Advances in cultivar choice, hazelnut orchard management and nuts storage for enhancing product quality and safety: an overview

Cristian Silvestri[1], Loretta Bacchetta[2], Andrea Bellincontro[3] and Valerio Cristofori[1,*]

[1] Department of Agriculture and Forest Sciences. University of Tuscia, Via San Camillo de' Lellis snc, 01100 Viterbo, Italy

[2] Biotechnology and Agroindustrial Division, ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Anguillarese 301, 00123 Rome, Italy

[3] Department for Innovation in Biological, Agro-food and Forest systems. University of Tuscia, Via San Camillo de' Lellis snc, 01100 Viterbo, Italy

* Correspondence to: Valerio Cristofori, Department of Agriculture and Forest Sciences, University of Tuscia, Via San Camillo de' Lellis, 01100 Viterbo, Italy. [telephone (+39) 0761-357559; fax (+39) 0761-357531; e-mail valerio75@unitus.it].

ABSTRACT

European hazelnut (*Corylus avellana* L.) is the major species of interest for nutritional uses within the *Betulaceae* family and its nuts are widely used throughout the world in the chocolate, confectionery and bakery industries. Recently his cultivation has been expanded in traditional producer countries as well as established in new places in the Southern Hemisphere, including Chile, South Africa and Australia. Introducing hazelnut in new environments could reduce its

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productivity, lead the trees to eco-physiological disorders and exposes the crop to high pressure of common and new pests and diseases. Thus, new approaches in cultivar choice guidance, in the sustainable orchard management and even in nuts storage and kernel quality evaluation are highly required for improving the hazelnut producing and processing chain. The main objective of this study was to systematize the published information regarding the recent findings of the cultural operations that directly influence the nut and kernel quality, support the varietal choice for new plantations and list the recent advances in nut storage and in its quality and safety evaluation.

Keywords: *Corylus avellana* L.; Cultivar choice, Fatty acids profile; Near Infrared Spectroscopy, Bioactive compounds

INTRODUCTION

The European hazelnut (*Corylus avellana* L.) is a major species of interest for nutritional uses within the genus *Corylus*. Other species of minor interest for commercial uses nevertheless considered important genetic resources for breeding include C*. americana*, *C. heterophylla*, and *C. colurna*.[1] European hazelnut is a deciduous, diploid (2n = 2x = 22), monoecious, wind-pollinated, dichogamous species, exhibiting sporophytic incompatibility.[2] The geographical distribution of this temperate nut crop ranges from Anatolian peninsula and the Caucasus region to Europe and North Africa, and the main and traditional hazelnut producing areas are located between the 40th and 45th latitude North, often near to the large water bodies as Black, Caspian and Mediterranean Seas.[3] **Relevant is also its cultivation in the States of Oregon and Washington (USA) near to the Pacific Ocean.**

Approximately more than 660,000 ha of the world's surface are used to cultivate hazelnuts and the in-shell production is still concentrated in few countries as Turkey (560,000 tons), Italy (110,000 tons), United States (34,000 tons), Georgia (32,000 tons), Azerbaijan (31,000 tons) and Spain (15,000 tons).[4] However, its cultivation has been recently expanded in these traditional countries as well as established in new places in the Southern Hemisphere, including Chile, South Africa and Australia.[5]

Introducing this nut crop in new environments could reduce its productivity, lead the trees to eco-physiological disorders related to the lack of resistance to low temperatures or inadequate chilling and heating requirements for vegetative and fertile buds, and exposes the crop to high pressure of common and new pests and diseases.[6]

During the growing season the most suitable temperature for plant growth ranges from 23-25°C during the day to 15-18°C during the night, meanwhile temperatures above 35°C accentuate stomata closure with a consequent growth break and photo-oxidation induction. Furthermore, due to the hazelnut leaf surface (80-100 cm^2) and its high Leaf Area Index,[7] the species has high transpiration when the relative air humidity is less than 70%.

The water requirement of European hazelnut ranges between 80 and 100 mm/month from April to August, and the species is quite adaptable to different soil conditions, avoiding clay types due to the risk of root asphyxia.[8,9]

Generally, the hazelnut world production shows an increasing trend from the beginning of the last century, in response to the demand of the confectionery industry which processes and uses large quantities of the harvested nuts.[10]

The cultivars are mainly selected to obtain uniform high-quality nuts and to meet the requirements of the food industry that focus its attention on the low incidence of defects in the kernel (double kernel, poor filled, rotten, mouldy, bug and mechanical damages) on high nut yield (kernel/nut ratio), on the nut and kernel shape and homogeneous kernel calibers (round shapes and 11 mm, 11-13 mm, 13-15 mm caliber classes are preferred), on the kernel flavour and aroma and on the high incidence of pellicle removal after kernel blanching and roasting.[11]

Furthermore, the potential for intrinsic kernel quality has gained attention with the aim of promoting nut consumption.[12,13] The nutritional properties of hazelnut and its health benefits, related to the richness of high-value fatty acids and natural antioxidants, have been emphasized.[14-16] Among the main chemical components in the kernel, lipids are considered the constituent giving a major contribution to the quality and storability of nuts and derived products.[17-20] Based on these premises, the following review describes the recent acquisitions both in cultivars choice and orchard management and in the post-harvest and storage management of the nuts for ensuring high quality and safety of in-shell and shelled nuts and of their processed products.

1 Technological traits of the main hazelnut varieties influencing the cultivar choice

The main hazelnut demand is for high quality nuts and kernels suitable for uses in chocolates and other confectionery. Hazelnuts are sold both as in-shell nuts and as in different caliber classes shelled nuts depending by the trading system. The shelled nuts can also be processed and sold as blanched, roasted, chopped kernel, flour and industrial paste.[21] Round-shaped nut cultivars with well-blanched kernels are preferred by the industry for their better workability than those with long or large shape nuts.

The low-quality kernels not suitable for food processing can be used to extract lipids and phenols for uses in food and cosmetics. Hazelnut oil is commonly commercialized in Turkey for its fatty acids profile classified into the oleic acid class.[19]

Shells represent about half of the harvested nut production, and are usually destined for thermal energy production for heating residential and industrial spaces (calorific shells value equal to 15-17 MJ kg^{-1}) thanks to their economy and ease of management and storage.

The shells are also used for mulching, since its shape promotes soil humidity conservation and its natural decomposition does not cause changes in soil pH. The application of shells and husks directly to the orchard has been proved very useful for soil health preventing weeds and as a source of microminerals during their decay.[22]

The shells undergoing to thermal hydrolysis processes with acidified water produce hemicelluloses or short-polymerized sugars with high nutritional interest.[23]

Despite hazelnut have a long utilization history with over 400 cultivars surveyed worldwide,[24,25] production is based on the use of a few dozen cultivars. These were selected from local and wild populations especially found in natural environments nearby to the Mediterranean basin and Black sea.[26]

High-quality kernels of few Italian, Turkish and Spanish cultivars set the quality standards for the industry which prefers cultivars characterised by a kernel/nut ratio at least of 45% and with a high incidence of kernel sizes within 11–15 mm. High pellicle removal after kernel blanching or roasting is also highly desired.

Based on their technological traits, the cultivars ‘Barcelona’ **(synonyms: ‘Castanyera’, ‘Fertile de Coutard’, ‘Grada de Viseu’ and ‘Grande’)**, ‘Ennis’, ‘San Giovanni’ and ‘Corabel’ are suited to be sold in-shell for fresh consumption. Currently, the industry mainly uses for market the Italian round-shaped cultivars and some Italian long-shaped cultivars as ‘Mortarella’, which are mainly produced in Italy; ‘Negret’ and ‘Pauetet’ produced in Spain; ‘Tombul’, ‘Palaz’ and ‘Fosa’, produced in Turkey; ‘Barcelona’ and some new "OSU varieties" produced in Oregon (USA) and Chile.[27]

The cultivars mainly spread in traditional hazelnut countries are listed in Table 1.

Turkish cultivars: there are 18 standard registered cultivars in Turkey mainly obtained from natural hybridization (*C. avellana x C. maxima*), with three recently registered (‘Okay 28’, ‘Giresun Melezi’, ‘Allahverdi’) as new releases.[28] **These new cultivars have been released from the breeding program carried out at the Hazelnut Research Institute (Giresun) which has the aim to get new selections characterized by high quality nuts, vigorous plants and new pollinators.**

Turkish varieties are grouped as 'Giresun' and 'Levant quality'. The first group produces high-quality nuts and include ‘Tombul’ and the main varieties used in the oldest hazelnut area of the Turkish Black Sea (Giresun, Ordu and Trazbon provinces). 'Levant quality' group varieties are mainly cultivated in younger hazelnut areas.[29]

Major and minor Turkish hazelnut varieties are also grouped into three classes depending on their nut shape: round-shaped group (‘Allahverdi’, ‘Cavcava’, ‘Çakıldak’, ‘Foşa’, ‘Giresun Melezi’, ‘Kalınkara’, ‘Kan’, ‘Kara’, ‘Kargalak’, ‘Mincan’, ‘Okay 28’, ‘Palaz’, ‘Tombul’, ‘Uzunmusa’); pointed shaped group (‘Sivri’, ‘İncekara’) and the long-shaped group (‘Yuvarlak badem’, ‘Yassıbadem’).

Italian cultivars: some high-quality kernel cultivars are very appreciated by the industry both for the excellent aroma and for the technological traits. ‘Tonda Gentile’ **(synonyms: ‘Tonda Gentile delle Langhe’, ‘Tonda trilobata’)** is recognized as one of the best hazelnut cultivar worldwide. The nuts are medium sized (2.5 g), with a kernel/nut ratio of approximately 45%, spherical shape, high pellicle removal, excellent taste and aroma, and good shelf life. Also ‘Tonda di Giffoni’ is very appreciated and is quite spread in the new hazelnut orchards worldwide. Its excellent pellicle removal and good taste and aroma makes it very popular by the traders. The cultivar ‘Tonda Romana’ is very used in central Italy for its high productivity. Despite having excellent taste and aroma this cultivar shows a low pellicle removal which may partially penalize its industrial uses. Recently Biancolillo et al.[30] applied a non-destructive method for the authentication of this specific high-quality Italian hazelnut; their results led to very high prediction capability in nut external validation, suggesting that near-infrared (NIR) spectroscopy a suitable methodology for a rapid and non-destructive authentication of the product.

The ‘Nocchione’ is distinguished for having low kernel/nut ratio (38-40%), despite showing good pellicle removal and excellent taste and aroma. This cultivar is mainly used as pollinizer of the inter-compatible main cultivars and therefore is mainly marketed as blended. The cultivars ‘San Giovanni’ and ‘Mortarella’ have high per cent kernel (46%), **medium-high** pellicle removal, excellent taste and aroma (especially ‘Mortarella’) but show a semi-elongated shape that make them less workable in the industrial chain. Anyway, both cultivars are very appreciated for chopped kernel and industrial paste.

<u>Spanish cultivars</u>: the ‘Negret’ is still the most appreciated cultivar in the main Spanish producing areas (**north-eastern:** Tarragona and Girona). It is highly appreciated by the industry for its good organoleptic characteristics and ease of pellicle removal after toasting. Notwithstanding, its agronomic traits show some restrictions as the weak vigour and sensitivity to iron chlorosis. This cultivar is also considered highly susceptible to the apple mosaic virus (ApMV), therefore the Institute of Agrifood Research and Technology (IRTA) carried out a clonal selection of this cultivar and the free virus clone ‘Negret-IRTA-N-9’ was recently selected.[31]

Other Spanish cultivars interesting for market are ‘Pauetet’ and ‘Gironell’. The first cultivar produces oval-shape nuts and shows a lower pellicle removal after roasting than 'Negret'. Similarly, 'Gironell' peel poorly after roasting even though it is appreciated for its small and round nuts and as pollinizer due to the large amounts of pollen that its catkins produce **and its large period of male flowering**.

Moreover, to this list should be added the French cultivar 'Barcelona' that has round large nuts intended for the table hazelnut market.[32] It is an old variety also cultivated in other countries under different names: 'Barcelona' (USA), 'Fertile de Coutard' (France), '**Grada de Viseu**' (Portugal) and 'Grande' (Asturias, Spain).[33]

The recent expanding cultivation of European hazelnut worldwide has not been adequately accompanied by preliminary main cultivars adaptation trials into new environments as well as by a valuable innovation of cultivars. Hazelnut breeding is poor if compared with those of other major crops and the most relevant breeding programme is conducted in Oregon State University (OSU). Over the last 40 years, OSU has accumulated dozens of advanced selections from cultivars, pollinizers and ornamentals (Table 2). Many of these releases have total or quantitative resistance to Eastern Filbert Blight, a high pressure fungal disease caused by *Anisogramma anomala* (Peck) E. Miller, which is spread in Oregon and Washington States (USA), and represents the main concern for local growers.[34] The new cultivars recently released in the breeding programme are mainly planted in the USA and Chile under legal protection agreements between OSU and the nurseries.

Other recent releases have been made in small breeding programs carried out in Turkey, Italy, France and Romania (Table 2) as well as in extra European countries even though these new varieties are not widespread yet.[35,36] Furthermore, in Europe, the "Agri Gen Res" programme financed the characterization and conservation of hazelnut genetic resources with the main objective of sharing information and recovering the maximum genetic diversity on farm maintained.[37]

2 Management of nutrition, pruning and irrigation for increasing the quality of hazelnuts: recent acquisitions

A new trend in developing high-density plantations and a more friendly environment hazelnut cultivation is in progress mainly in large orchards spread in the new cultivating areas, including some trials of Precision Agriculture applications.[52,53] **Planting high-density orchards in new areas requires more attention in choosing and spatializing the right amount of pollinators as the hazelnut is an inter and self-incompatible species. In these cases the recommended 10% of pollinators in the orchard can be increased up to 15%.**

An additional need is to get new rootstocks both to increase plantation density and to avoid the seasonal control of suckers requested by this suckering species. A solution may be to use suitable selections of non-suckering *Corylus colurna* (Turkish hazelnut) as rootstocks or some C. Colurna x C. avellana hybrids, as Dundee and Newberg (two hybrid selections released in Oregon in the 1990s). Some trials for testing and releasing this new plant material are in progress in Spanish[54] and Serbian[55] research institutions.

Currently, the agronomic management of specialized orchards is highly mechanized, with the exception of Turkish areas where the orchard management is mostly conducted manually, due to the orography of the plantations, which are mostly established in sloping areas, and for their prevalent irregular orchard design that make low mechanization levels.[56]

Among orchard conduction, soil management is crucial to maintain fertility and to facilitate the mechanical harvesting of nuts, that in regular, large and flat orchards is carried out with trained or self-propelled vacuum cleaner machines. Soil management through controlled grassing using spontaneous flora or other suitable shading cover crops is an example of the effective integrated fruit-growing technique application which partially offsets the problem of dust rising during mechanical harvesting of the nuts, attenuates erosion and hydrogeological instability and promote the in-shell nut quality due to the chances to make double harvesting and thus reducing the permanence of nuts on the ground.[57]

Also the strategies for pests[58-60] and diseases[61-63] control affect the quality of the nuts and various Integrated Pests Management (IPM) and organic IPM protocols have been developed and applied in the main hazelnut producing districts both for preserving the tree health and contain the incidence of nut losses and kernel defects.

Anyway, among the cultural operations high and direct influence in nut and kernel quality depends on orchard nutrition, pruning, and even on irrigation in areas with limited water availability or irregular rain distribution during the year.[64] For this reason the recent innovations affect these cultural practices in the hazelnut orchard management are briefly summarized.

2.1 Nutrition

The orchard nutrition highly influence the nut quality in hazelnut, and similarly to other crops, nitrogen is the nutrient that requires the highest management accuracy due to its high mobility in the soil. Some authors[65] on Italian trials noticed as nitrogen leaves concentration was about 3% in early May shrinking to 1.6% in September-October as a consequence of leaf ageing and nitrogen removal to the perennial organs, without differences in dynamic between young and adult orchards and between irrigated and non-irrigated plants.

Shoots showed the highest nitrogen content at the end of April (2.0 - 2.4% **DW**) that decreased until the end of July, showing an higher content in irrigated plants.

Nitrogen is also present in mature nuts and shows the highest content during kernel filling (5% of kernel **DW**) indicating that this growth phase has a high requirement of nitrogen availability.[15]

More in general, the estimated total nitrogen uptake was very low in young plants, meanwhile in the adult orchard the uptake exceeded 70 kg ha^{-1}. Furthermore, nitrogen removed from the orchard through nuts and pruned wood ranged from 10-12% in young plants to 60% of the adult ones.

Hazelnut has also high demand for potassium, while phosphorus requirement is lower, and the literature agrees that for mature and healthy plants grown in medium fertile soils the correct ratio for the three major elements (nitrogen : phosporus : potassium) is 1:0.5:1.[66]

In mature orchards, the annual macronutrients requirement is about 80-90 units of nitrogen divided into two-three administrations (vegetative bud break stage, kernel filling and post-harvest) and 40 and 80 units per hectare of phosphorus and potassium, respectively, administered in unique spring solution.

The hazelnut also requires high amounts of calcium and magnesium, and this last nutrient together to manganese is directly involved during the fatty substances accumulation in the kernel.

On hazelnut, calcium plays an essential role during the kernel filling stage,[67] in pollen survival and pollen tube development and guidance, in gametic interaction and fertilization in flowers.[68]

A recent study conducted in a plot trial established in Willamette Valley (Oregon) on a well-drained cloquato silt loam soil confirmed as 110 units of calcium nitrate application just prior of rapid shell expansion increased marketable kernel and yield in 'Barcelona and 'Lewis' cultivars.[67]

Even though no scientific evidences have yet been confirmed between brown stain and mold incidence in nuts to boron and calcium deficiencies, a research carried out in Oregon using foliar application containing nitrogen, calcium, boron and other chelated micronutrients have shown significant lower presence of those defects together to the increase in kernel/nut ratio, nuts/cluster and yield.[69]

A research carried out in Slovenia[70] noticed as three applications of boron and zinc during the growing season (end of April, May and June) increased the fruit set and reduced the blank incidence in 'Tonda di Giffoni'. In a trial recently conducted in Iran[71] the authors revealed an high impact on qualitative traits of the kernel (fat, ash, protein, and phenolic compounds) collected in trees treated using foliar applications of boron. **Similarly, a trial conducted in Portugal confirmed as the boron applications during the growing season have positively influenced the hazelnut filling in the cultivar 'Butler'.[72]** Other trials recently carried out have released some optimized foliar nutrition protocols tested in Italy on cultivar 'Tonda Gentile'[73] and on cultivars 'Tonda Romana' and 'Nocchione',[74] in Oregon on different cultivars[75] and in Chile on the 'Barcelona' cultivar.[76] Thanks to these literature evidences, accompanied by newly available cultivar-specific foliar diagnostic (Table 3), foliar applications of macro and micronutrients are becoming routine in commercial orchards, and two–three administrations during the growing season are recommended by the extension services, often combined with other compatible agrochemicals for pest and disease treatments. This nutritional technique is also supported by the proven ecophysiological condition that the elements are quickly absorbed by the leaves, digested and used by the tree and thus are not dispersed in the environment.

Furthermore, foliar applications help the grower in spraying other substances as kaolin and seaweed-based extracts for increasing the orchard resilience and, as recently found in a field work[77], to be used as valid long-term tools to mitigate negative effects of climate change in physiological behavior of hazelnut tree.

2.2 Pruning and shaping

The hazelnut is a suckering plant tending to develop into multi-stemmed bush, and its vegetative habits is exploited by the growers for shaping the commercial orchards, mainly in traditional Turkish and Italian hazelnut districts. Anyway, many growers prefer to shape plants in single trunk with an open V-shape, and this is routine in some hazelnut districts such as in Oregon (USA) and Cancon (France). This shaping facilitates mechanical harvesting and permits more sunlight penetration into the orchard.[79] Furthermore, some operations such as sucker removal, irrigation and weed control are facilitated. Anyway, this shape has also some disadvantages. For instance, young single trunk plants are more vulnerable to storm damages, due to their shallow rooted. Moreover, the multi-stemmed bushes permit to the grower to gradually renew the plants eliminating the old stems to be replaced selecting new lignified suckers. In addition, regarding yields, field evidences did not show significant differences in mature orchards between the two different shaping.

Contrariwise, the annual pruning of mature trees is very relevant. Indeed, some researchers[80] observed that hazelnut productivity is positively related to the develop of mixed one-year-old shoots, indicating a shoot length of 15-20 cm as ideal for an high fertile buds incidence.

Pruning of adult trees is usually done during winter time and it is focused to the removal of suckers, old, diseased, or dead wood and broken or bad oriented branches.[81] A lack of regular pruning causes the reduction of shoot vigor, and drastically reduce the light penetration within tree canopy both inducing yield and kernel quality decline and increasing the biennial bearing aptitude.[82]

Recently has been observed as the pruning intensity significantly affected the yield in mature orchard grown at multi-stemmed bush.[83] Plants subjected to high intensity pruning, through the removal of about 40% of wood to renew the crown, mainly shortening vigorous and badly orientated branches on the top of the tree, showed ah higher cumulative yield over three year investigation in comparison to low intensity pruning plants. Also the nut and kernel quality was positively affected since the kernel/nut ratio was 1% higher in high intensity pruned plants that also showed a lower incidence of blanks and poorly filled kernels. These enhancements were also confirmed by the measured light infiltration at the base of the trees in the different thesis of the trial among the vegetative seasons, that positively influenced the reproductive phase and the floral induction of new buds in the inner portion of the plants.

To reinforce the role of light in the fertile bud induction on hazelnut, some authors[84] highlighted their finding in trials subjected to summer pruning protocols carried out in May, where the mature plants showed an increased yield starting with second year after pruning and showing a decrease in biennial bearing. Anyway, differently to other major temperate fruit crops where summer pruning is routine, more trials need to be carried out on hazelnut for better understanding the role of this seasonal operation on yield and nut quality.

Considering that pruning is labor intensive operation, particularly on hazelnut due to its growth habit tending to become a shrub, a new trend to prune mechanically the plants is being developed mainly in new large orchards. Even though there are not evidences that this new approach in managing the tree shape can directly influence the nut quality, pruning operations are made faster and the shape of tree result strongly modified among the rows, facilitating some other cultural operation as the chemical distribution during the pests and diseases control.

The trials recently carried out on this topic according that the initial loss of production due to the high amount of productive branches removed by the rotating blade in the first year of application can easily recovered in the following years.[85,86]

Furthermore, starting from the second year of investigation a increased vegetative response with a high development of the shoots in the inner and apical part of the crown were recorded.

For reducing the initial yield losses a scheme of hedging and topping has been recently proposed. The first cutting is advised when the branches of the two contiguous rows crosses each other (normally from years 10–12 in new plantations depending on cultivar vigor and orchard design). Hedging interventions can be foreseen over 3-5 years depending by the cultivar and plantation vigor, meanwhile topping can be less frequent than hedging and can be carried out on whole orchard during the same growing season.

A promising technique for managing hedging involves cutting one side of two rows facing each other during the first year on an inter-row every three, and leaving the second following inter-row spaces unaltered. In the second year the first pruned inter-row is not cut, meanwhile is cut the second one, leaving the two following ones unchanged and resuming the sequence. The third year ends by pruning all the inter-row threads not yet pruned in previous years. This three year pruning rotation, eventually diluted on four-five years following the same scheme, allows to maintain a constant rhythm of renewal of the plantation.[87]

As for the summer pruning also for mechanical applications more research is needed taking into account the orchard design and the cultivar vigor and growth habit to establish right scheme for different case studies.

2.3 Irrigation

Hazelnut is considered rather sensitive to water stress because of his sub-optimal capacity of stomata regulation, amplified in environments with limited rainfall and in soils with low water capacity, and it responds quickly to the increase of vapor pressure deficit by reducing stomatal aperture and consequently carbon assimilation. Furthermore, stomatal conductance is regulated by many factors affecting leaf gas exchange, including the genotype influence, as demonstrated in recent finding[88] aimed to evaluate stomatal sensibility to air vapor pressure deficit and to determine correlations with hydraulics characteristics of leaves in three Italian hazelnut cultivars. The results demonstrated as 'Tonda Gentile' suffered the largest stomatal limitation at increasing levels of deficit in comparison with 'Tonda Romana' and 'Tonda di Giffoni', both commonly considered suitable cultivars for warm environments. Concerning the hydraulic characteristics of the leaves, 'Tonda di Giffoni' had considerable highest bulk elasticity. More in general, the results contribute to explain the higher adaptability to different environments of 'Tonda di Giffoni' and 'Tonda Romana' in comparison to 'Tonda Gentile'. Furthermore, the lower sensitivity to air vapor pressure deficit and the higher schlerophylly of 'Tonda di Giffoni' suggest as this cultivar suffers less gas exchange limitations in hot and dry environments proving to be suitable for cultivation in such limiting condition.

Considering that hazelnut has been recently planted in areas where precipitation is scarce and irrigation is needed, a modeling stomatal responses in different climatic conditions and soil water availability has been recently approached.[89] The team researchers installed five measurement sites in different countries (France, Georgia, Australia, Chile), considering different cultivars ('**Tonda Gentile**', 'Tonda di Giffoni', 'Ennis'), and under different irrigation regimes. In each site the sap flow in six trees were measured together to the soil water content, the stem diameter variations and the meteorological parameters. In two sites (Australia and France) the stomatal conductance and the carbon assimilation were also measured. Results showed that in all sites and cultivars, trees strongly reduce the stomatal aperture when the vapor pressure deficit exceeds 10 hPa, which leads to a decrease in the assimilation rate. The daily course of stomatal aperture showed that the maximum is reached very early in the morning. Hazelnut responses at leaf level were coherent with those at the tree canopy level, establishing a crucial basis for the future modeling of water use at the orchard level. The carbon assimilation was mainly controlled by stomatal sensitivity to vapor pressure deficit and also in conditions of high soil water content the photosynthetic capacity of the species is reduced. These results also support previous findings[90] regarding hazelnut leaf photosynthesis where the highest assimilation was associated to a soil water content at least of 60% field capacity.

Other negative effects of water stress documented on hazelnut were an early growth break in shoots and fruits and an early leaf fall and a higher susceptibility to certain diseases.[90-92] Regarding the direct influence of water stress on nut quality some researchers noticed an increase in empty nuts (blank) and a decrease of kernel/nut ratio.[93] The seasonal cycle of hazelnuts shows the overlapping of different vegetative and reproductive processes (shoots growth, fruit set, shell expansion and kernel filling, flower bud initiation and differentiation) from beginning of June to end August depending by the cultivars and environments of growing and this makes the availability of water a priority to overcome physiological competition between different organs. The literature agrees as hazelnut needs at least 800 mm of rain well distributed throughout the year.[9]

Hazelnut is normally irrigated using drip irrigation and in large and flat orchards sub-irrigation systems are becoming routine.

The proven high efficiency of water use connected to localized irrigation systems also allows the administration of nutrients via fertigation, by installing a proper fertilizer mixers and injection systems. In drip irrigation normally two anti-occlusion and self-compensating drips per plant are applied, one on each side, at a distance of about 1 m from the trunk.

Micro-jets are also common in new high-density orchards and provide large volumes of water in less time than drip systems. The sub-irrigation technique is based on the administration of irrigation water by capillary ascent, cancelling evaporative phenomena. The installation of self-compensating drip-off wings, at a depth of 20–40 cm, is mechanically performed and in mature orchards is positioning only a single irrigation line in the centre of each inter-row, while in young orchards the dripping wings are buried at distances of about 80–100 cm from both sides of each row of plants.[87]

As for other crops, water balance is still the most reliable approach to determine the volumes of water supply calculating crop evapotranspiration as ETc = ETo x Kc, where ETo is the estimated daily water loss (determined using a class A evaporimeter or directly calculated from the new generation weather stations), and Kc is the crop coefficient which is specific for each development phase of the plant. For hazelnut the current monthly Kc available in the literature were determined in Spanish environment on cultivar 'Negret' and in France on cultivars 'Barcelona' and 'Ennis' (Table 4).

Furthermore, some experiments may drive in choosing the irrigation turns during the growing season in the commercial orchards with the aim to ensure high production level while preserving water. A trial carried out in Portugal[92] showed as the measurements of leaf gas-exchange parameters, leaf water potential, and leaf metabolites under four different irrigation treatments based on crop evapotranspiration levels (ETc 100, 75, 50 and 0%) were of higher entity at the irrigation supply of ETc 100 and ETc 75, confirming that irrigation during hazelnut growth have a great influence on its physiological parameters.

Moreover, a long term evaluation of hazelnut response to drip irrigation conducted in Italy on 'Tonda Romana' and established considering randomized plots irrigated with same irrigation treatments applied in the previous trial, have shown that irrigation supply aimed at returning 75% of the crop evapotranspiration allows a suitable balance between vegetative growth and production.[94] The percent kernel was higher and the empty and defected nuts was lower when compared to those of the other treatments.

3 Standards of technological traits and defects acceptance for market and table uses of in-shell nut, dried and roasted kernel and its bioactive compounds content

Most of the hazelnuts produced worldwide are addressed to processing companies, whereas fresh consumption represents more or less the 10%,[10] this implies the market standards mainly driven by the requirements of the confectionary industry. High kernel peeling incidence in kernel blanching and roasting processes is also very appreciated by the confectionery industry which employ these products for obtaining butter paste or snacks, and also as ingredients for many food products (i.e. cookies, ice cream, breakfast cereals, cakes, chocolates, coffee, bread, liqueurs, spreads).

3.1 Standard traits and quality and defects acceptance for hazelnut market and table uses

Hazelnut kernel quality standards include physical (dimension, weight, colour), compositional, mechanical-acoustic, and sensory properties.[97] Nut and kernel size, nut and kernel shape, thin shell, low kernel defect, tasty kernel, and high content of fatty acids and protein are among the main characteristics considered in the evaluation of nut and kernel quality of hazelnuts.[19,98-100] The recent development of acoustic determinations on hazelnut kernels allow the evaluation of crispness and crunchiness sensory perceptions, thus improving the quality assessment for food preparations.[101,102] Furthermore, nut and kernel defects are serious problems for commercial trade in hazelnuts.[2] Nevertheless, the percentage of defective nuts is influenced by both genetics (some varieties are more susceptible to defects as double kernel and mould) and environmental conditions (protracted rainfall during the nuts harvesting time **and pest and disease damages**) that promote expression of some defects. Among them, blanks, brown stain disorder, doubles, mouldy kernels, kernels with black tips, shrivelled kernels and poorly filled nuts are of main interest.[103] The United Nations Economic Commission for Europe[104] provided the hazelnut commercial quality standards with the aim to help and facilitate the international trade and high-quality production for consumer interests. The latest meeting in Geneva (Switzerland, 2019) did not adopt revised standards in the case of hazelnut in-shell and kernel. The Organization for Economic Co-operation and Development (OECD)[105] developed hazelnut standards as well in 2011, which can be considered one of the hazelnut quality reference list. The minimum requirements concerning the market and commercial quality for direct consumption are reported in Table 5 with the kernel moisture content not higher than 6%. It is known that high moisture content can accelerate the development of micro-fungi producing specific enzymes able to break down carbohydrates into their monomers. Furthermore high moisture content can also hydrolyze lipids into free fatty acids.[106] In nuts, these chemical reactions often result in a bitter taste perception by consumers[107] with negative impacts on the various applications at industrial level.[25]

According to the size and the presence of defects, hazelnut yield are classified into: “Extra” Class, Class I and Class II. The minimum size is 9 mm for hazelnut kernels in Extra Class and Class I, and uniformity in size (expressed by a size range not exceeding 3 mm) is a key parameter. The OECD describes Class II standards as a maximum of 20% defective in-shell hazelnuts, with a maximum of 12% blanks or poorly filled, and 6% rancid, mouldy, rotting, or damaged by pests. In the case of kernels, OECD Class II allows a maximum of 18% defective hazelnuts, with no more than **8%** of poor filled kernels (including shrivelled or shrunken), 2.5% mouldy, and 6% rancid, rotten, or with an off odour or flavour, or with insect damaged.

Concerning the shape, larger and particularly rounded types are preferred for in-shell markets. Raw hazelnuts accommodate both rounded and oblong types, and size preference is dependent on their utilization (fresh or confectionary market).

Common size classes used by in-shell market are small (up to 13 mm), medium (13.01 to 18 mm), large (18.01 to 19.5 mm), very large (19.51 to 22 mm) and jumbo (over 22 mm), as widely accepted also by the hazelnut processing industry.

Shell defects are relevant only for nuts destined for the in-shell markets. These defects include damage by insects, scarring by bacterial blight, mould or stains making up more than 25% of the shell surface. Some cultivars are affected by superficial shell cracks which favourites mouldy; localised discoloration of the shell is classed as a defect if it covers more than 25% of the surface area of the shell. Nuts with shell defects are usually removed by hand after drying.

One of the most important quality parameter is the incidence of blanks, since this defect decreases the yield and kernel/nut ratio in nut samples, causing lower income and increased costs of harvesting and sorting;[103,108] this defect is unacceptable mainly in nuts sold in-shell. The external appearance of blanks is similar to that of normal nuts. However when pollination stimulates the shell to develop, the kernel fails to develop normally. Either fertilisation fails to occur or embryo development is stopped at an early stage, leaving a small and poor filled kernel.[109,110]

Brown stain is often described as physiological disorder that causes distorted shells and leads to an increase in the incidence of blanks and poorly filled nuts. The main symptom is the presence of brownish liquid that soaks the side or end of the nut. Staining begins when nuts are about half grown. The cause is still unknown, but in severe attacks the shell becomes distorted and the kernel destroyed.[111] Among kernel alterations, poorly filled nuts showed kernels that fill between 25% and 50% of the shell cavity, whereas shrivelled kernels fill more than 50%.[112] Sunken areas in the kernel are visible when the growth of nuts is altered for example in the case of a rapid kernel growth in extremely high temperatures. Furthermore, double kernels are considered defect because the resulting individual kernels are usually below the minimum size for most kernel grades. Mould can also sometimes develop in the gap between the two kernels.

Hazelnuts can be damaged by green shield beetles (*Nezara viridula*) and other bugs as *Gonocerus acuangulatus* and *Haliomorpha halys.*[113,60] These feed on both developing and mature kernels; thus damage entity depends on the time of attack. If the shell is still soft and the kernel is still developing, the kernel can be deformed and/or brown spots appear on the surface of the kernel. The kernel develops a disagreeable taste. If the attack occurs after the shell has hardened and the kernel is fully developed, then the damage may be limited to the development of white spots. Damaged kernels become rancid more easily than normal kernels. The OECD standards allow this sort of damage as long as the kernel flesh is not affected and the spot does not exceed 3 mm in diameter and 3 mm in depth.

Another aspect concerns mould and rancidity which are actually two factors strongly affect the market acceptability of hazelnuts. Mould is often associated with severely shrivelled kernels and the fungi (*Aspergillus*, *Pennicillium*, *Cladosporium*, *Phomopsis* spp.) may be secondary opportunists invading stressed kernels.[103] In susceptible cultivars, visible mould is formed on necrosis of the kernel tip (black tips of kernel). Extra costs were incurred because of the necessity of carefully controlling in-shell quality and removing large numbers of **mouldy** kernels from shelled nuts. Quality deterioration during storage such as lipid oxidation, is one of the primary mechanisms of quality loss. At the same time, any changes in flavour, colour, texture, and nutritive value and the production of toxic compounds are all important parameters for quality considerations. Some kernels deteriorate internally with no significant change to the appearance of the pellicle.

Another high concern influencing health, quality and shelf life both in-shell and shelled hazelnuts is the possible aflatoxins contamination during the storage, mainly when nuts are not well dried after harvesting.

Aflatoxins (AFs), among the toxic compounds called mycotoxins, are secondary fungal metabolites which are right now considered as the most toxic, hazardous and widely presents. They are produced mainly by several moulds included in the *Aspergillus* spp. (prevalently *Aspergillus flavus* and *Aspergillus parasiticus* and, rarely, *Aspergillus nomius*) which use to grow in soil, decaying vegetation, hay, and grains.[114] In nature, there are a certain number of different AFs, but four of them are the most diffused and exactly: aflatoxin B1 (AFB1), aflatoxin B2 (AFB2), aflatoxin G1 (AFG1) and aflatoxin G2 (AFG2). **The** AFB1 and the mixtures of different AFs are demonstrated to be human carcinogens[115] and it was reported to determine liver cancer.[116] Moreover, AFs can cause several toxic effects in human and animal health, like teratogenicity, mutagenicity, and immunotoxicity.[117] It is also considered that a number of diseases, including several syndroms and hepatitis may also related to AFs intake.[118] The consume of contaminated foods, even with low levels of AFs, may lead to the chronic aflatoxicos is with stunting in children, immunity suppression, cancer and reduced life expectancy.[119] A large amount of agricultural crops can be affected by AFs, even including tree nuts (pistachio, almond, walnut, hazelnut, coconut and brazil nut) as a consequence of *Aspergillus* section *Flavi* infection before and/or after harvest.[120] The AFs contamination associated to fungi infection of agricultural products is considered the biggest problem in Turkey,[121] where hazelnuts, together with pistachios and figs (also subjected to the AFs contamination), are the most important crops. Turkey is the world's major producer of in-shell hazelnut and this is a potential problem for a large diffusion of contaminated hazelnut kernels in the widely world market.[122] One of the major problems related to the hazelnut production is the primary infection and growth of aflatoxigenic fungi and subsequently aflatoxin formation and contamination of hazelnuts. Hazelnut infection by aflatoxigenic fungi can occur in the orchard before harvest, during harvesting procedure and/or more specifically during storage after cracking the shell.[123] It should be evidenced that preventive measures both in pre-harvest and post-harvest stages are essential to ensure that hazelnuts remain either free of or contaminated by the least amount AFs as possible.[122]

3.2 Bioactive compounds content in hazelnut kernel

Kernel blanching and roasting are processes that highly influence the flavour and aroma of the kernel and partially influence its constituents integrity.[124] The main differences among kernel blanching and kernel roasting is the temperature and time of the heating treatment which is also related to the pellicle removal aptitude of each cultivar. For roasting process the heating treatment is usually carried out in large ovens programmed at temperature of +150 °C for 30 min, meanwhile for blanching the process involves a temperatures not higher than +120°C for 15 min.

According to Kaleoglu et al.[125] facility of kernel peeling is affect by genotype and represents one of the crucial requirement in order to obtain products in optimal condition for industrial uses. When pellicle remains after toasting, it confers a bitter taste that lowers the product value.

Actually blanching and roasting positively affect the specific organoleptic properties of hazelnuts such as taste, crunchiness colour and texture, due to the complete kernel dehydration.[126] However, differences in both chemical and physical properties are documented as a consequence of process conditions, different temperatures (from +100 to +160°C) and times (from 10–60 min). In general, according to different authors,[124,127,128] an increased smell and intensity of a number of taste attributes such as oily and sweet flavour, is detected in roasted hazelnuts than in the raw counterparts. Nevertheless, excessive heat during drying or processing can produce a damage negatively affecting the flavour, appearance or edibility of the product. As a consequence of temperatures and roasting periods increased, generally, a modest increase of oleic and saturated fatty acids and a decrease of linoleic acid, expressed as relative percentages, occurred.[129,130] Similarly, an increase of triacylglycerols containing oleic acid moieties and a decrease of those containing linoleic acid moieties were found in the roasted samples.[131] Roasting at high temperature, could caused a decrease of the beneficial phytosterols (maximum 14.4%) and vitamin E homologues (maximum 10.0%) and a negligible increase of the trans fatty acids.[18] Otherwise, some authors[130] who evaluated for the first time serotonin content in Turkish hazelnut cultivars, showed as roasted hazelnuts had no different in terms of serotonin content with respect to raw hazelnuts (treated at +150 °C for 30 min).

From biochemical point of view raw hazelnuts, like the other nuts, are commodities riches in fats, protein with valuable content in fiber, phytonutrients and antioxidants such as vitamin E.[132]

Health benefits of hazelnut consumption arise from the synergic action of unsaturated fatty acids (60% **DW**) or bioactive compounds including plant sterols and dietary fiber.[133-135] Among primary fatty acids, oleic acid was the predominant one in all the extracted hazelnut oils, ranging from 73% to 85% and including palmitoleic, the mono-unsatured fatty acids (MUFA) make up the largest portion (mean value of 80.85%) followed by polyunsaturated fatty acids of about 10.70%.[19,101] Furthermore, a research[136] reported as the total lipids were constituted by 98.8% triacylglycerols and 1.2% polar lipids. Nuts are cholesterol-free, but their fatty fraction contains sizeable amounts of chemically related non-cholesterol sterols, belonging to a heterogeneous group of compounds known as plant sterols or phytosterols. Hazelnuts contain about **1.22 g kg^{-1}** of phytosterols, with the highest content of B-sitosterol and a number of minor sterols, sterol esters and stanols.[14] Several phenolic acids were identified in kernel of *Corylus avellana*[137] also recently denoting a large group of phenylpropanoids in the hazelnut extracts, with flavonoids being the most abundant sub-class.[138]

4 Main tools for hazelnut storage management and quality evaluation

The storage conditions and the aptitude to be stored, together with the quality maintenance during post-harvest life are crucial keys for nuts. These aspects play a fundamental role for the product destined to the food industry and confectionery, as well as for the nuts addressed to the in-shell market and to the direct consumption. The hazelnut average composition is dominated by the mono and polyunsaturated fatty acids (linoleic and linolenic acids) meanwhile the saturated fraction is less than 10% **DW**,[19] followed by a considerable content of micro-nutrients (mainly sterols), essential minerals, free phenolic acids and other phenolic compounds, together with organic acids.[139] Lipid oxidation and degradation can be considered as the prevalent markers of the storability of fat-containing crops like hazelnuts: their estimation is a good tool of hazelnut shelf-life evaluation and of quality definition.[140] Commercial industry often uses to store unshelled hazelnuts under environmental conditions even for long-term period (Figure 1), based on the original quality of the harvested nuts.[141] However, the post-harvest life of hazelnuts is greatly dependent on the temperature and relative humidity associated to the storage conditions,[142,143] even considering that to overcome the storage, hazelnuts must be dried. Storage techniques and processing methods are also strategic as procedures able to block, or at least control, the effects of the lipid degradation and thus the loss of quality together with the shelf-life extension of kernels.[144] In the hazelnut market, the nuts distribution is managed for a period over one year after harvest; as a consequence, the control of storage parameters becomes fundamental. The modulation of environmental parameters (low temperature and reduced relative humidity) can be also associated or can be alternative to the use of controlled gaseous atmosphere (e.g. inert conditions by N_2 and/or CO_2 saturation), in reducing the effects of enzymatic and chemical oxidations, or controlling the loss of quality attributes, largely used in common foodstuffs.[145] The low temperatures combined to a controlled relative humidity content (less than 60%) have the effect to regulate the pathogen action (mainly fungi, also associated to aflatoxin insurgence);[146] while the use of inert atmospheres is finalized to remove the O_2 from the storage environment, by controlling the origin of chemical oxidation.[145] Scientific data concerning hazelnut storage techniques are not very large, even if some authors have discussed the effects of postharvest management on the physic-chemical characteristics of kernels. In 2001, some authors[147] published an article reporting the results coming from experimental tests carried out on the hazelnut storability, where two different temperature conditions (+4 and +20°C, respectively), and four separated low O_2 atmospheres (1, 5, 10, and 20%) were tested both on in-shell and shelled nuts. The authors concluded that the lower temperature, associated to atmosphere at oxygen concentration below the 10% are the best solution for delaying the occurrence of lipidic rancidity. Jung et al.[148] demonstrated that the ideal storage condition or packaging method varied among cultivars due to their different moisture adsorption and physic chemical and enzymatic stability during storage. Mencarelli and et al.[145] observed how, for hazelnuts produced and marketed by developing countries or coming from world areas where very low is the cure concerning the drying and storage operations, more and more it is paying attention to the aflatoxin occurrence. Just recently, Botondi[146] described the potential microbial contamination at several stages of postharvest industrial processing of hazelnuts and along their storage chain, by defining the contamination risks. The role of CO_2 as powerful biocide agent against pathogens and insects is already well known, which is at the same time joined to the effect of oxygen removal as oxidation and peroxidation controller.[149]

Some authors tested the effect of two different storage atmospheres, at 100% of N_2 and 100% of CO_2 respectively, on shelled and dried hazelnuts cultivars 'Tonda Romana', and 'Akakocha' during a five-months storage at +4°C of temperature. They evaluated the kernel response versus a control kept at environmental atmosphere conditions, underlining good results for the treated samples in maintaining a good colour, a low level of acidity and peroxides, with no significant differences between the cultivars.[145] The same authors also have tested several other combinations of temperatures (2, 4, 10 and +20°C) associated to modified atmospheres at 100% of N_2, 98% of N_2 +2% of O_2, 96% of N_2 +4% of O_2, and environmental air conditions on shelled and dried hazelnut cultivar 'Tonda Romana' during a period of three months of storage. In hazelnut samples kept at +4 and +10°C with 2 and/or 4% of O_2 a colour modification was observed, while the same nuts together with those remained in air evidenced a significant improvement of the acidity content. Peroxide content still stay at the level measured on the nuts just before starting the storage procedure only at +4°C and 100% of N_2 atmosphere. Finally, VOCs (volatile organic compounds) profile revealed how at +2°C hexenal and hexanol do not demonstrated any accumulation, with no differences among all the atmosphere combinations. On the other hand, at +20°C, only hazelnuts stored under 100% of N_2 condition revealed a low content of the same C6 volatile compounds. As well known, C6 aldehydes and alcohols, related to the LOX biochemical pathway, are very significant markers of lipidic peroxidation processes.[150,151] Other authors confirmed that hexanal is a good indicator of oxidation process in charge of fatty substrates.[152,153] Similar results of those reported by Mencarelli et al.[145] have been obtained by Ghirardello et al.[144] comparing a traditional storage (in room at environmental conditions) of in-shell hazelnuts to a refrigerated storage (+4°C and 55% **RH**) of shelled nuts, managed with or without a modified atmosphere (1% O_2 + 99% N_2) for a long-term period of one year. Acidity values and peroxidation markers were lower in samples stored under modified atmosphere, while in traditional stored kernels they over passed the threshold of un-marketability. Additionally, De Santis et al.[152] in a storage test lasted nine months, carried out at two different temperature conditions (+4 and +20°C, respectively) and with no O_2 presence (N_2 saturation and/or vacuum condition), observed a significant decrease in the amount of phenolic compounds in control hazelnut samples (stored in air) as a consequence of the oxidative process.

Conversely, in another study, the phenolic content and profile of shelled hazelnuts was not affected by different temperature conditions (environment, +5°C, and -25°C), and by the O_2 availability (air, vacuum, or N_2 atmosphere).[153] The hazelnut shelf-life can be estimated by employing accelerated stability testing method.[140] Data derived from the stability test can be used as references for estimating the parameters of degradation, so to predict the kernel shelf-life.[154] Arrhenius equation[155] is the most employed stability test, and kinetic models are used for evaluating the effects of parameters (prevalently the temperature) on the degradation reaction rate which is detected by the usual parameters related to the nut quality.[156]

Main commercial parameters involved in the quality definition and, consequently, in the evaluation of hazelnut storability are the moisture content, oil content, acidity value, peroxides and lipidic oxidation indexes. Phenols content and/or antioxidant capacity can also be used as quality attribute or for describing the added value of hazelnuts in terms of human health promotion.[157] All these parameters are usually measured by using traditional laboratory protocols, known as destructive analytical methods and they are described, in detail, in the literature dedicated to the nut analysis and well reassumed in a recent article.[158]

4.1 Non destructive hazelnut analysis for quality evaluation

In the last decades, it is increasing the general opinion that all wet chemistry analyses are time-consuming, expensive in relation to the required chemical reagents and, depending on the detections, to the laboratory equipment; moreover, they are also considered not completely environmental free.[159] At the same time, the adequate and urgent need of quality assurance for fresh and processed food commodities is increasing the request of accurate, fast, real-time, valid and non-destructive technologies aimed to the quality evaluation.[160] Non-invasive techniques for nuts, even including **hazelnuts**, have reached in recent years a certain popularity and there are various works attesting their progressive evolution.[161] Basically, these techniques are addressed to predict analytical parameters by measuring **physico-chemical** characteristics based on optical, acoustic, and density traits.[158] In nuts, the most diffused, studied and verified non-destructive technologies are related to the use of Near Infrared Spectroscopy (NIRS) finalized to predict the moisture content, acidity, lipid oxidation and fatty acids content, including the assessment of internal disorders.[161-164] The use of X-ray and NMR spectroscopy is very low and limited, as well as the application of the RGB image analysis as alternative to the visual inspection methods.[165]

The fundament of Visible (Vis)-Near Infrared (NIR) spectroscopy is the vibrational character of the organic bonds (C-H, O-H, N-H) related to the food molecules, when exposed to an electromagnetic excitation. Absorbance at specific wavelengths, related to a modulate irradiance, describes the presence of organic molecules and, as a consequence, the spectral response can be used for measuring chemical quality attributes avoiding the fruit destruction.[166] Chemometric approaches must to be associated to NIRs detections in order to perform the essential correlation between original spectra and destructive analyses needed for the building-up of the algorithms known as predicting models.[167] Moreover, performed models aimed at predicting analytes and parameters are validated trough statistical indexes able to confirm the robustness of correlations and the minimization of errors. The accuracy of calibration and prediction procedures is described by the determination index (R2c and R2p, respectively), and the standard error in calibration (RMSEC) or in prediction (RMSEP). Finally, the RPD (ratio performance to deviation) index is a very useful tool for comparing the standard error in prediction to the standard deviation of the analytics.[168] Furthermore, Bellincontro et al.[163] used a Vis-NIR device to detect, in whole hazelnuts, the moisture content and the acidity and for discriminating geographical origins, while several authors employed different NIRs equipments, working under different configurations, for evaluating lipid oxidation, and internal defects presence.[161,164] Bellincontro et al.[169] using the NIR-AOTF spectroscopy coupled to MRI (Magnetic Resonance for Imaging), performed a preliminary study on whole hazelnuts for predicting oxidation status on the basis of water and oil presence. Even Moscetti et al.,[170] by employing an AOTF-NIR device, performed a discrimination on nuts of the cultivar ‘Tonda Romana’ deriving from different production areas and based on the ‘Protected Designation of Origin’(PDO). Predicting selection were obtained using chemometric modelling trough partial least square discriminant analysis (PLSDA)[171] and support vector machine discriminant analysis (SVMDA).[172] Traceability of hazelnuts was also tested by

Manfredi et al.,[173] using a portable FT (Fourier Transformed)-Infrared spectroscopy (IRs) equipment and, always by PLSDA modelling, a predictive selection of separate cultivars was carried out and was proposed by the authors as rapid, effective and *in-situ* method of evaluation. Some authors[174] experimented the use of a probe able to test the dielectric properties of in-shell hazelnuts, measured by conductance and capacitance, which were used as non-destructive detections for the moisture content prediction. The same PLSDA was used in a recent work in combination with RGB image analysis for evaluating the defective hazelnuts.[165] In detail, based on the RGB images of hazelnuts samples assigned to sound, rotten and pest-affected classes, the authors pointed out a classification model able to perform a correct discrimination of defective fruits with an accuracy of 97%. With respect to the NMR technique, Di Caro et al.[175] performed a study where underlined some preliminary results of the use of nuclear magnetic resonance on oils extracted from healthy and unhealthy hazelnuts as first approach for an automatic detection of the hidden defects in whole hazelnuts.

CONCLUSION

The crop expansion of hazelnut recorded in the last years supported by increased raw material demand from confectionery industry that processes about 90% of the harvested nuts, encourages the research to provide new solutions for the orchard and post-harvest management. A new generation of hazelnut cultivation approach will be towed by new advances achievable from applications of Precision Agriculture which are in progress[53] and that tend to determine and manage the optimal dosages of nutrition, water, and other chemical requirements in hazelnut as already happen for other major crops.

The information compiled in this review help to direct researchers and growers towards a sustainable intensification of hazelnut cultivation in both traditional and new areas, and aid development of new agronomic solutions and of post-harvest management to promote the resilience of hazelnut orchards also facing climate changes.

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Figure 1.

Whole in-shell hazelnuts stored in a semi-open warehouse at environmental conditions (top, left); shelled hazelnuts bagged in big bags of one ton and stored in cold room at +4°C, 65±5% of RH, and under partial oxygen control (top, right); whole roasted hazelnut kernels stored in cold room at +4°C, 65±5% of RH, and pocket in aluminum bags under vacuum (bottom, left); whole roasted hazelnut kernels stored in cold room at +4°C, 65±5% of RH, bagged in big bag of one ton under N_2 atmosphere (bottom, right).

Table 1.
List of the traditional and most used cultivars in the main hazelnut producing areas.
* Italic underlined traits highlight the preferred cultivars by the industry for taste and aroma.

Cultivar **(Synonyms)**	**Origin**	**Areas of cultivation**	**Main uses and traits ***
Barcelona (Fertile de Coutard, Castanyera)	**France**	Oregon (USA), Chile, France	Kernel market and in-shell market. Large nut with round shape, 40-43% kernel, medium pellicle removal in blanched kernel. Vigorous tree, moderately productive, late maturity.
Çakıldak	Turkey	Ordu **(TR)**	Kernel market. Small nut with round shape, 50% kernel, high pellicle removal. Low vigor tree, alternate bearing, early maturity.
Camponica	Italy	South of Italy	In-shell market. Large nut with round shape, 45% kernel, medium-high pellicle removal. Vigorous tree, early mid-season maturity.
Ennis	USA	Oregon (USA), France	In-shell market. Very large nut slightly long shape, 40-43% kernel, low pellicle removal. Moderately vigorous tree, productive, late maturity.
Foşa	Turkey	Trabzon **(TR)**, Akcakoca **(TR)**	Kernel market and in-shell market. Small nut with round shape, 50% kernel, high pellicle removal. *Good flavor*. Moderately vigorous tree, early maturity.
Mortarella	Italy	South of Italy	Kernel market. Medium to small nut with long shape,

			<45% kernel, medium-high pellicle removal. <u>*Excellent flavor*</u>. Low vigor tree with high yield, early maturity.
Negret	Spain	**Northeast of Spain**	Kernel market. Small nut with ovoid shape, **48-50%** kernel, very high pellicle removal. <u>*Good flavor*</u>. Moderate tree vigor, high yield, mid-season to late maturity.
Nocchione (Montebello, Comune di Sicilia, Santa Maria del Gesù)	Italy	Center and South of Italy	Kernel market and in-shell market. Medium to large nut with round shape, 38–40% kernel, high pellicle removal. Moderate tree vigor and spreading growth habit, high yield, early to mid-season maturity.
Palaz	Turkey	Ordu **(TR)**	Kernel market. Small nut with round shape, 50% kernel, very high pellicle removal. <u>*Good flavor*</u>. Low-medium tree vigor, alternate bearing, early maturity
Pauetet	Spain	**Northeast of Spain**, France	Kernel market. Small nut with ovoid shape, 48–50% kernel, **medium-high** pellicle removal. <u>*Good flavor*</u>. Vigorous tree, high yield, mid-season to late maturity.
San Giovanni	Italy	South of Italy, **Northeast of Spain**	Kernel market. Medium nut with long shape, 47–48% kernel, medium-high pellicle removal. Vigor tree, high yield, early maturity.
Segorbe	Spain	France	Kernel market. Medium nut with round shape, 40–45%

			kernel, **high** pellicle removal. Vigorous tree, late maturity.
Tombul	Turkey	Turkey	Kernel market. Small nut with round shape, 54% kernel, very high pellicle removal. *Excellent flavor*. Low vigor, medium productivity, early maturity.
Tonda di Giffoni	Italy	Central and South of Italy, **Northeast of Spain**, Chile, **other areas**	Kernel market. Medium nut with round shape, 46–48% kernel, high pellicle removal. *Excellent flavor.* Medium-high vigor, high yield, mid-season to late maturity.
Tonda Gentile (Tonda Gentile delle Langhe; Tonda trilobata)	Italy	North of Italy	Kernel market. Small to medium nut with triangular-round shape, 46–48% kernel, very high pellicle removal. *Excellent flavor*. Medium-high vigor. Moderate productivity. Very early maturity.
Tonda Romana (Tonda Gentile Romana)	Italy	Central Italy	Kernel market. Medium nut with round shape, 45–47% kernel, medium pellicle removal, *Very good aroma*. Medium vigor, high yield, mid-season to late maturity.

Table 2.
Most relevant releases of new cultivars, pollinizers and ornamentals achieved in the hazelnut breeding programmes at Oregon (USA), Turkey, Italy, France and Romania.

Name	Type of selection	Year of cross	Year of release	References
Oregon State University (Corvallis, Oregon, USA)				
Willamette	Cultivar	1973	1990	Mehlenbacher,[38]
VR 04-31	Pollinizer	1976	1990	
VR 11-27	Pollinizer	1976	1990	
VR 20-11	Pollinizer	1976	1990	
VR 23-18	Pollinizer	1976	1990	
Lewis	Cultivar	1981	1997	
Clark	Cultivar	1982	1999	
Rosita	Ornamental	1984	1999	
Gamma	Pollinizer	1991	2002	
Delta	Pollinizer	1989	2002	
Epsilon	Pollinizer	1992	2002	
Zeta	Pollinizer	1992	2002	
Santiam	Cultivar	1989	2005	
Sacajawea	Cultivar	1990	2006	
Yamhill	Cultivar	1990	2008	
Red Dragon	Ornamental	1997	2008	
Jefferson	Cultivar	1993	2009	Mehlenbacher et al.,[39]
Eta	Pollinizer	1999	2009	Mehlenbacher et al.,[40]
Theta	Pollinizer	1999	2009	
Tonda Pacifica	Cultivar	1981	2010	Mehlenbacher et al.,[41]
Dorris	Cultivar	1997	2012	Mehlenbacher et al.,[42]
York	Pollinizer	1997	2012	Mehlenbacher et al.,[43]
Felix	Pollinizer	1998	2012	
Wepster	Cultivar	1997	2013	Mehlenbacher et al.,[44]
McDonald	Cultivar	1997	2014	Mehlenbacher et al.,[45]
Burgundy Lace	Ornamental	1998	2015	Mehlenbacher et al.,[46]
PollyO	Cultivar	2001	2018	Mehlenbacher et al.,[47]
Hazelnut Research Institute (Giresun -Turkey)				
Okay28	Cultivar	-	2012	Anil et al.,[28]
Giresun Melezi	Cultivar	-	2012	
Allahverdi	Cultivar	-	2015	
University of Turin[a]; University of Perugia[b] (Italy)				
Daria[a]	Cultivar	1963	1996	Botta et al.,[48]
Tonda Francescana[b]	Cultivar	1983	2012	**Farinelli et al.,[49]**
Tonda Etrusca[b]	Cultivar	1983	2014	
French National Institute for Agricultural Research (France)				
Corabel (Fercoril)	Cultivar	1969	1987	Mehlenbacher,[50]

Feriale	Cultivar	1979	2006	
Ferwiller	Cultivar	1980	2006	
S.C.D.P. Valcea (Romania)				
Arutela	Cultivar	1979	2005	Botu et al.,[51]

Table 3.
Minimum and maximum content of the main macro- and microelements present in adult hazelnut leaves considered 'standard' by the international literature, and average values. Leaves sampled at the end of July from the mid-shoot of the current season's growth. Samples were collected by walking a "W" across the block collecting leaves randomly.

	Tonda Gentile [78]	**Barcelona [66]**	**Tonda Romana [74]**	**Nocchione [74]**
N (%)	2.4 (2.32-2.46)	2.3 (2.21-2.50)	2.1 (1.82-2.32)	2.1 (1.86-2.36)
P (%)	0.3 (0.21-0.36)	0.3 (0.14-0.45)	0.2 (0.15-0.27)	0.2 (0.16-0.30)
K (%)	1,4 (1.28-1.49)	1.4 (0.81-2.00)	1.0 (0.81-1.15)	1.0 (0.79-1.22)
Ca (%)	2.0 (1.9-2)	1.8 (1.01-2.50)	1.6 (1.50-1.75)	1.3 (1.31-1.36)
Mg (%)	0.7 (0.68-0.77)	0.4 (0.25-0.50)	0.2 (0.20-0.22)	0.2 (0.19-0.24)
Fe (ppm)	55 (46-62)	225 (51-400)	195 (183-207)	265 (230-300)
Mn (ppm)	40 (40-42)	145 (26-265)	60 (54-67)	90 (72-108)
Zn (ppm)	90 (82-99)	40 (16-60)	20 (17-23)	70 (61-80)
Cu (ppm)	15 (11-16)	10 (5-15)	15 (14-18)	15 (9-19)
B (ppm)	70 (68-70)	50 (31-75)	75 (64-85)	65 (55-77)

Table 4.
Hazelnut crop coefficients (Kc) determined using lysimeters in Tarragona (Spain) on 'Negret' (500 **plants ha^{-1}**) and in Clermont-Ferrand (France) on 'Barcelona' and 'Ennis' (416 **plants ha^{-1}**).

Month	**Cv Negret (Spain)** [95]	**Cvs Barcelona and Ennis (France)** [96]
April	0.30	-
May	0.40	0.5
June	0.62	0.7
July	0.70	0.87
August	0.55	0.87
September	0.35	-

Table 5.
Minimum requirements for kernels addressed to direct consumption.

Characteristics	**Description**
intact	the absence of part of the tegument or a scratch/chafing and scraping less than 3 mm in diameter and 1.5 mm in depth shall not be considered as a defect
sound	produce affected by rotting or deterioration such as to make it unfit for human consumption is excluded
clean	practically free of any visible foreign matter sufficiently developed; no shrunken or shrivelled kernels that are extremely flat and wrinkled, or with desiccated, dried out or tough portions affecting more than 50 per cent of the kernel
free from blemishes	areas of discoloration or spread stains in pronounced contrast with the rest of the kernel affecting in aggregate more than 25 per cent of the surface of the kernel

the presence of hazelnut kernels with a brown or dark brown centre	normally accompanied by a small separation of the cotyledons.
free from living pests or from damage caused by pests	including the presence of dead insects and/or mites, their debris or excreta. However, pest damage caused by "cimiciato" is allowed, provided that there is only one spot on the kernel that does not exceed 3 mm in diameter by 3 mm in depth
free from rancidity, foreign smell and/or taste	