the self-incompatible cultivars, only 'Coratina' showed the lower values of gynosterility. 'I-77' exhibited gynosterility higher than 50%, identifying it as the most critical cultivar in terms of genetic sterility.

5. Conclusions

Floral biology gains more relevance every year in olive cultivation, being a key factor for reproductive efficiency, yield, and long-term adaptability of cultivars under varying environmental and management conditions. This study focused on the floral phenograms and genetic sterilities of ten olive cultivars grown in an SHD orchard under Mediterranean conditions, with particular attention to gynosterility and self-compatibility.

Flowering phenograms display distinct interannual shifts and cultivar-specific patterns. Early flowering cultivars ('Arbequina', 'Arbosana') showed significant anticipation compared to mid- or late-flowering ones ('Koroneiki', 'Urano', 'Don Carlo'), suggesting potential temporal overlaps that may favor cross-pollination. Climatic variability, particularly in chilling accumulation, combined with crop load, proved to be a decisive factor influencing flowering timing and reproductive success.

The analysis of flowering phenology showed that most cultivar combinations exhibited an overlap exceeding 70%, indicating generally good pollination success. 'Arbequina' and 'Frantoio' emerged as the most reliable pollinizers, while other cultivars, such as 'Coratina', 'Fs-17', and especially 'I-77', showed critical mismatches with the studied genotypes.

Clear cultivar-dependent variability in gynosterility values was observed, confirming the genetic basis of this trait but also revealing environmental modulation due to canopy position and light exposure. Cultivars such as 'Cima di Bitonto', 'Coratina', 'Arbequina', and 'Arbosana' showed rates less than 30% of sterile flowers, while 'I-77' and 'Koroneiki' exhibited higher than 50%, severely affecting their reproductive efficiency. Self-compatibility trials indicated 'Arbequina', 'Koroneiki', 'Cima di Bitonto', and 'Frantoio' as pseudo-self-compatible, whereas the others were clearly self-incompatible and thus unsuitable for monovarietal SHD plantings without compatible pollinators.

Overall, olive cultivars differed markedly in genetic sterility. 'Cima di Bitonto' and 'Frantoio' showed the highest rank considering self-compatible and low gynosterility levels, while the self-incompatible 'I-77' exhibited extremely high gynosterility, indicating greater reproductive constraints.

The research confirms that floral biology, through its genetic and phenological components, plays a decisive role in defining cultivar adaptability and reproductive efficiency in SHD olive orchards. Nevertheless, this work also highlights the need for further investigations encompassing a broader range of olive cultivars, like the latest patented cultivars, extended monitoring periods, and multi-site comparisons.

This research was conducted in an SHD orchard under Mediterranean conditions. Future research should extend these investigations to different climatic areas and cultural management in order to validate and generalize the present findings and to better assess cultivar performance under contrasting environmental and agronomic conditions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/horticulturae12010110/s1.

Author Contributions: Conceptualization, F.M., F.N., F.L., G.A.V. and S.C.; methodology, G.A.V. and S.C.; software, F.N.; formal analysis, F.L.; investigation, F.N. and G.A.V.; resources, F.N. and S.P.G.; data curation, F.N., S.P.G., F.L. and G.A.V.; writing—original draft preparation, F.M.; writing—review and editing, F.M., F.N. and S.C.; visualization, F.M. and S.P.G.; supervision, G.A.V. and S.C.; project administration, F.M., G.A.V. and S.C.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to thank Luca Giuseppe Palella for the incredible effort in this work.

Conflicts of Interest: Authors Francesco Maldera, Francesco Nicolì and Salvatore Campooseo are members of the company NIKA srl, accredited Spin Off of the University of Bari Aldo Moro and innovative Start Up. The remaining Authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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