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ORIGINAL ARTICLE

Study on Nut Shell Lignification Progress in Hazelnut (*Corylus avellana* L.) cv. Segorbe

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K E Y W O R D S

Belted hazelnuts;
Environmental stressors;
Filbert;
Growth curve;
Phenology;
Sclereid;
Shell hardening

A B S T R A C T

Seed protection is a key element in plant survival and plant dispersion. In hazelnuts, shell lignification begins from the tip to the basal scar. Therefore, hardening time is a race between seed survival against environmental stress. While new pests and stochastic weather events are increasing, fundamental shell lignification features are missing in the common Segorbe cultivar. In this purpose, progress of lignification was studied using hardness and morphological changes in fresh and dried Segorbe hazelnuts collected weekly in 2020 and 2021, respectively. The growing degree days (GDD) were calculated for key lignification process stages. In dried hazelnuts, the lignification process causes morphological deformation lead to belted hazelnut symptoms. Lignification increased progressively from week 22 (1353.6 GDD) to week 26 (1353.6 GDD). Shell length was 48–84% of their final size. The shell was fully lignified at week 27 with a kernel size of 4.99±0.32 mm. In fresh nuts, shell size increased from 83 to 92%, and hardening increased by a factor of 2.85, reaching 21 kgf, between weeks 25 and 26 (2272.8 GDD), with a kernel size of 4.75±2.05 mm. Lignification occurs in four weeks. When kernel size is ~5 mm, and shell growth ends, a hard wall protects the kernel from stressors. Belted hazelnut symptoms, reflected in the ratio of lignified and shriveled shell parts, and shell hardness, are discussed in the context of the susceptibility of Segorbe cultivars to environmental stressors.

Introduction

Evolutionary plant propagation is primarily influenced by seed protection and dispersal strategies (Dardick and Callahan, 2014). Fruits usually fall into two categories: dry and fleshy. In fleshy fruits, dispersion often depends on animal consumption (endozoochory), ingesting the fruit, and excreting the seed elsewhere. Dry fruits are dispersed by physical forces or animals, such as dyszoochory. Nuts contain high nutrient amounts in the form of lipids and proteins that provide a competitive advantage but strong predation pressures, from a mutual benefice relationship to parasitism (Jahanbani *et al.*, 2016; Perea *et al*., 2011; Vander Wall, 2001). Vander Wall (2010) found that the effort associated with physical barriers, such as hard seed coats, that take time to remove causes animals to hoard and subsequently spread seeds rather than consume them immediately. In addition, the presence of metabolically expensive compounds, such as tannins, in the seed coat may reduce parasitism by insects or microbes (Gantner, 2009; Laks, 1989; Vander Wall, 2010). In hazelnuts, where seed dispersion strongly depends on seed protection (Laborde and Thompson, 2009; Vander Wall, 2001), lignified exocarp (shell) is formed by a

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long and complex physiological process beginning during winter pollination.

Hazelnuts belong to the genus *Corylus* and order Fagales. Like most Fagales, hazelnuts show a delay between pollination and fertilization. Pollination occurs in winter, leading to ovarian growth. In spring, the two ovules move to the anatropous position (BBCH stage 750). In southwestern France, ovules are fertilized at the end of May. Unfertilized ovules lead to blank nuts (shells without a kernel). When the ovary is 7–10 mm long (Germain, 1994), the bicarpel ovary wall develops to form the pericarp (future shell) and endocarp, the large white spongy cells surrounding the ovules (i.e., parenchyma). One ovule develops while the other aborts. The growth of both ovary and ovule shows a classical sigmoid curve (Paradinas *et al*., 2022). The timing of these events has biological consequences for hazelnuts and environmental stress (Vander Wall, 2001).

In southwestern France, the rapid growth of the ovary and the ovule occurred between May 14 and July 8 and June 3 to July 29, 2021, respectively, depending on the cultivar (Toillon *et al*., 2021b). Around June, when the shell reaches 50–100% of its final size (BBCH stage 751), the ovule size is 10–20 mm. The pericarp begins to lignify from the tip and gradually progresses to the basal scar (i.e., the hilum). At the end of July, the shell is fully lignified, and the embryo is encapsulated in a hard wall to protect the seed from environmental stress. In ripe hazelnuts, shell hardening is mainly due to the biochemical components lignin, cellulose, and hemicellulose (Lopes *et al*., 2012) and physical structures such as sclereid layers and cribovascular bundles (Caramiello *et al*., 2000; Huss *et al*., 2020). At hazelnut maturity, the hardness of the shell reaches up to 769.3 N (Valentini *et al*., 2006).

While the hazelnut shell is one of the hardest walls among dry fruits (Huss *et al*., 2020; Schüler *et al*., 2014), many environmental stressors may occur during its long lignification process, including climatic events and predations that lead to seed death (An *et al*., 2020; Vander Wall, 2001). Studies have shown that before ovule growth or full pericarp hardening, the stink bug increases the number of aborted hazelnuts (blank nuts) (Hamidi *et al*., 2022a; Hedstrom *et al*., 2014). When the European hazelnut weevil *Curculio nucum* L. (Coleoptera) attacks early hardening shell cultivars, the damage was less (Guidone *et al*., 2007; Valentini *et al*., 2015). The larvae of the filbert worm, *Cydia latiferreana* (Lepidoptera), penetrate the nut by the micropyle, the softer part of the shell (Chambers *et al*., 2011; Thompson, 1941). Potential non-exclusive explanations include the phenology of phenotype, nut growth, and lignification process, which are factors related to the rate of seed damage and cultivar resistance (Guidone et al., 2007; Moraglio et al., 2009; Valentini et al., 2015; Nazarideljou and Azizi, 2015), unconfirmed by Piskornik *et al*. (1989) and Moraglio *et al*. (2014). Early or late growth may explain reduced susceptibility to hazelnut weevils that select the optimal nut phenology to oviposit, such as Tonda di Giffoni and Corabel, respectively (van Wijk, 2022).

Segorbe cultivars (*Corylus avellana* L., Corylaceae) are among the main European hazelnut cultivars grown in southwestern France. Segorbe shows phenological development intermediate between the early Tonda di Giffoni and the late Corabel cultivars. While little is known about progressive lignification of nut shell in Segorbe cultivar, ~40% of wormy nuts are harvested in untreated areas (personal observations). Furthermore, as global climate change increases, hazel trees are beginning to bud and grow foliage earlier, and late spring frosts are more common. In 2021 and 2022, several late spring frosts drastically reduced orchard yields in southwestern France (e.g., 30% in 2021).

While new pests (Hamidi *et al*., 2022a) and late spring frosts (Zohner *et al*., 2020) increase, fundamental features of shell lignification are missing in the Segorbe cultivar. Therefore, this study was carried out to clarify progressive stages of nut growth, shell lignification process, and rheological features during nut development of hazelnut cv. Segorbe. Rheology was recorded on fresh nuts and the visual lignification process on dried nuts. Finally, the timing of the end of lignification was estimated using cumulated growing degree days (GDDs). The results are discussed in the context of environmental stressors that lead to seed death.

Material and Methods

Field study

The orchard was planted in Cancon, France (44°32'40.0 "N 0°36'02.9 "E; 109 m above sea level) in 2001 with Segorbe cultivar. The orchard recently became organic. In France, Segorbe is a mid-late hazelnut cultivar (Germain *et al*., 2004). In southwestern France, male Segorbe flowering occurs from the third week of December to the second week of January. The female flowering follows male flowering, beginning in the third week of January and ending in the third week of February. Bud flush occurs during the third week of March. Nut fall begins during the second week of September, four days before Barcelona hazelnuts.

Rheology of hazelnuts

Twenty nuts were collected weekly between April 8 and July 28, 2020. Due to the high size variability of collected nuts, smallest to biggest nuts were selected. Among the collected hazelnuts, shell and kernel lengths were measured for ten hazelnuts by using a digital caliper at cross-sections. The ten remaining nuts were used to measure their mechanical properties with a rheometer (LLOYD LS1; Lloyd Materials Testing; Bognor Regis, UK) with NEXYGENPlus software (Ametek; Berwyn, PA, USA). Each nut was placed on the platform, and the force was applied along the width in the median zone (adapted from Guidone *et al*., 2007; Valentini *et al*., 2015). Because of the nut size variability, a plate sonde of Ø 50 mm was used to measure the hardness of the whole nuts. Three force measurements were performed on freshly collected hazelnuts: (1) hardness (kgf), corresponding to the force required to reach a given deformation; (2) elongation from the preload to the maximum force (mm), corresponding to the distance covered by the load cell between the first contact with the hazelnut and the maximum force applied before the hazelnut breaks; (3) work measured as a preload at the maximum force or unit of work (kgf mm^{-1}) (Ametek, personal communication).

Lignification process on dried hazelnuts

The morphological changes in hazelnuts, from nutlets to mature nuts, were assessed with ten bunches of hazelnuts from ten trees collected weekly between May 6 and July 29, 2021. Each week's samples were combined in the same net sleeve suspended in an aerated greenhouse. In January 2022, 30 dried hazelnuts from each net sleeve were examined to record the external features of the shells.

After removing cupules from the hazelnuts, shell length and lignified part were measured with a digital caliper. The lignified part was identified by a smooth and undistorted shell appearance, while the unlignified part was the remaining deformed and shriveled part of the shell body (Hamidi, personal observations). The length of both sections was measured by using a digital caliper. Shells were then broken, and their kernel length was measured from cross sections.

Finally, for both trials, hazelnut phenology was classified according to the BBCH system (Paradinas *et al*., 2022).

GDD calculation

The GDD required to complete lignification was calculated for both trials. Consistent with Črepinšek *et al*. (2012), we used a base temperature (Tbase) of 2°C from January 1 for the start time. Temperature data were collected from a Davis weather station (model wl_5min; Demeter; Paris, France) located at Saint-Étienne de Fougères (44°24'47.9" N 0°33'45.8" E; 46 m above sea level), 18.74 km from the field study site. GDDs was the key phenological steps in the lignification process such as

$$GDD = \frac{Tmin + Tmax}{2} - Tbase$$

With *Tmin* corresponding to the daily minimal temperature (°C) and *Tmax* for the daily maximal temperature.

Statistical analyses

Descriptive data are presented as mean and standard deviation (SD). Groups were compared with a Kruskal-Wallis test and correlation with Speraman's rank test using the XLSTAT software v.2017 (Addinsoft; Paris, France). Nonlinear regression were performed using the Origin software v.2016 (Origin Lab Inc.; Northampton, MA, USA).

Results

Hazelnut rheology

The hardness of the nutlets ranged from 7 to 10 kgf (68.64–98.06 N) between weeks 21 and 24 (Fig. 1).

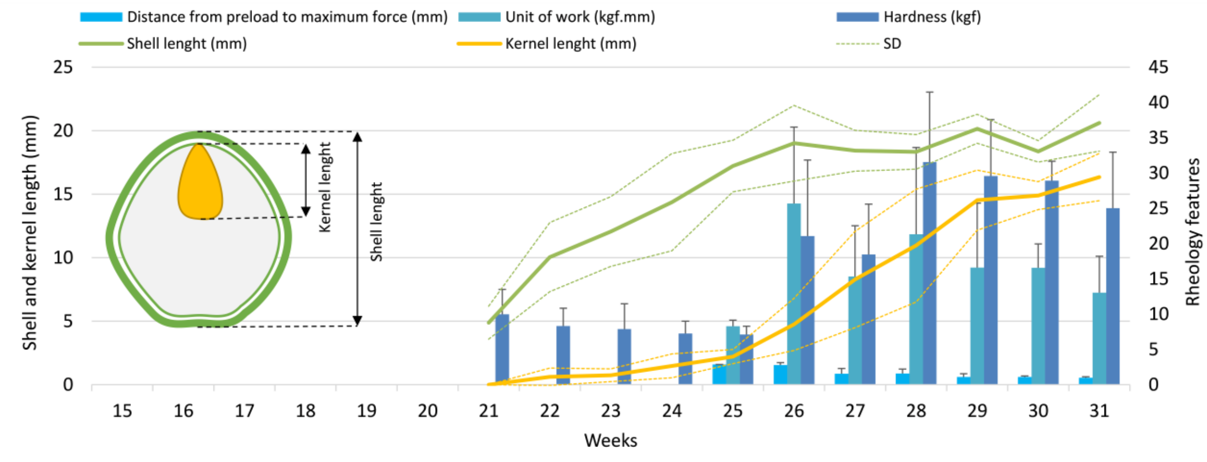

Fig. 1. Rheology features and size of fresh growing hazelnuts cv. Segorbe in 2020

From week 26, all tree rheology parameters were generally significantly higher than in previous weeks, indicating the lignification process had begun (Table 1). For example, hardness increased from 7 to 21 kgf (68.64 to 205.94 N) between weeks 25 and 26 (p<0.05, Kruskal-Wallis test).

Table 1. Rheology features of growing 'Segorbe' hazelnuts cultivar in 2020.

Weeks	Hardness (kgf)	Distance from preload to maximum force (mm)	Unit of work (kgf mm^{-1})
21	9.97±3.52c		
22	8.33±2.50c		
23	7.88±3.58c		
24	7.26±1.75c		
25	7.11±1.19c	2.89 (one value)	8.29±0.85c
26	21.08±10.75a	2.78±0.34a	25.68±10.82a
27	18.46±7.13ab	1.57±0.72b	15.34±7.18bc
28	31.56±9.92ab	1.59±0.62b	21.33±12.28ab
29	29.57±8.01a	1.1±0.45bc	16.6±9.13bc
30	28.93±2.75a	1.1±0.15bc	16.57±3.37abc
31	25.01±7.94a	0.99±0.14c	13.05±5.16bc

Means within a column followed by different letters are significantly different (Dunn test, p<0.05).

Kernel development increased by 46% from week 25 to 26, while shells reached 80–90% of their final size. Kernel size reached 4.75±2.05 mm and 1869.5 cumulative GDDs at week 26. Elongation from the preload to the maximum force (mm) decreased with kernel development from week 26 (2.78±0.34 mm) to 31 (0.99±0.14 mm; r=-0.62, p<0.0001, n=58; Spearman's rank correlation test). Kernel size is correlated with shell hardening following a sigmoidal curve (R^2=0.64, F=123.84; nonlinear regression test). The kernel completes its development at week 29 with 2272.8 cumulative GDDs.

From week 21 – 31, shell hardening increased over time following a sigmoid curve (R^2=0.93, F=37.34; nonlinear regression test).

Morphometric characteristics

The nutlets formed bunches between weeks 18 and 20. The shell was distinguishable, and physical morphometrics were recorded, beginning in week 21. Hazelnuts were small, <5 mm, and the shell fully shriveled between weeks 21 and 22 (Fig. 2).

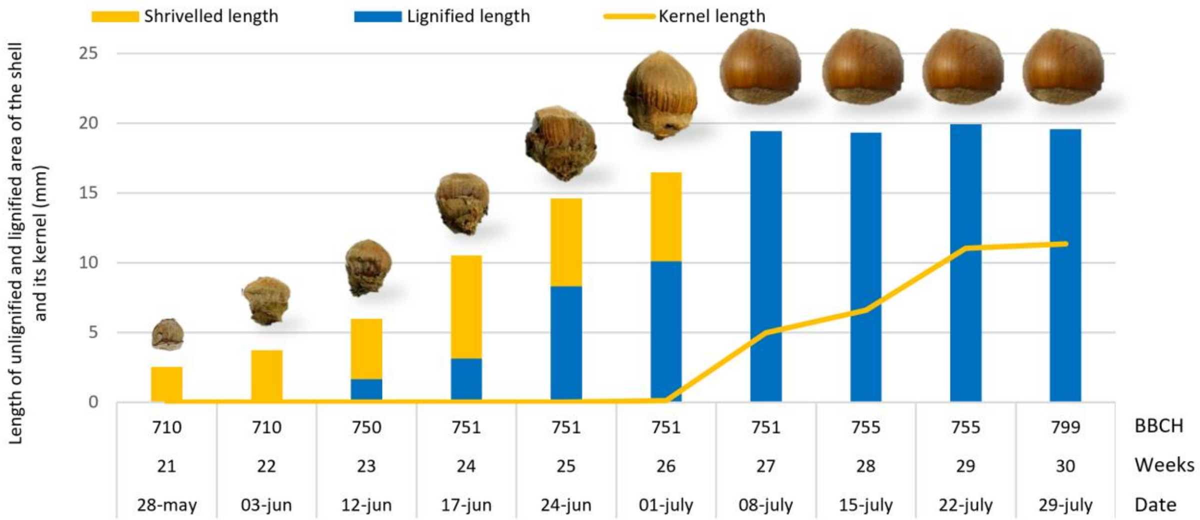

Fig. 2. Mean of shriveled and lignified part measured on hazelnut cv. Segorbe in 2021.

The first sign of lignification (i.e., the unshriveled part) at the tip of shells were observed at weeks 21-22. Indeed, an average length of 1.33% of the lignification shell was measured. Nuts sized 48% of its final size. The lignified portion increased as the shell grown, leading to belted nuts symptoms observed at harvest by growers. Belted hazelnuts are also characterized by a split shell at the tip. The bicarpel splits at the joins of the carpels. Between weeks 25 (1746.5 GDD) and 26 (1862.2 DD), shell length increased from 48% to 84% of their final size. An average of 33% of the shells showed strong channels (strips) transversely. At week 27 (1987.7 GDD), shells were fully lignified, and the first kernels were observed and measured. Kernel sized 4.99±0.32 mm (mean±SD). From weeks 27 to 30, shells were smooth and ripe without shriveled part or apparent strips, and the nuts were free from cupules.

From week 21 – 30, the ratio of lignified and shriveled shell parts increased over time following a sigmoid curve (R^2=0.96, F=134.72; nonlinear regression test).

Comparison of phenological development of both trials

Winter was milder in 2020 than in 2021. The phenology of the orchard was late by approximately seven to ten days between monitoring periods in 2021. Indeed, the shell reached its final size at week 26 with a kernel sizing 5 mm in 2020 compared to week 27 in 2021.

Discussion

To the best of our knowledge, the lignification process in the Segorbe cultivar and, more broadly, belted nuts symptoms have not been previously described. This work studied morphological changes in dried hazelnuts and rheological changes in fresh hazelnuts. The first sign of lignification in dried hazelnuts was observed at week 22; beginning at the tip, and the shell was shriveled or partly lignified by week 27. Shriveling and strip deformations may be related to water loss from the parenchyma, which shows numerous vascular bundles covering shells from tip to basal scar (Caramiello *et al*., 2000; Huss *et al*., 2020). The shell completed its physiological lignification and growth processes at week 27 (1987.7 GDD). The basal scar was free from the remaining cupule, and the first kernels were found among the remaining dried parenchyma. Lipid accumulation beginning at week 27 may help to enhance kernel size, resulting in more visible dried parenchyma (Cristofori *et al*. (2015). A kernel size of >5 mm, at the end of shell development, appears to be a good indicator of complete shell lignification in the Segorbe cultivar. The results obtained with fresh nuts accord with these findings. Indeed, when kernel size was >5 mm, the shell was almost fully developed (80–90% of its final size), and shell hardness increased significantly by week 25, reaching its maximal hardness the following week. Accounting for the one-week delay due to the mild winter of 2020, the sharp increase in hardness recorded in fresh nuts corresponds to complete shell lignification.

The results of both methods showed that lignification began while the shell was 48% of its final size, while in fresh nuts; the first signs of shell hardness began when nuts were 83.5% of their final size. Therefore, dry nut observations enabled us to observe the first signs of lignification with hardness under the threshold of rheology measurements. Hardening in fresh hazelnuts of the Pauetet and Ennis cultivars begins when shells reach 80–90% of their final size and continues until the kernel reaches its full size (Valentini *et al*., 2015). Therefore, using a needle probe to measure hardness may enable us to follow the lignification process of the nutshell more precisely.

This study's findings indicate that lignification begins from the tip and spreads to the basal scar, from BBCH stages 710 to the end of 751. The ovule grows rapidly among the parenchyma at this time, and a lignified wall protects the young kernel. During the period where only the tip is lignified, insect attacks can occur on the remaining half of the fruit. Personal observations show that if the parenchyma is damaged, the white parenchyma turns brown at the injury site and extends to the rest of the ovary cavity within 24 hours. Depending on the kernel size, it can either cease growing or shrivel, and both outcomes probably occur in pest attacks. Therefore, lignification stage is an important biological process protecting against external physical damage.

As suggested by previous studies, the susceptibility of cultivars to some hazelnut pests might be related to shell hardening. True bugs and European hazelnut weevil feeding on partially lignified nuts leads to belted nuts symptoms (Tavella *et al*., 1996, Hamidi *et al*., 2022b) or blank nuts (Hamidi *et al*., 2022a, 2022b) at harvest. However, rapid shell hardening may reduce the egg-laying success of *C. nucum* (Guidone *et al*., 2007; Moraglio *et al*., 2009; Valentini *et al*., 2015), although this was not confirmed by Piskornik *et al*. (1989) and Moraglio *et al*. (2014). In peresent study, the kernel of the Segorbe cultivar was fully lignified by weeks 26 and 27, providing greater protection from environmental stressors. However, the egg-laying activity of *C. nucum* in Segorbe orchards occurs during the kernel development and for several weeks after the completion of lignification (Toillon *et al*., 2021a, Hamidi *et al*., 2022b). In Segorbe cultivar, protection window is short. Relationship between damage and lignification progress is therfore more complex than expected causation is needed to clearly establish the relationship between hardness, lignification, and susceptibility to pests. For example Piskornik (1994) and Vander Wall (2001) suggest that the tannin concentration in the endocarp and pericarp may contribute to hazelnut resistance to pests. Therefore, in the context of integrated pest management (IPM), the dynamic physicochemical properties of hazelnut cultivars require investigation. Belted hazelnut symptoms, such as the ratio of lignified and shriveled shell parts, may indicate the time of death of the hazelnut. Indeed, the time of death of the hazelnut can be related either to a pest peak, such as true bugs and/or weevils attacks, or to a climatic stress such as late frost or heat waves. This information contributes to help to diagnose *a posteriori* the observed damage.

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Conflict of interests

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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