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Phenology, Yield and Nut Traits Evaluation of Twelve European Hazelnut Cultivars Grown in Central Italy

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Abstract: European hazelnut (*Corylus avellana* L.) cultivation has grown worldwide in recent years, even though the world's production is still fulfilled by a few dozen cultivars well adapted to the local environments of their selection. After Turkey, Italy is the second largest producer of hazelnuts, and the province of Viterbo, in central Italy, is recognized as one of the most suitable districts for hazelnut cultivation. The production in this area relies almost entirely on local cultivar 'Tonda Gentile Romana', whereas cultivar 'Nocchione' is used as the main pollinizer. More recently, cultivar 'Tonda di Giffoni' has been introduced in new local plantations. Cultivation of many cultivars in different areas is of fundamental importance to test their adaptability to different environmental conditions, a need currently accentuated by ongoing climate change. With this aim, a European hazelnut collection field was established in 2000 in Caprarola municipality (Viterbo province), where plants of twelve hazelnut cultivars were observed over four growing seasons for their phenological, agronomic and nut traits. The cultivars studied, namely 'Barcelona', 'Camponica', 'Ennis', 'Merveille de Bollwiller', 'Negret', 'Nocchione', 'Riccia di Talanico', 'San Giovanni', 'Tombul', 'Tonda di Giffoni', 'Tonda Gentile' and 'Tonda Gentile Romana', showed a high diversity in their phenological behaviour, yield efficiency and nut and kernel traits. Cultivars 'Negret', 'Tombul' and 'Tonda Gentile', with poor yields over the years of research, do not seem suitable to be cultivated as main cultivars in the studied environment, contrary to 'Camponica' and 'San Giovanni', which produced abundantly, reaching a total of almost 30 and 25 kg plant^{-1} of in–shell hazelnuts, respectively. Cultivars 'Tonda Gentile Romana' and 'Nocchione' confirmed their yield consistency, whereas 'Ennis', 'Barcelona' and 'Tombul' seem suitable to be introduced as pollinizers thanks to their male blooming overlapping with the female blooming of the main cultivar 'Tonda Gentile Romana'. Cultivar 'Tonda di Giffoni' did not perform well in the studied environment, despite being recognized as one of the highest-yield cultivars.

Keywords: *Corylus avellana* L.; blooming; self–incompatibility; yield efficiency; kernel traits

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1. Introduction

European hazelnut (*Corylus avellana* L.) is a temperate perennial crop, monoecious and wind–pollinated species that requires cross–pollination due to its sporophytic incompatibility [1].

Italy is the second largest hazelnut-producing country in the world, recording 105,650 tons of in–shell nuts in 2022. This is only behind Turkey, which in the same year produced 765,000 tons, and ahead of Azerbaijan, USA, Chile and Georgia, which produced 72,100, 70,300, 62,550 and 33,400 tons of in–shell nuts, respectively [2]. European hazelnut is also an excellent source of biomass for energy uses [3], and its pruned wood and shells are suitable to produce high–quality biochar, as well as woodchips and pellets to be used in modern combustion devices [4]. Furthermore, the use of hazelnut shrubs to produce high–quality timber is a widespread practice in the Campania region (Italy), often in combination with walnut trees to obtain defect–free logs and annual nuts production at the same time [5].

Hazelnut cultivation in Italy has recently increased both in traditional and newly introducing areas, as recorded in the Latium region (central Italy), one of the most relevant Italian hazelnut districts, where the hazelnut land has changed from about 19,000 ha in 2010 to more than 25,000 ha in 2023 [6]. In this region, as a consequence of the increasing demand from the confectionery industry of in–shell and shelled nuts, new plantations have been recently established that occupy highly mechanizable flat lands previously used for annual crops and pastures, and they are sometimes characterized by not completely suited soils and microclimates for hazelnut cultivation [7].

Areas suitable for hazelnut cultivation usually have a climate characterized by cool summers and mild winters, preferably near large watersheds, such as the Mediterranean basin, the Black Sea slopes of northern Turkey or the Pacific Ocean nearby Willamette Valley of Oregon [8].

A few dozen hazelnut cultivars currently represent the basis of worldwide hazelnut production [9], as highlighted in Italy, where a very limited number of cultivars are grown in the major hazelnut producing regions. For instance, in Latium, hazelnut production is mainly achieved using 'Tonda Gentile Romana' as the main cultivar in combination with 'Nocchione' as the main pollinizer [10].

Furthermore, the recent increase in regional hazelnut land use has also been accompanied by an evolution of the plant training system and planting layouts, often featuring higher density than in the past, but not accompanied by an expansion of the cultivar platform used. Thus, it is still characterized by the use of one or a few cultivars highly appreciated by the confectionery industry due to their nut and kernel traits, such as the round shape of the nuts and high kernel peeling after blanching or roasting [11]. This agronomic framework, affecting both traditional and new hazelnut plantations, is often associated with high risks of pathological biotic and abiotic pressures, recently augmented by the climate changes affecting the Mediterranean basin [12]. Accordingly, many phenological time–course trends have been studied in fruit trees, and most are consistent with warming temperatures [13,14]. Thus, proper climatic adaptation of the cultivars, although being a remarkably long process, has been proven to be essential for proper vegetative growth and plant yielding; this adaptation process can be evaluated by continuously monitoring the plant's response in terms of phenology and agronomic traits for multiple years [15]. This is also confirmed for European hazelnut since it is a species quite sensitive to water stress [16] and highly influenced by temperature (especially for chilling requirements), able to affect the quality of male and female flowers as well as flowering time [17–21].

With the aim of expanding the actual narrow genetic base of European hazelnut cultivation in the Latium region, driving cultivar choice in the new orchards or in those too old that need to be replaced, a hazelnut collection orchard has been established in a suitable area surrounding the Vico Lake in Viterbo province [22], where the most relevant hazelnut cultivars and some other minor varieties are currently grown and studied in their adaptation to the selected environment.

2. Materials and Methods

2.1. Plant Material and Experimental Site

Mature plants in full production phase of twelve cultivars of *C. avellana* were included in this study over the period 2014–2018, namely 'Barcelona' (synonym Fertile del Coutard), 'Camponica', 'Ennis', 'Merveille de Bollwiller', 'Negret', 'Nocchione', 'Riccia di Talanico', 'San Giovanni', 'Tombul', 'Tonda di Giffoni', 'Tonda Gentile' (synonym Tonda Gentile delle Langhe or Tonda Gentile Trilobata) and 'Tonda Gentile Romana'. These cultivars are part of a larger hazelnut collection field, including a total of 49 accessions of different origins and commercial relevance. The varietal collection was established by Regional Agency for Agricultural Development and Innovation in Latium (ARSIAL) in the year 2000, using one–year–old self–rooted suckers collected by other Italian hazelnut collection fields previously established, and the varietal guarantee has been explored using microsatellite markers [23]. The hazelnut collection orchard is in a typical hazelnut–growing area of Viterbo province (Italy), named "Le Cese" (Municipality of Caprarola, Latium–Italy. Latitude 42°20′54″ N; longitude 12°11′38″ E; altitude 570 m a.s.l.), near the volcanic Vico lake, extensively recognized as one of the most suitable Italian districts for European hazelnut cultivation.

Furthermore, according to Köppen classification, the climate of the study area corresponds to hot–summer Mediterranean climate (CSa), with the warmest month's average temperature above +25 °C. The five–year meteorological data was downloaded from a station of the Latium region, placed near the experimental station at an altitude of 520 m a.s.l. (Figure 1). Data from 2014 to 2018 reported a mean annual air temperature of +15.7 °C and an annual precipitation of 962 mm. The warmest and driest months were June, July and August, whereas the highest monthly precipitation was recorded in November (about 133 mm).

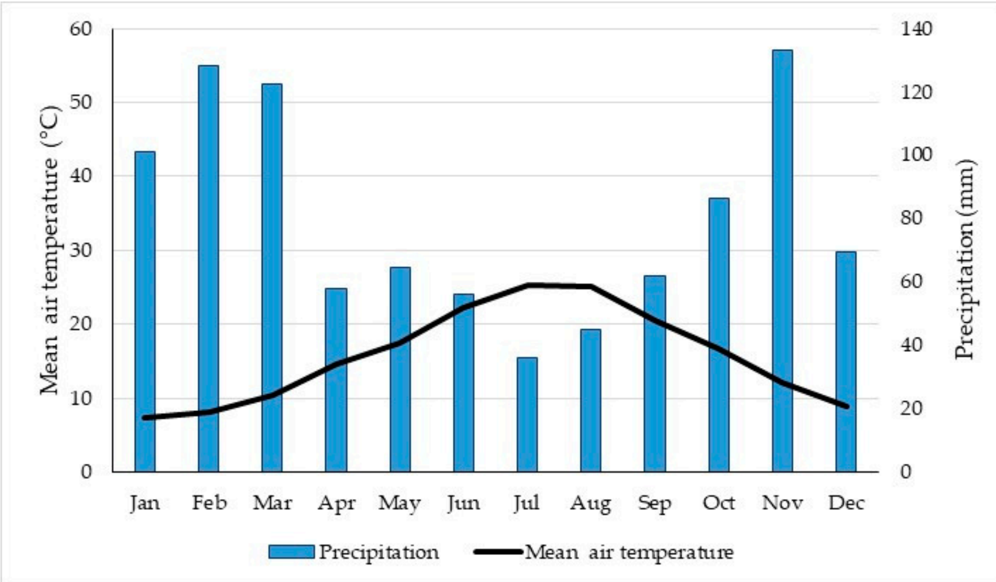

Figure 1. Mean monthly precipitation and air temperature of the study area (average over the period 2014–2018). Data source: ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale. URL: http://www.scia.isprambiente.it (accessed on 31 January 2019).

Each accession in the collection field is represented by three adjacent plants in the same row trained as multi–stemmed open vase in accordance with the natural bushy development of the species, planted at a spacing of 5.0 m × 4.0 m, irrigated through a sub–irrigation system, and managed with standard orchard management techniques. Namely, the soil was managed with a natural green cover crop, and annually, the orchard received the applications of the following quantities of main fertilizers: 90 kg ha^{-1} nitrogen, 60 kg ha^{-1} phosphorus and 90 kg ha^{-1} potassium. The orchard management and the integrated pest and disease control were also yearly applied by ARSIAL according to the guidelines of the current regional Rural Development Plan [24].

2.2. Soil Mapping and Analysis of the Collection Field

The regional soil map (scale 1:250,000) frames the soilscape as "soils along moderately steep slopes on volcanic pyroclastic deposits and lavas in the volcanic complexes of Bolsena, Vico and Bracciano lakes". The land uses are mainly forest and arboreal crops, and the soil typologies vary from *Cambic Umbrisols* to *Eutric Arenosols* and *Haplic Luvisols* [25]. To determine soil spatial variability within the experimental field, the soil was surveyed by an electromagnetic induction sensor (EMI) Mini–Explorer (GF–instruments, Brno–Medlánky, Czech Republic) to evaluate the possible soil heterogeneity, which could affect the interpretation of plant phenological and agronomical observations detailed in the following sections. The EMI sensor allows to measure the soil's apparent electrical conductivity

(ECa) at different depths, which is correlated with soil texture, bedrock depth, compaction, moisture and eventual salinity.

The EMI proximal survey showed strong homogeneity of ECa at the three reference depths (0–50, 0–100 and 150 cm) (Figure 2). For this reason, it is likely that the physical and hydrological features of soil, namely texture, soil depth, stoniness, bulk density and water retention, were homogeneous within the experimental field. Although ECa was poorly related to chemical features, with the only exception being salinity, it is possible to suppose with high probability that its soil features and its functionality were homogeneous within the experimental field. The exclusion of soil variability effect is fundamental in a field study of plant phenology and yield, as demonstrated by previous research [26,27]. To determine the main characteristics of soil within the study area, topsoil samples were collected in three different sites of the field, then grouped and analyzed by laboratory methods. The soil of the study area showed a sandy clay loam texture (sand = 66%, clay = 27%) and slightly acid pH with mean values of 6.1. The soil organic matter (SOM) was relatively high (2.3% d.w.) and the base saturation was 56% of the total exchange complex (CEC). Exchangeable calcium, magnesium and potassium were well-balanced with values of 771, 273 and 172 mg kg^{-1}, respectively, whereas the soil assimilable phosphorous was low (13 mg kg^{-1}). Such soil typology, derived by volcanic pyroclastic deposits, is one of the most common in this district of hazelnut production, around Vico lake and Viterbo province.

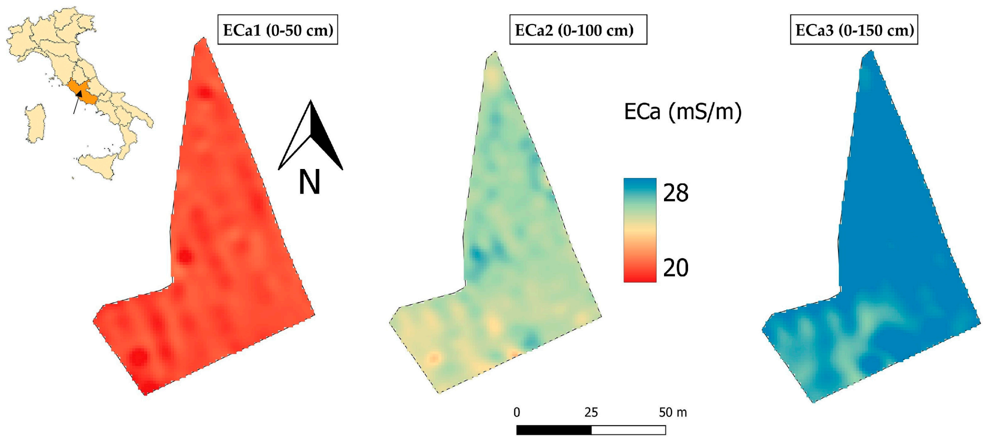

Figure 2. Maps of apparent electrical conductivity (ECa) at three depths (0–50, 0–100, and 0–150 cm) measured by GF Mini–Explorer and interpolated by ordinary kriging within the hazelnut collection field. The maps showed a strong homogeneity of soil ECa, and then a strong homogeneity of soil physical–hydrological features.

2.3. Phenology and Flowering Time

The flowering and leaf bud break times of each cultivar were observed between the 2014/15 and 2017/18 blooming seasons through weekly field observations during winter and early spring. Male flowering (pollen shedding) was recorded at stages Fm1 (start: 5% of flowers are open, turned the colour from light–green to yellow, and start to shed pollen), Fm2 (peak: 50% of flowers are open) and Fm3 (end: last flowers are open), and female flowering at stages Ff1 (start: 5% of flowers are open and have extended stigmas), Ff2 (peak: 50% of flowers are open) and Ff3 (end: last flowers are open), according to phenological phases proposed by Solar and Stampar [15] and reported in Figure 3.

Date of leaf budbreak was recorded when over 50% of terminal buds were enlarged and the bud scales had opened to expose the green of the leaves inside, referring to the phenological stage C as described by Germain and Sarraquigne [28]. Finally, the entire ripening period of the cultivars studied was recorded.

Figure 3. Female flowering at stages Ff1 (**top left**), Ff2 (**top middle**) and Ff3 (**top right**). Male flowering at stages Fm1 (**bottom left**), Fm2 (**bottom middle–left**) and Fm3 (**bottom middle–right**). Leaf budbreak (**bottom right**).

2.4. Trunk Cross–Sectional Area, Yield and Yield Efficiency

During the harvest seasons, the in–shell nut production of each plant was picked up by hand to determine the yield. Harvesting was conducted in two steps; the first intervention was carried out when about 50 per cent of the hazelnuts had fallen to the ground, while the second one was conducted when the remaining portion of hazelnuts had finished dropping.

The harvested nuts per plant were dried in the laboratory with a thermostatic heater (KW Apparecchi Scientifici srl, serie W107TO, Siena, Italy) according to hazelnut market guidelines (kernel moisture not exceeding 6% for both consumption and storage in shell) and then weighed with a lab balance. After weighing, each group of harvested in–shell nuts was properly stored at room temperature in the laboratory until further analysis. At the same time, trunk cross–sectional area (TCSA) was determined at 30 cm above the ground for all cultivars investigated and expressed as the sum of the TCAs of each trunk per plant. Furthermore, yearly yield efficiency (YE) was calculated as the ratio between the yearly yield and yearly TCAs (YE = yield TCA^{-1}).

2.5. Nut and Kernel Traits

Every harvest season, from 2014 to 2017, a sample of twenty in–shell nuts per plant (sixty nuts per cultivar) were randomly sampled and measured for their quantitative nut and kernel traits, according to the hazelnut descriptors available in the literature [29,30]; furthermore, the average kernel/nut ratio of each cultivar was also calculated.

2.6. Statistical Analysis

The data collected on each plant over the four–year research, with the only exception being the qualitative observation of blooming and leaf bud break, were subjected to a two–way ANOVA to validate the effects of "cultivar", "year" and their interaction. Differences have been accepted as statistically significant when $p \leq 0.01$, and mean separation was performed using Fisher's test. Percentages were subjected to angular transformation according to the formula (x + 0.5) 1/2 before data analysis. All data were processed in XLSTAT version 2021.4, a statistical software for Microsoft Excel 365.

3. Results

3.1. Phenological Traits

Male and female flowering times of the twelve cultivars over four continuous blooming seasons, recorded in mid–winter and early–spring from 2014/15 to 2017/18, are presented in Figure 4, as well as their leafing times, recorded in general between early February and the end of March.

Overall, looking at the entire male blooming period, the longest time windows were shown by 'Barcelona', 'Riccia di Talanico' and 'Negret', while 'Merveille de Bollwiller' and 'Tonda di Giffoni' had the shortest ones. Generally, seasons 2015/16 and 2017/18 were characterized by a shorter pollen shedding time window compared to the other research seasons. The earliest pollen shedding was reported during the first three weeks of December for Italian cultivar 'Tonda Gentile'. A tendency towards precocity was also observed in 'Negret', 'San Giovanni' and 'Nocchione', whose male full blooming occurred between the middle of December and the beginning of January. From the end of December, 'Camponica' and 'Barcelona' resulted in pollen shedding, which continued until the middle of January. A similar trend was also observed in 'Tonda di Giffoni', with an exception registered during season 2014/15, where male full blooming of this cultivar took place from the second week of January to the end of the same month. An intermediate behavior in male blooming characterized 'Riccia di Talanico' and 'Tombul', which showed a full blooming phase from the first half of January to the end of the month. 'Ennis' showed an alternate trend, entering the pollen shedding phase from the first half of January until the third week of the month during seasons 2015/16 and 2017/18. Conversely, during seasons 2014/15 and 2016/17, its pollen shedding was concentrated between the second half of January and the beginning of February. The latest flowering cultivars resulted to be 'Tonda Gentile Romana' and 'Merveille de Bollwiller', which shed pollen from the end of January to the middle of February. 'Tonda Gentile' and 'Negret' showed a marked protandrous blooming pattern, with catkins elongating even more than three weeks before female flowers.

With reference to the whole female blooming period, season 2014/15 showed a longer time window compared to the other blooming seasons. Italian cultivar 'San Giovanni' resulted to be the earliest for reaching female full blooming, which took place generally from the second week of December to the first half of January. 'Nocchione' and 'Riccia di Talanico' also showed an early behaviour, with female full blooming occurring from the middle of December until the third week of January. Although female full flowering ended about two weeks earlier, a similar trend was observed for 'Tonda di Giffoni'. Cultivar 'Tonda Gentile' had an intermediate full female blooming that lasted throughout January, as did 'Camponica'; however, the latter showed an irregular trend as the 2015/16 and 2017/18 seasons were characterized by earlier female flowering. Female full blooming took place around the second week of January until the first half of February for 'Negret', 'Barcelona', 'Tonda Gentile Romana' and 'Tombul'. Cultivar 'Merveille de Bollwiller' had a late female full blooming, which took place from the second half of January until the second week of February in both seasons 2014/15 and 2015/16 and until the end of this month in the last two growing seasons. Cultivar 'Ennis' showed a late flowering as well, with an irregular pattern since female full flowering started around the second half of January during seasons 2015/16 and 2017/18 and concluded at the beginning of February. Conversely, during seasons 2014/15 and 2017/18, female blooming occurred later, taking place from the beginning of February until the second half of the month. Cultivar 'Tonda Gentile Romana' and partially 'Merville de Bollwiller' and 'Tonda di Giffoni' showed a protogynous blooming pattern, with female flowers maturing about two weeks earlier than male flowers.

Leafing time of the cultivars has been classified according to the descriptors for hazelnut (*Corylus avellana* L.) edited by FAO and CIHEAM [31]. The earliest bud break was reported for 'San Giovanni' and 'Tonda di Giffoni', for which this phase took place during the first three weeks of February in all of the four evaluated seasons. Early bud break, concentrated mainly in the second half of February, was also shown by 'Camponica' and 'Tonda Gentile', with the only exception during season 2014/15 where both leafed during the second week of March. 'Riccia di Talanico' leafed from the end of February to the first half of March, and an intermediate leafing time, mainly concentrated in the first half of March, was also registered for 'Ennis'. Furthermore, 'Barcelona', 'Tombul' and 'Tonda Gentile Romana' showed a similar trend since bud break occurred during the second week of March in all the evaluated seasons except for season 2015/16, when an anticipated leafing time was observed. The latest bud breaks were registered mainly during the second half of March for 'Negret' and 'Merveille de Bollwiller'. Cultivar 'Nocchione' also showed an intermediate–late behavior in leafing mixed and vegetative buds during both the first and the last evaluated seasons, while during the other growing seasons, bud break happened during the end of February, showing a slightly irregular pattern.

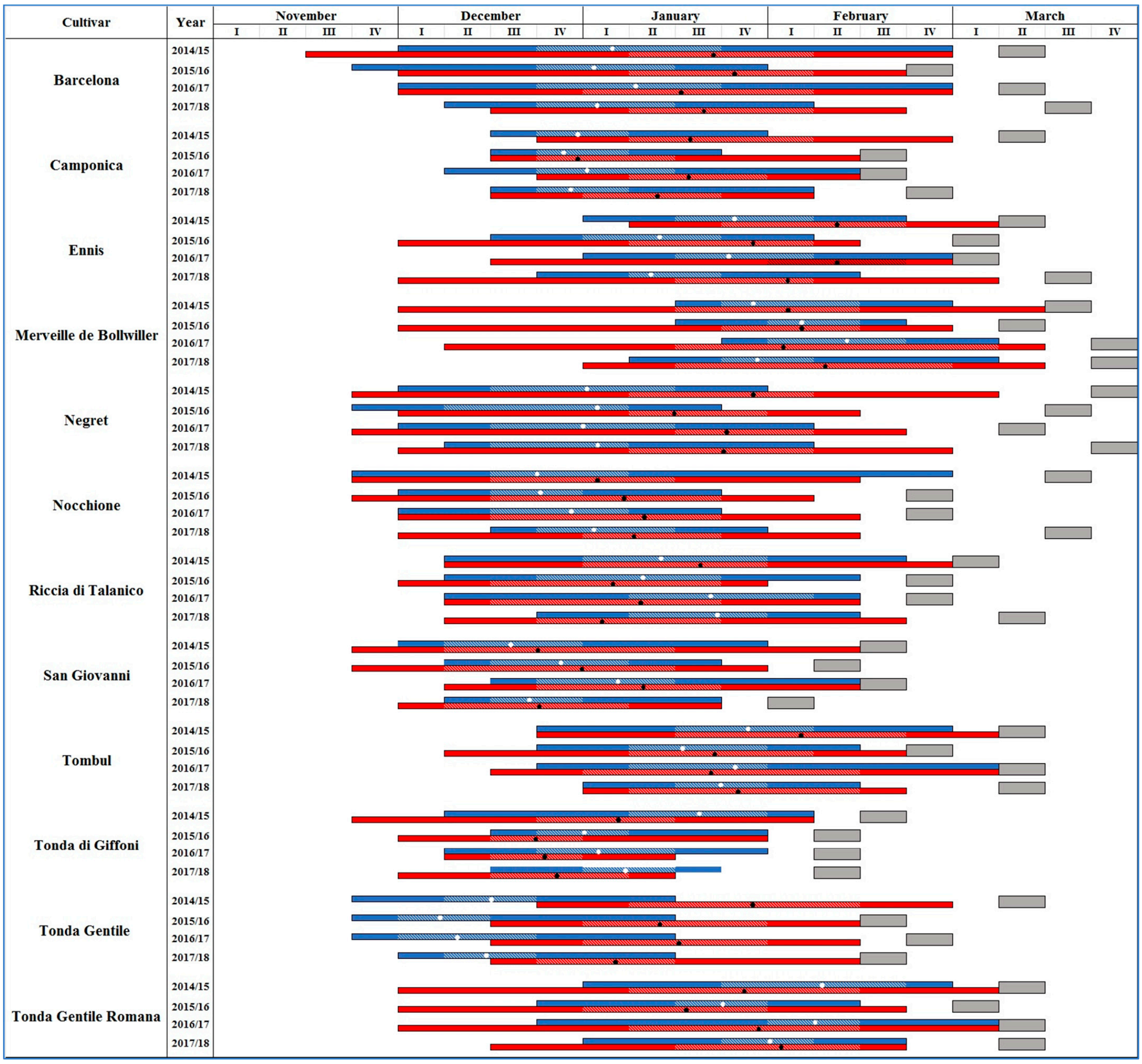

Figure 4. Phenograms of male and female flowering and leafing times for the twelve hazelnut cultivars studied over four years of investigation (blooming seasons 2014/15–2017/18). Blue histograms indicate male blooming (beginning: catkins start to elongate and few are pollen shedding; end: last few male catkins are still shedding pollen). The portion of "shaded blue histogram" indicates the window of full male blooming, while the "white dot" indicates the peak of male blooming (about 50% of catkins are elongated and shedding pollen). Red histograms indicate female blooming (beginning: red–dot stage appears on female flowers and few have extended stigmas; end: last few female flowers are still receptive). The portion of "shaded red histogram" indicates the window of full female blooming, while the "dark dot" indicates the peak of female blooming (about 50% of glomerules have extended receptive stigmas). Grey histograms identify the leafing dates of the twelve cultivars studied.

The ripening of hazelnut clusters (husks and in–shell hazelnuts) in the considered environment generally occurred from the last ten days of August, when the first portion of in–shell nuts started to fall on the ground, until the end of September. The earliest ripening cultivars during the research years were 'Camponica, 'San Giovanni', 'Tonda Gentile' and 'Tombul' (although for this latter cultivar, the natural dropping of the hazelnuts to the ground does not occur due to the morphology of its husk overlaying the in–shell nut), characterized in general by a ripening window between 20 August and 10 September, followed by 'Ennis', 'Merveille de Bollwiller', 'Nocchione' and 'Riccia di Talanico' (from last week of August to half September). Otherwise, 'Barcelona', 'Negret' and 'Tonda Gentile Romana' showed a later ripening, mainly occurring during the second half of September. Finally, 'Tonda di Giffoni' was the most scalar ripening cultivar as it was characterized by ripe fruits starting in the last week of August and ending during the first week of October.

3.2. Trunk Cross–Sectional Area, Yield and Yield Efficiency

Table 1 reports data regarding the plants' vigour and productivity, namely trunk cross–sectional area determined at 30 cm above the ground (TCSA) and expressed as the sum of the TCAs of each trunk per plant, the yield per plant of in–shell nuts, and the relative yield efficiency (YE). Values are grouped as the mean of "cultivar" and "year". By looking at the interaction of these two combined factors (cultivar × year), a statistically significant interaction was found for plant yield (Table 1; Figure 5), whereas TCSA and YE were not affected by statistical significance at $p \leq 0.01$.

Table 1. Tunk cross-sectional area (TCSA) yield per plant and yield efficiency (YE) of hazelnut cultivars studied and collected at Le Cese (Viterbo province, Italy). Values are expressed as mean ± SD of four–year determinations. Means within a column followed by the same letter are not significantly different to Duncan's multiple range test at $p \leq 0.01$ (n.s.: non-significant; **: significant at $p \leq 0.01$).

Cultivar	Year	TCSA (cm^2)	Yield (kg $tree^{-1}$)	Yield Efficiency (kg cm^{-2})
Barcelona	4–year average	495.6 ± 143.3 a	5.53 ± 0.90 bcd	0.011 ± 0.002 ef
Camponica	4–year average	286.7 ± 81.8 bcd	7.34 ± 1.90 a	0.026 ± 0.005 a
Ennis	4–year average	326.5 ± 78.8 bc	3.51 ± 0.55 e	0.011 ± 0.002 ef
Merveille de Bollwiller	4–year average	144.4 ± 49.2 e	3.72 ± 0.57 e	0.027 ± 0.006 a
Negret	4–year average	169.1 ± 59.2 e	1.61 ± 0.34 f	0.010 ± 0.003 ef
Nocchione	4–year average	230.5 ± 42.7 cde	5.81 ± 0.64 bc	0.025 ± 0.003 a
Riccia di Talanico	4–year average	330.3 ± 28.8 bc	4.72 ± 0.96 d	0.017 ± 0.006 cd
San Giovanni	4–year average	278.8 ± 68.4 bcd	6.28 ± 0.63 b	0.023 ± 0.003 ab
Tombul	4–year average	196.9 ± 54.7 de	1.82 ± 0.42 f	0.010 ± 0.003 ef
Tonda di Giffoni	4–year average	385.7 ± 71.4 b	5.22 ± 0.68 cd	0.014 ± 0.002 de
Tonda Gentile	4–year average	330.7 ± 54.7 bc	2.23 ± 0.65 f	0.007 ± 0.002 f
Tonda Gentile Romana	4–year average	321.2 ± 38.7 bc	5.54 ± 0.85 bcd	0.019 ± 0.004 bc
2014	average cvs.	234.6 ± 94.5 b	3.55 ± 1.52 b	0.016 ± 0.008
2015	average cvs.	272.1 ± 119.4 b	4.31 ± 1.79 ab	0.017 ± 0.008
2016	average cvs.	301.8 ± 129.0 ab	4.79 ± 1.75 ab	0.018 ± 0.008
2017	average cvs.	357.1 ± 142.6 a	5.13 ± 2.39 a	0.015 ± 0.007
Cultivar		**	**	**
Year		**	**	n.s.
Cultivar × Year		n.s.	**	n.s.

Despite a wide heterogeneity within the sampled cultivars throughout the four years, some common features concerning yield trends were registered. Across the four years, almost every cultivar underwent an increasing pattern, with 2017 being the most productive year for most accessions. However, cultivars 'Negret', 'Tombul' and 'Tonda Gentile Romana' had their productive peak in 2016. Indeed, such growth in yield was further confirmed by ANOVA involving "Year" as an independent variable, which detected a statistically higher yield in 2017 when compared to the one from 2014. The greatest yield values were found for cultivar 'Camponica' in the year 2017 (9.9 kg plant^{-1} on average), while 'Negret', 'Tombul' and 'Tonda Gentile' cultivars were the least productive ones; this behaviour was particularly exacerbated in the year 2014, when the same cultivars produced an average of 1.2, 1.3 and 1.6 kg plant^{-1} of in–shell nuts, respectively. Post–hoc analyses of aggregated data highlighted significantly lower yields in 'Negret', 'Tombul' and 'Tonda Gentile' in comparison to every other cultivar. On the other hand, 'Camponica' plants were found to be the best performing cultivar, regardless of the considered year.

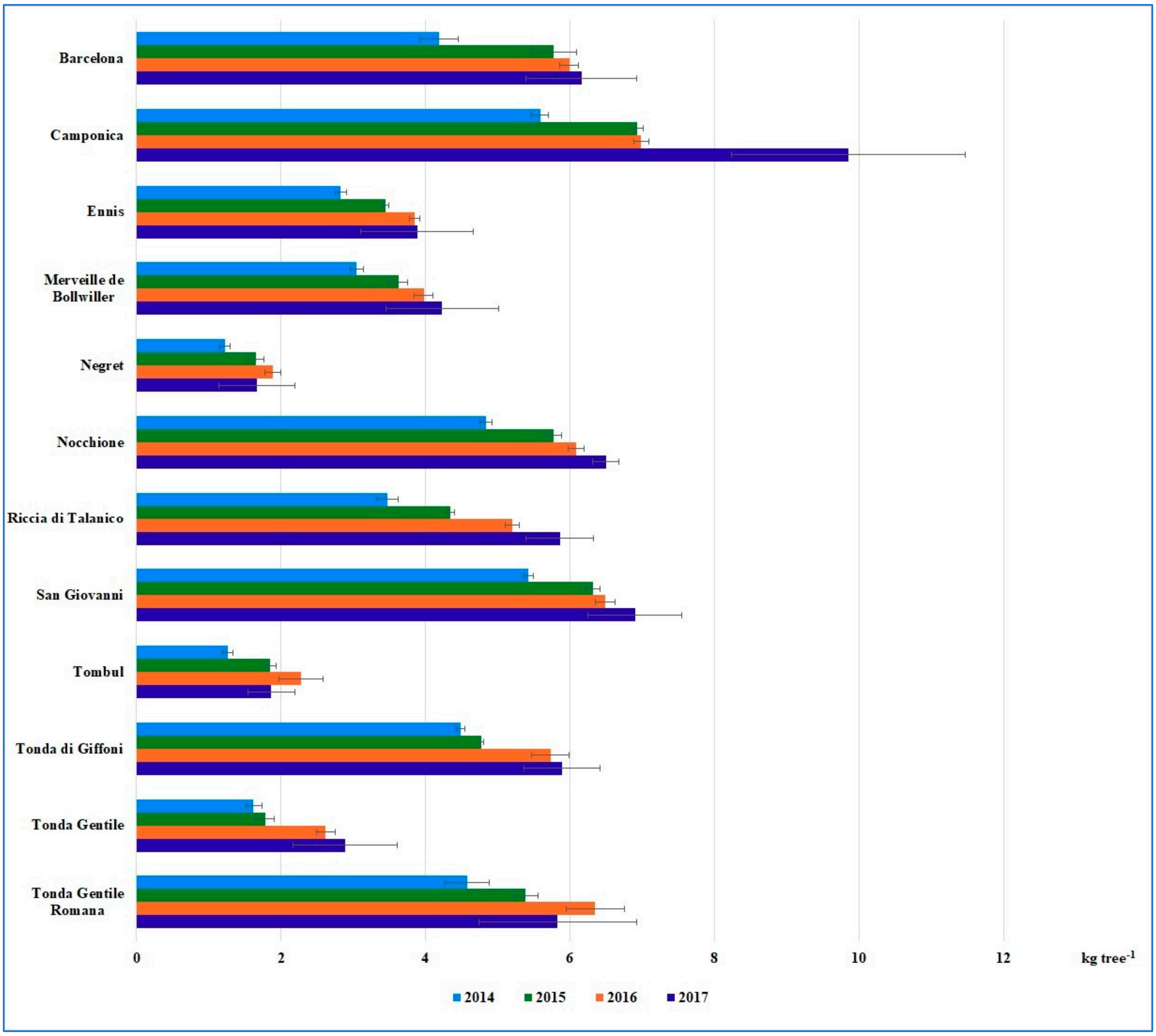

Figure 5. Yield per plant of hazelnut cultivars studied and collected at Le Cese (Viterbo province, Italy). Values are expressed as mean ± SD of four–year determinations.

As already mentioned, no statistically significant interaction between factors took place for TCSA. However, both the "Cultivar" and "Year" factors happened to singularly have a significant impact on such parameters. As a general trend, TCSA went through an overall enlargement over time, as the 2017 aggregated values (35 cm^2) appeared to be 24% higher in comparison to the ones recorded in 2014 (i.e., 235 cm^2). Cultivar–wise, average TCSAs ranged from about 145 cm^2 up to almost 500 cm^2 in 'Merveille de Bollwiller' and 'Barcelona', respectively. The YE was significantly impacted by cultivar effect only, without any remarkable change across the four–year research window. Plants belonging to the 'Merveille de Bollwiller', 'Camponica', and 'Nocchione' varieties showed the highest YE among the rest of the studied accessions, showing mean values of 0.027, 0.026 and 0.025 expressed as average four–year research, respectively. On the contrary, in 'Tonda Gentile', remarkable trunk section values did not translate into high productivity, causing this cultivar to be identified as the lowest in terms of YE (0.007) within the studied varietal platform, followed by 'Negret and 'Tombul' (both 0.010) and 'Barcelona' and 'Camponica' (both 0.011).

3.3. Nut and Kernel Traits

Nut and kernel traits of the hazelnut cultivars studied, expressed as mean values of four–year determination, are reported in Table 2.

Table 2. Nut and kernel traits of the European hazelnut cultivars studied. Values are expressed as mean ± SD of four–year determinations. Means within a column followed by the same letter are not significantly different to Duncan's multiple range test at $p \leq 0.01$.

Cultivar	Nut Weight (g)	Kernel Weight (g)	Shell Weight (g)	Kernel/Nut Ratio (%)
Barcelona	3.50 ± 0.35 ab	1.44 ± 0.19 b	2.05 ± 0.23 b	41.30 ± 3.33 de
Camponica	3.45 ± 0.46 abc	1.69 ± 0.25 a	1.76 ± 0.2 c	48.92 ± 2.48 a
Ennis	3.75 ± 0.49 a	1.37 ± 0.31 bcd	2.45 ± 0.24 a	37.06 ± 5.59 f
Merveille de Bollwiller	2.01 ± 0.17 g	0.90 ± 0.08 fg	1.11 ± 0.09 f	44.86 ± 0.84 bc
Negret	1.82 ± 0.22 gh	0.90 ± 0.17 fg	0.91 ± 0.09 g	49.46 ± 4.99 a
Nocchione	3.11 ± 0.62 cd	1.22 ± 0.27 cde	1.84 ± 0.35 c	39.59 ± 1.47 ef
Riccia di Talanico	2.39 ± 0.15 f	1.10 ± 0.05 ef	1.29 ± 0.12 e	46.12 ± 2.00 abc
San Giovanni	2.75 ± 0.18 e	1.29 ± 0.09 bcde	1.46 ± 0.11 d	47.03 ± 1.99 ab
Tombul	1.48 ± 0.37 h	0.79 ± 0.29 g	0.74 ± 0.12 g	49.55 ± 5.59 a
Tonda di Giffoni	3.22 ± 0.28 bcd	1.39 ± 0.17 bc	1.81 ± 0.15 c	43.11 ± 2.66 cd
Tonda Gentile	2.62 ± 0.35 ef	1.17 ± 0.24 de	1.45 ± 0.13 de	44.21 ± 4.49 bcd
Tonda Gentile Romana	2.88 ± 0.33 de	1.35 ± 0.22 bcd	1.53 ± 0.09 d	46.39 ± 3.04 abc

Considerable variability in values among cultivars was observed for each investigated trait, including nut, kernel and shell weight, and kernel/nut ratio. With regard to nut weight, cultivar 'Ennis' showed the highest value with an average of 3.75 g, followed by 'Barcelona' and 'Camponica', characterized by mean weights of 3.50 g and 3.45 g, respectively. Conversely, 'Tombul' and 'Negret' ranked as the cultivars with the lowest average nut weight, recording mean values of 1.48 g and 1.82 g, respectively. Cultivar 'Camponica' also stood out in terms of kernel weight, with average values of 1.69 g, while 'Tombul' placed lowest with mean values of 0.79 g. The shell weight exhibited a similar tendency to nut weight, with 'Ennis' leading with an average weight of 2.45 g and followed by 'Barcelona' with mean values of 2.05 g, whereas the lowest values were recorded for 'Negret' and 'Tombul' with values of 0.91 g and 0.74 g, respectively.

The highest kernel/nut ratio, statistically different from that of other cultivars, was observed in 'Tombul', 'Negret' and 'Camponica', with mean values of 49.55%, 48.92% and 48.92%, respectively. Conversely, the lowest percent kernel was recorded for 'Ennis', 'Nocchione' and 'Barcelona' with mean values of 37.06%, 39.59% and 41.30%, respectively. Furthermore, the other cultivars ranked in the class of high–percent kernel varieties with mean values between 47.03% for 'San Giovanni' and 43.11% for 'Tonda di Giffoni'. This last cultivar, along with the two other most relevant Italian varieties for market uses, namely 'Tonda Gentile' and 'Tonda Gentile Romana', showed mean values between 43% and 46%, in line with the values reported in the literature [15,29].

Finally, nut characterization over the four research–year showed a high stability in the traits studied for 'Camponica', 'Merveille de Bollwiller', 'Nocchione', 'Riccia di Talanico', 'San Giovanni' and 'Tonda di Giffoni' when compared to the other cultivars, which showed higher variability, particularly for the kernel/nut ratio.

4. Conclusions

Figure 6 reports the cumulative yield over the four research years listed as t ha^{-1} of in–shell nuts considering a planting density of 500 plants ha^{-1}, according to the planting layout of the collection field. Yield and nut and kernel trait performances are set in an environmental context characterized by a hot–summer Mediterranean climate and slightly acidic soil of volcanic origin, according to our findings.

Cultivars provided heterogeneous results on cumulative yield. Overall, 'Camponica' was the most yielding cultivar, reaching almost 15 t ha^{-1} of in-shell hazelnuts produced over the four growing seasons. Considerable values were also reached by 'San Giovanni', 'Nocchione', 'Tonda Gentile Romana' and 'Barcelona', as their cumulative yields ranked between 11 and 13 t ha^{-1}. Nevertheless, cultivars such as 'Negret', 'Tombul' and 'Tonda Gentile' were characterized by more modest yields (3, 3.5 and 4.5 ha^{-1}, respectively). Despite hazelnut production across cultivars being considerably diverse in terms of size, similar traits in how yields changed over time were found. Growing season 2014 represented the worst year in terms of harvested hazelnuts for all the studied accessions, conversely to the season 2017, which was generally the most productive in the cumulative production pool on a four-year basis.

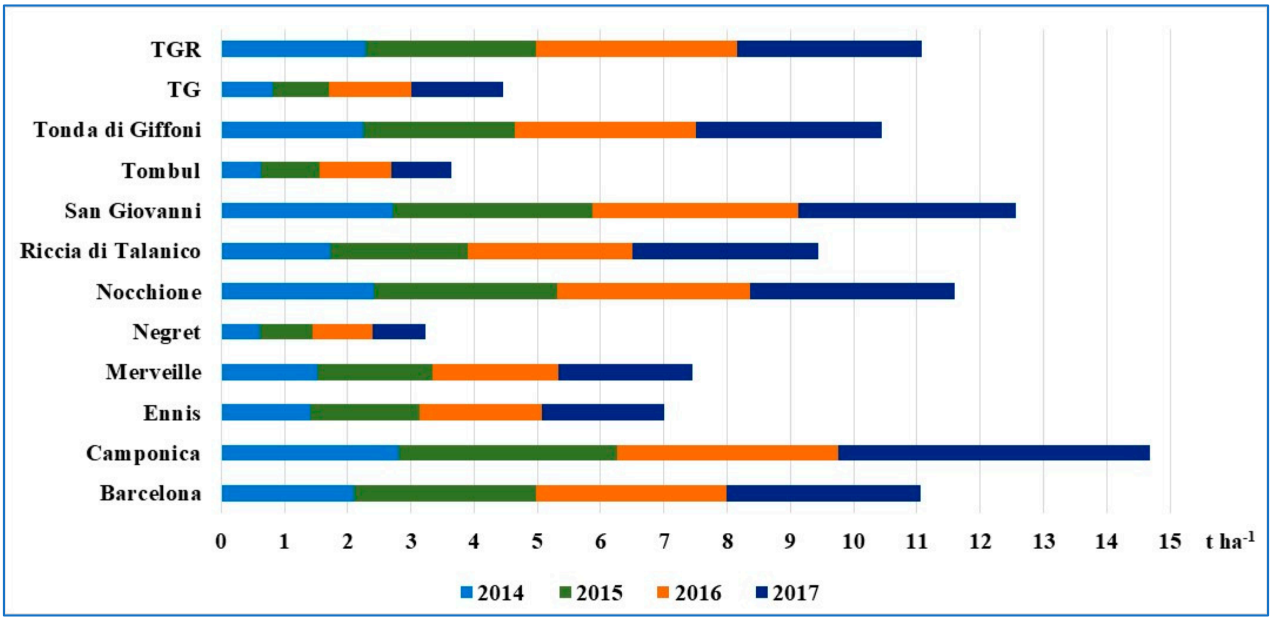

Figure 6. Cumulative yield expressed as t ha^{-1} over the four research years of the cultivars grown in the collection field "Le Cese" (Viterbo province, Italy) (TG = 'Tonda Gentile'; TGR = 'Tonda Gentile Romana').

This slight general yearly yield fluctuation confirms the aptitude of the European hazelnut to biennial bearing, which is correlated with the age of the plant [32]; in our field plot, the results were more amplified for 'Camponica' and 'Barcelona' than for the other cultivars.

Cultivars 'Negret', 'Tombul' and 'Tonda Gentile', yielding poorly over the research years, seem unsuited to be grown as main cultivars in the studied environment. Contrariwise, 'Camponica' and 'San Giovanni' released the best yielding, although leafing occurred too early in the studied environment, as well as for 'Tonda di Giffoni', exposing them to cold–back damages during the late winter—early spring.

Cultivars 'Tonda Gentile Romana' and 'Nocchione', traditionally grown in central Italy, confirmed a satisfactory yield consistency. 'Tonda di Giffoni', recently introduced in central Italy, even if recognized as one of the most productive cultivars [10], did not perform enough in the studied environment. This probably occurred as a result of its early leafing recorded in the field plot, highlighting its exposure to frost during cold spring returns, which partly compromised its production in 2014 and 2015. Furthermore, its large "window time" for nut ripening pointed out its high susceptibility to kernel mold infections, as also confirmed in the literature [33].

Cultivars 'Ennis', 'Barcelona' and 'Tombul' seem suitable to be introduced as pollinizers of the main local cultivar 'Tonda Gentile Romana' thanks to their blooming overlapping, as well as for their inter-compatibility [34]. These cultivars could integrate 'Nocchione' in serving as the main local pollinizer currently used in central Italy.

Finally, according to the trait "percent kernel", calculated excluding the incidence of the commercial nut defects, the round-shaped nut varieties 'Camponica', 'Negret', 'Riccia di Talanico', 'Tombul' and 'Tonda Gentile Romana' stood out with the highest average values (over 45%), a feature particularly appreciated by the confectionary industry and growers [11].

These multiple years of evidence may contribute to identifying suitable hazelnut cultivars for a varietal innovation in the regional older hazelnut orchards to be replaced, for the new plantations ongoing in the environment studied, and for other similar settings. Furthermore, the results may be used to implement new breeding programs on European hazelnut and its relatives.

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