Review

Alternative Woods in Oenology: Volatile Compounds Characterisation of Woods with Respect to Traditional Oak and Effect on Aroma in Wine, a Review

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Abstract: The interest of winemakers to find new woods that can give their wines a special personality and the need for cooperage wood have led to the use of other woods than traditional oak. The aroma of wines is undoubtedly one of the quality factors most valued by consumers. Volatile compounds from wood are transferred to wines during ageing. The type and quantity of aromas in wood depend on several factors, with the species, origin and cooperage treatments, particularly toasting, being very important. The transfer of volatile compounds to the wine depends not only on the wood but also on the wine itself and the type of ageing. This review therefore aims to recapitulate the volatile composition of alternative oenological woods at different cooperage stages and to compare them with traditional woods. It also summarises studies on the effect of wine aromas during ageing both in barrels and with fragments of alternative woods. In summary, it is observed that both woods and wines aged with alternative species of the *Quercus* genus present the same volatile compounds as traditional ones, but differ quantitatively; however, non-*Quercus* woods also differ qualitatively.

Keywords: *Quercus*; oak; *Q. pyrenaica*; cherry; ash; chestnut; mulberry; alternative woods; volatile compounds; wine

1. Introduction

Wine is a product that offers a clear example of a saturated market, so winemakers and winegrowers are looking for sustainability and for quality and differentiation to come first. Aroma is undoubtedly one of the most important quality factors, as it provides a profile of identification to wines, as well as being one of the main qualities perceived by consumers, along with colour and taste. Thus, a special emphasis is currently being placed on oenological practices that affect any of these characteristics, whether through agronomic techniques, processes during fermentation or processes during the postfermentation stage.

In oenology, the use of wood during fermentation and/or wine ageing processes is a common practice in most wine-producing regions of the world. For centuries, wood has been used to make barrels. Originally built for the need to transport wine, today they are used because they are capable of improving the three main sensory characteristics (aroma, colour and taste) of wine. Such is the importance that wood has acquired that it has gone from only being part of the barrels at the time of ageing red wines to being present throughout the entire winemaking process, from the grapes to the end of the process, in all types of white, rosé, red, sparkling, sweet wines, etc., and in all types of alternative formats, barrels, vats of different sizes, etc., and even in bottles made of this material [1].

Oak wood has prevailed in the manufacture of barrels mainly because of its abundance and mechanical resistance. Moreover, this wood positively modifies the characteristics of the wine, acquiring a complex aroma as well as stabilising the colour and improving the

clarification and storage of the wine, gaining fame over time [2–7]. Among the oaks, the most traditional species for wine ageing used are: *Q. alba* (the so-called American oak), *Q. sessilis* (*Q. petraea*) and *Q. robur* (*Q. pedunculata*) (the so-called French oak). The first two species are the most commonly used for wine ageing, while *Q. robur* is very common for Brandy ageing and is less and less used in oenology due to its high ellagitannin content, its high oxygen permeability and its low release of aromatic compounds [4,8,9].

In many wine regions of the world, the use of new oak barrels (or barrels with a limited period of use) increased from the 1990s onwards due to the change that occurred favouring quality. This trend led to an increase in demand for new barrels, resulting in the need to explore new sources of quality cooperage wood [5,10–12]. This gave rise to the exploitation of the same species (*Q.petraea* and *Q.robur*), but from different origins, with different countries such as Spain, Hungary, Poland, Russia, Ukraine, Romania and Portugal entering the market. Many of these woods have been used for a long time but have been less studied and characterised. These oaks are of the same species as the "French" ones, but as the structure of the wood and the final chemical composition depend on other factors such as geographical origin and forest management treatments, it is important to study them. Studies of the woods of these species from these geographical origins showed similar characteristics to traditional American and French oaks, being suitable for contact with quality wines [3,13–18], and some even claim that these origins have intermediate characteristics between French and American oaks. With the introduction of these geographical origins, French oaks have been colloquially referred to as European oaks.

On the other hand, the interest in giving wines their own or special personality has led to the proposal of alternative oaks to *Q. petraea*, *Q. robur* and *Q. alba* that can give certain differentiating notes that are positively valued by the consumer. In this context, a market opportunity has opened up for other nontraditional or alternative woods, namely oak species that have not been used in cooperage such as *Q. faginea* Lam., *Q. pyrenaica* Wild., *Q. farnetto* Ten, *Q. oocarpa* Liebm. and *Q. humboldtii* Bonpl and others less known such as *Q. serrata*, *Q. mongolica* or *Q. denta* [5,12]. In addition, the cooperage industry has been forced to offer a wider range of products from non-oak woods, such as *Robinia pseudoacacia* L. (false acacia), *Castanea sativa* Mill. (chestnut), *Prunus avium* L. and *Prunus cereasus* L. (cherry), *Fraxinus excelsior* L. and *Fraxinus americana* L. (European and American ash, respectively) [12,19–24]. In fact, many of these woods had been used for many years, but most of them had been neglected in terms of cooperage use. However, due to the continuous quest to differentiate some wines from others, they have been given another chance. Others have been around for centuries, such as chestnut, but advances in the knowledge of wood, processes and ageing have led to the production of higher quality contact wood for wine. As a result, many producers are opting for local woods and are using barrels made from woods other than *Quercus* [5].

The components that are released from the wood to the wine are called the "extractable fraction" and represent approximately 10% of the dry wood weight. These compounds are difficult to classify due to their varied nature. Ellagitannins are the most abundant, but there are also others with different chemical structures such as low molecular weight phenols and volatile compounds. Some of these compounds are the origin of many of the interesting organoleptic characteristics found in wines that have been in contact with wood and their presence has led winemakers to increasingly use wood throughout the winemaking process [4,5,11,12].

Volatile compounds from oak transferred to wine are of great sensory importance because they contribute aromatic notes of "vanilla", "sweet", "almond", "wood", "coconut", "spice", "smoked" and "toasted" (Table 1), increasing its complexity [25,26]. The volatile compounds generally found in traditional oaks are those also found in alternative oaks and other woods. Despite this, the genus and species of wood affects the aromatic profile and there are compounds such as volatile phenols, lactones, furanic compounds, aldehydes and others that can differentiate them and, above all, provide quantitative and qualitative differences [13,24,27–29]. A clear example is the long-known generalisation with traditional oaks, where the highest amount of *cis*-β-Methyl-γ-octalactone lactone (*cis* lactone) is associated with *Q. alba* [4,18,30].

Table 1. Information on some of the main and most-studied volatile compounds in wood and wine aged with them.

	Derived from	Common Name	IUPAC Name	Molecule	Aroma Notes	Olfactory Threshold
Volatile phenols	Lignin and polyphenols	Guaiacol	2-Methoxyphenol		Smoke, sweet, medicine [31]	9.5 µg/L [32]
		4-Ethylguaiacol (4-EG)	4-Ethyl-2-methoxyphenol		Phenolic, smoked [31], leather [33]	47 µg/L [27]
		4-Methylguaiacol (4-MG)	4-Methyl-2-methoxyphenol		Spicy, phenolic, light green [16]	20 µg/L [34]
		4-Vinylguaiacol (4-VG)	4-Vinyl-2-methoxyphenol		Clove [31]	40 µg/L [32]
		Eugenol	2-Methoxy-4-(prop-2-enyl) phenol,		Clove, honey, spicy [31], cinnamon [16]	6 µg/L [32]
		Isoeugenol	1-Methoxy-4-(prop-2-enyl) phenol		Floral [32], clove, woody [16],	6 µg/L [32]
		Syringol	2,6-Dimethoxyphenol		Smoke, burned, wood [35]	570 µg/L [36]
Furanic compounds	Polysaccharides	Furfural	2-Furancarboxaldehyde		Bread, almond, sweet [31]	15 mg/L [31]
		5-Methylfurfural	5-Methyl-2-furancarboxaldehyde		Almond, caramel, burnt sugar [31]	16 mg/L [31]
		Maltol	3-Hydroxy-2-methyl-4*H*-pyran-4-one		Honey, toasty, caramel [37]	5 mg/L [37]
		5-Hydroxymethylfurfural	5-Hydroxymethyl-2-furaldehyde		Caramel [33]	100 mg/L [34]
Lactones	Lipids	*trans*-β-Methyl-γ-octalactone	*trans*-4-Methyl-5-butyldihydro-2-(3H)-furanone		Coconut, woody, vanilla [31]	140–370 µg/L [38]
		cis-β-Methyl-γ-octalactone	*cis*-4-Methyl-5-butyldihydro-2-(3H)-furanone		Coconut, woody, vanilla [31]	20–46 µg/L [38]
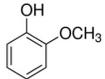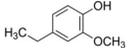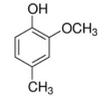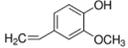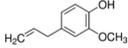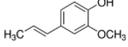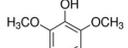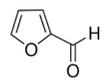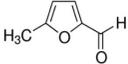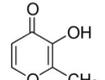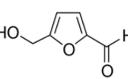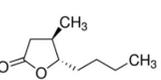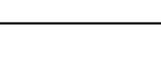
Table 1. *Cont.*

	Derived from	Common Name	IUPAC Name	Molecule	Aroma Notes	Olfactory Threshold
Phenolic aldehydes/Phenyl ketones	Lignin	Vanillin	4-Hydroxy-3-methoxybenzaldehyde		Vanilla [31]	1000 µg/L [32]
		Syringaldehyde	4-Hydroxy-3,5-dimethoxybenzaldehyde		Vanilla [31]	50 mg/L [39]
		Acetovanillone	1-(4-hydroxy-3-methoxyphenyl)ethanone		Vanilla [31]	1000 µg/L [39]
		Butyrovanillone	1-(4-Hydroxy-3-methoxyphenyl)butanone			
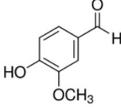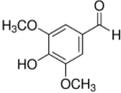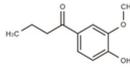
Numerous factors influence the concentrations of volatile compounds found in wood or in wine aged with it, one of the most important being the wood toasting, although there are others, such as silvicultural treatments to the trees and the type of wood drying [40–43]. The toasting of wood increases the quantity and complexity of the compounds yielded by the wood to the wine, as it induces the formation of new volatile compounds by thermal degradation of the wood or increases the existing ones. Depending on the temperature and exposure time, toasting can be light, medium or heavy. The temperature, time and toasting cooperage method (fire or hot air convection) also affect wood aroma compounds [13,27,43–46]. Volatile phenols, phenolic aldehydes and phenylketones come from the thermodegradation of lignin [41]. These compounds mainly give the wine smoky, woody, vanilla and spicy aromas (Table 1). Furanic compounds come from the thermal degradation of polysaccharides [44], providing aromas of toasted almond, nuts, caramel, burnt sugar, bread and sweets (Table 1). This family of compounds enhances the aroma of oak and accentuates that of other compounds such as lactones [47,48]. The two isomers β-Methyl-γ-octalactone (*cis* lactone and *trans* lactone) are mainly formed during toasting by dehydration of 2-methyl-3-(3,4-dihydroxy-5-methoxybenzo)-octanoic acid, [49] giving the wine woody and coconut aromas (Table 1). It should be remembered that even if a compound does not exceed the minimum concentration marked by the perception threshold for its aroma to be expressed, molecules interact with each other, enhancing the aroma of another compound or giving aromatic nuances [47,50]. Other factors that influence the content of these aromas in the final wines are the contact time of the wine with the wood, the wood-wine ratio, whether the wood is new or has been previously used with other wines [51–53] and the type of contact (barrels or wood's pieces) [40,52,54,55], among others. In addition to all the aforementioned factors, the concentration of volatile compounds from wood in the wine depends on the grape variety and maturity, as each wine has a different capacity to extract these compounds from woods [29,56,57].

The aim of this review was to recapitulate and compare the composition in volatile compounds studied by gas chromatography of woods other than those traditionally used in oenology (*Q. alba*, *Q. petraea* and *Q. robur*), at each of the different cooperage stages (green wood, after being seasoned and after toasting), and of the wines that have been in contact with them both in barrels and/or with pieces of wood.

2. Volatile Wood Composition

This section summarises the volatile composition of the different alternative woods. The woods studied from the *Quercus* genus were *Q. pyrenaica*, *Q. faginea* and *Q. humboldtii* and from non-*Quercus* species, *Robinia pseudoacacia* (acacia), *Castanea sativa* (chestnut), *Prunus avium* (cherry), *Fraxinus excelsior* (European ash), *Fraxinus americana* (American ash) and *Morus alba* (mulberry). Volatile compounds in green, dried and toasted wood are represented in Tables 2–4, respectively. In green wood, aroma studies were found in *Q. pyrenaica* species. However, mulberry was characterised in dried wood and *Q. humboldtii* in toasted wood. If traditional woods were analysed in the works on alternative woods, they were also included. Most of the studies were carried out after toasting because this is the process that most affects the volatile composition of the wood. The compounds represented belonged to very different chemical families, such as volatile phenols, lactones, furanic compounds and phenolic aldehydes. Their concentrations covered a very wide range, reaching up to 59 μg/g in green wood (Table 2), 80.9 μg/g in dried wood (Table 3) and even up to more than 5078 μg/g in toasted wood (Table 4).

Table 2. Volatile compounds expressed as µg/g of wood found in extracts of green woods of different botanical origins.

Species	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Alternative woods *Q. pyrenaica*																		
Gata/Peña de Francia [58]	0.18	0.06	0.51	0.61	5.2	0.61	0.47	2.6	0.22	0.28	3.7	4.8	36	7.4	3.4	4.4	0.38	0.06
Gata/Peña de Francia [11,59]	0.21	0.07	0.76	0.67	5.7	0.71	0.51	2.4	0.25	0.27	3.8	6.4	59	12	3.6	5.1	0.50	0.08
Gudarrama [11,59]	0.16	0.02	0.36	0.64	2.3	0.28	0.17	2.4	0.19	0.24	1.7	0.84	15	17	3.8	5.4	0.26	0.04
Cantábrica mountain range [11,59]	0.24	0.14	0.52	0.72	1.5	0.26	0.23	1.4	0.33	0.23	2.7	7.3	27	7.5	2.4	4.8	0.24	0.04
Sistema Ibérico [59]	0.16	0.02	0.39	0.52	1.6	0.32	0.21	1.9	0.41	0.24	1.7	29	14	4.9	ne	ne	0.20	0.03
Aliste-Margarita [11]	0.12	0.07	0.08	0.54	0.73	0.24	0.34	0.9	0.22	0.17	3.2	2.8	12	3.8	1.5	3.5	0.21	0.02
North of Sistema Ibérico [11]	0.13	0.04	0.49	0.86	2.2	0.44	0.31	1.7	0.24	0.23	2.9	10	18	4.9	4.4	14	0.35	0.05
Gredos and Sierra de Ávila [11]	0.09	0.04	0.07	0.39	0.55	0.26	0.07	0.57	0.24	0.19	1.7	0.54	1.7	2.5	1.7	3.0	0.16	0.03
Traditional Quercus																		
Q. petraea [58]	0.09	0.01	0.06	0.39	2.1	0.18	0.07	1.2	0.22	0.24	0.63	18	37	3.9	2.2	2.7	0.16	0.56

Acronyms: 4-EG: 4-Ethylguaiacol; 4-MG: 4-Methylguaiacol; 4-VG: 4-Vinylguaiacol; *trans* WL: *trans* lactone (*trans*-β-Methyl-γ-octalactone); *cis* WL: *cis* lactone (*trans*-β-Methyl-γ-octalactone); ne: analysed by HPLC.

Q. pyrenaica Wild

The most studied volatile composition has been in *Q. pyrenaica* wood, in green wood [11,58,59], dry wood [23,58,60–64] and toasted wood [6,20,40,62–67] (some not considered in the table [20,62,67]).

Table 2 shows the volatile composition of green *Q. pyrenaica* wood from different origins. It can be seen that Spanish wood from Gata/Peña de Francia forest was the most aromatic while wood from Gredos and Sierra de Ávila forest was the poorest. The most abundant compound was *cis* lactone, the wood from Gata/Peña de Francia forest being the one with the highest contents, even higher [59] or similar [58] to *Q. petraea*. In most of the sources, the content of the *cis* lactone isomer was higher than that of the *trans* lactone isomer, which is usually observed in traditional oaks. This *trans* lactone isomer in *Q. pyrenaica* woods was, in general, lower than in *Q. petraea*. Therefore, it is observed that the sum of lactones in *Q. petraea* (55.3 µg/g) is higher than in *Q. pyrenaica* wood (30.7 µg/g) (Figure 1a). The wood of *Q. pyrenaica* showed a high content of volatile phenols (Figure 1a), as most of these compounds had higher concentrations than those found in *Q. petraea* (Table 2). The green wood of this species showed higher furanic compounds contents than those observed in *Q. petraea* wood, 4.9 vs. 2.3 µg/g (Figure 1a). This is especially due to 5-HMF, as the contents in *Q. pyrenaica*, even in the poorest source (1.7 µg/g) is almost three times higher than in *Q. petraea* wood (0.63 µg/g). The green wood of *Q. pyrenaica* also had elevated phenolic aldehydes and acetovanillone contents (Table 2 and Figure 1a), being generally higher than *Q. petraea*. However, the green wood of *Q. pyrenaica* was rather low in butyrovanillone, regardless of its origin (Table 2).
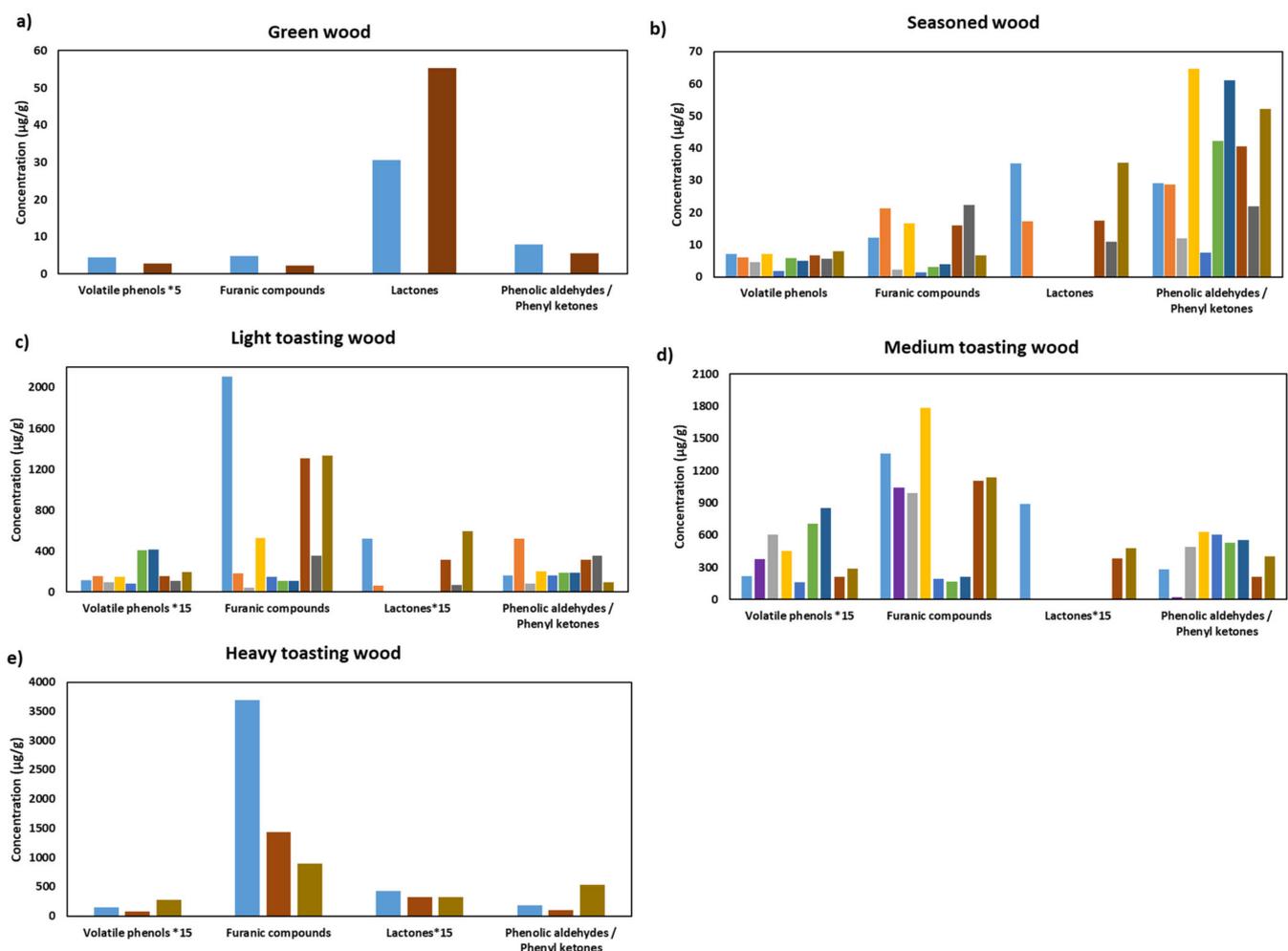
Figure 1. Graphical representation of the averages of the sum of the compounds in wood volatile phenols, furanic compounds, lactones and phenolic aldehydes/phenyl ketones by wood species, after the different cooperage treatments: (**a**) green, without treatment; (**b**) seasoned (carried out in oven and in open air); (**c**) light-toasted (light toasting, 190 °C for 10 min, 160–170 °C for 20 min and for 35 min); (**d**) medium-toasted (medium toasting, 180 °C for 45 min, 200 °C for 15 min and 35 min, 210 °C for 20 min and 45 min, and medium plus toasting); (**e**) heavy-toasted (heavy toasting and 250–260 °C for 27 min).

The origin and preparation of the wood have a great influence on the volatile composition, which makes the comparison between different studies difficult. Therefore, it was only possible to see how drying affects it in the study by Cadahía et al., 2007 [58], as it analysed the same woods when green (Table 2) and with different seasoning times (12, 18 and 24 months) (Table 3). The seasoning time increased the content of all compounds, although the fluctuations were probably due to the formation from their precursors but also to the removal by leaching or evaporation [41,68,69], as can be observed for volatile phenols, phenyl ketones and lactones (Table 3). However, phenolic aldehydes after 12 months of seasoning increased by 4 µg/g and subsequently showed a decrease of up to 2.6 µg/g at 24 months. The highest contents of furanic compounds were found after 18 months of seasoning. Oak *Q. pyrenaica* wood undergoes changes during the drying process, which may seem limited compared to the toasting process as well as traditional woods [58].

The dry wood of *Q. pyrenaica*, as in green wood, showed higher *cis* lactone than *trans* lactone (Table 3). In general, both isomers were found in concentrations within the range of traditional oaks. The seasoned wood from Gata/Peña de Francia forest, an origin that already showed a high concentration when green (Table 2), stood out for its high *cis* lactone

content, even higher than that of *Q. alba* (Table 3). Meanwhile, the wood from the Salamanca region (Spain) had the highest *trans* lactone content (33.8 µg/g) [23], being six times higher than the other *Q. pyrenaica* woods and even more than twice as high as the traditional ones. However, *trans* lactone was not detected in wood from the Gerês forest in Portugal [63]. The average lactone concentration of seasoned wood from *Q. pyrenaica* was very similar to *Q. alba* and higher than *Q. petraea* (Figure 1b). The highest vanillin contents were found after oven drying in both *Q. pyrenaica* and traditional woods. Oven-dried and generally air-seasoned woods of *Q. pyrenaica* had lower vanillin concentrations than *Q. petraea* and *Q. alba*, with the exception of those from the Salamanca and Alava provinces in Spain. The content of volatile phenols and furanic compounds in the seasoned *Q. pyrenaica* woods was between the values of *Q. petraea* and *Q. alba* (Figure 1b). It was observed that the concentration of eugenol, isoeugenol and 5-HMF in some seasoned woods of *Q. pyrenaica* were even higher than those found in traditional woods (Table 3). Alañon et al., 2012 [61] placed the dry wood of *Q. pyrenaica* aromatically closer to *Q. alba*, especially because of the low content of furanic compounds, which did not correlate with that observed by most authors, and the high content of lactones. These authors [61] indicated that this species is very rich in terpenic and norisoprenoid compounds, with particularly higher levels of α-terpineol and methyl dihydrojasmonate than traditional *Quercus* and chestnut woods.

Alañón et al., 2011 [60] studied the influence of geographical location on the aroma of dried wood and found that altitude was the most influential parameter, with geographical location also having an important impact on extraction. Thus, higher altitudes and/or clay-textured soils showed lower concentrations of some volatiles [60]. Therefore, the content of all volatile compounds in Ourense's forest wood was lower than in the wood from forests from Lugo and Pontevedra (Spain) [60].

On the other hand, the way *Q. pyrenaica* wood was dried, in a traditional or accelerated way, had less influence on the volatile composition than the size of the piece of wood and the intensity of the toasting [40]. This is probably due to the fact that this wood undergoes less volatile compound formation than traditional wood during this drying process. Jordao et al., 2005 [63] showed that *Q. pyrenaica* wood was poor in total volatile composition after being seasoned, presenting about 30–40 µg/g compared to more than 50 µg/g for the traditional ones. However, after toasting, *Q. pyrenaica* wood showed the highest contents [63] at about 5000 µg/g after toasting at 250–260 °C and 5979–8332 µg/g after toasting at 160–170 °C, while in the traditional ones it was 1161–2153 µg/g and 2201–4794 µg/g, respectively. The difference after toasting of this species compared to the traditional ones was mainly due to furfural, 5-HMF and vanillin [63]. Fernandez de Simón et al., 2010 [66] also observed a higher concentration of furanic compounds in *Q. pyrenaica* woods together with furaneol and *cis* lactone; however, vanillin concentrations in this study were lower than traditional ones. However, Cadahía et al., 2003 [64] observed that the concentrations of all compounds in *Q. pyrenaica* after toasting were between the concentrations of traditional oaks, closer to those of *Q. petraea* wood.

The level of toasting in *Q. pyrenaica*, as in traditional oaks, has a great influence on the concentration of many of the volatiles. This process increases the content by hydrothermolysis and pyrolysis reactions; however, if the temperature increases a lot and is maintained for a long time, the volatile compounds are degraded [40,64,66,70]. Jordao et al., 2005 [63] showed that almost all aromas were higher after toasting at 160–170 °C than after toasting at 250–260 °C. Similar results were shown by Fernandez de Simón et al., 2010 [66], where it was seen that aromas were formed as the toasting was increased as in traditional woods, but with a very high toasting temperature, they were degraded, especially with heavy toasting.

Table 3. Volatile compounds expressed as μg/g of wood found in extracts of seasoned woods of different botanical origins.

Species	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Seasoned in oven (0% IH)																		
Alternative woods																		
Q. pyrenaica (Lugo) [60]	1.0	ns	ns	1.2	3.8	2.6	1.2	ns	ns	ns	ns	5.9	21	3.6	21	36	1.2	4.0
Q. pyrenaica (Pontevedra) [60]	0.9	ns	ns	1.5	3.2	1.6	1.0	ns	ns	ns	ns	4.7	25	5.3	25	43	1.2	4.3
Q. pyrenaica (Ourense) [60]	0.6	ns	ns	0.9	1.6	2.3	0.5	ns	ns	ns	ns	3.6	18	4.9	19	33	1.0	3.7
Q. pyrenaica (Portugal) [61]	2.6	ns	0.8	3.1	2.4	0.3	0.9	0.6	0.4	ns	2.5	9.3	39	4.2	19	12	2.9	5.3
Castanea sativa (Portugal) [61]	5.2	ns	1.5	3.0	2.5	1.2	1.5	3.6	2.3	ns	6.9	nd	nd	nd	81	22	4.8	10
Traditional *Quercus* [61]																		
Q. petraea	4.5	ns	1.1	3.4	1.1	0.3	0.9	12	3.6	ns	6.2	2.1	6.1	2.9	46	26	3.4	6.9
Q. robur	4.3	ns	0.9	4.6	1.4	0.2	0.6	17	5.0	ns	27	2.9	3.2	0.5	6.4	24	0.5	2.2
Q. alba	0.9	ns	0.2	3.4	3.4	0.4	0.9	5.8	0.4	ns	0.9	1.6	39	12	70	23	2.7	7.4
Seasoned in open air (nonspecific)																		
Alternative woods [62]																		
Q. pyrenaica (Portugal)	0.4	ns	ns	ns	0.9	ns	0.4	1.9	0.0	ns	1.7	2.3	6.7	2.9	4.8	ns	1.9	ns
Q. pyrenaica (Portugal)	1.3	ns	ns	ns	2.7	ns	0.4	13	0.3	ns	2.4	2.7	7.2	2.7	4.8	ns	0.0	ns
Q. pyrenaica (Portugal)	0.3	ns	ns	ns	1.1	ns	0.0	4.6	0.0	ns	2.7	2.5	5.3	2.2	5.5	ns	0.0	ns
Q. alba, stellata, lyrata, bicolor	1.5	ns	ns	ns	4.5	ns	0.0	9.8	0.6	ns	0.8	2.7	35	13	5.8	ns	0.9	ns
Castanea sativa (Portugal)	0.4	ns	ns	ns	0.7	ns	0.5	2.3	0.3	ns	0.9	0.2	0.3	1.5	2.9	ns	1.3	ns
Traditional *Quercus* [62]																		
Q. petraea	1.2	ns	ns	ns	1.2	ns	0.4	14	0.8	ns	1.0	1.9	4.9	2.6	8.3	ns	0.4	ns
Q. robur	0.1	ns	ns	ns	1.0	ns	0.0	4.5	0.3	ns	0.3	2.9	7.2	2.5	1.2	ns	0.0	ns
Alternative woods *Q. pyrenaica* Gata/Peña de Francia [58] *Seasoned in open air (12 months)*																		
	0.2	0.1	0.4	1.1	5.7	0.5	0.4	3.5	0.9	0.4	4.2	3.5	50	27	5.3	6.5	0.5	0.1
Alternative woods *Q. pyrenaica* Gata/Peña de Francia [58] *Seasoned in open air (18 months)*																		
	0.2	0.0	1.1	1.2	3.9	0.3	0.2	4.9	1.6	0.4	3.4	4.6	73	24	4.5	5.0	0.3	0.1
Seasoned in open air (24 months)																		
Alternative woods																		
Q. pyrenaica (Salamanca) [23]	0.4	0.0	0.4	0.9	5.5	1.4	1.1	11	0.2	1.4	13	34	32	0.9	12	48	0.6	3.1
Q. pyrenaica (Gata/Peña de Francia) [58]	0.5	0.1	0.3	2.2	7.3	0.7	1.7	3.2	1.0	0.3	4.9	5.3	68	20	4.9	4.2	0.7	0.1
Q. pyrenaica (Gerês forest of Portugal) [63]	nd	ns	nd	ns	nd	nd	ns	3.9	ns	ns	0.9	nd	10	-	2.5	15	ns	ns

Table 3. *Cont.*

Species	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Q. pyrenaica (Guarda forest of Portugal) [63]	nd	ns	nd	ns	nd	nd	ns	4.5	ns	ns	1.3	8.3	5.3	0.6	1.6	17	ns	ns
Robinia pseudoacacia [23]	0.4	0.1	0.0	0.4	0.1	1.0	0.8	0.5	0.0	0.9	0.2	nd	nd	-	1.7	6.0	0.2	0.7
Robinia pseudoacacia [65]	0.9	ns	0.1	ns	0.2	3.4	1.9	0.9	0.1	1.4	0.5	ni	ni	-	3.5	10	0.3	1.0
Castanea sativa [23]	0.1	0.0	0.1	0.3	2.0	2.2	0.1	5.5	0.1	1.1	14	nd	nd	-	24	53	0.5	2.0
Castanea sativa [65]	0.2	ns	0.2	ns	4.5	2.4	0.3	6.7	0.2	2.0	21	ni	ni	-	17	38	0.4	1.9
Prunus avium [23]	0.2	0.0	0.0	0.3	0.1	0.0	0.4	0.5	0.0	0.4	0.2	nd	nd	-	1.1	2.6	0.2	0.4
Prunus avium [65]	0.5	ns	0.1	ns	0.1	0.6	1.5	0.7	0.1	0.5	0.5	ni	ni	-	2.4	6.9	0.3	1.0
Fraxinus excelsior (Europe) [23]	0.1	nd	0.1	0.4	0.2	1.3	0.2	0.8	0.0	0.2	0.9	nd	nd	-	7.3	45	0.2	0.6
Fraxinus excelsior (Europe) [65]	0.1	ns	0.2	ns	0.6	7.7	0.6	0.5	0.1	0.5	3.3	ni	ni	-	10	20	0.4	1.3
Fraxinus americana (American) [23]	0.1	0.02	0.8	0.6	0.4	2.4	0.2	1.2	0.0	0.8	1.6	nd	nd	-	15	51	0.4	2.0
Fraxinus americana (American) [65]	0.2	ns	1.2	ns	0.9	2.1	0.9	1.3	0.1	0.9	2.0	ni	ni	-	14	37	0.9	2.4
Traditional *Quercus*																		
Q. petraea [23,58,63]	nd-1.3	nd-0.0	nd-0.6	0.2–1.0	1.3–6.5	0.7–4.3	0.1–0.2	3.4–7	0.1–0.2	0.2–0.8	0.3–4	5–15	14–56	1.7–9	2–12	2.7–47	0.4	1.4–1.9
Q. alba [23,63]	0.0–3.3	nd	0.1–1.5	0.18	1.4–5.9	1.1–1.8	0.1	1.2–4.7	0.2	0.48	0.4–6.3	2.5–5	22–26	5.2–8.9	6.8–7.5	16–20	0.4	1.5
Seasoned in open air (24–36 months)																		
Alternative woods northern Italy [71]																		
Robinia pseudoacacia	nd	ns	ns	nd	nd	ns	nd	ns	ns	ns	ns	ns	ns	ns	1.7	10	ns	ns
Castanea sativa	nd	ns	ns	nd	0.7	ns	nd	ns	ns	ns	ns	ns	ns	ns	5.2	4.2	ns	ns
Prunus avium	nd	ns	ns	nd	nd	ns	0.1	ns	ns	ns	ns	ns	ns	ns	0.1	0.4	ns	ns
Mulberry	0.0	ns	ns	nd	nd	ns	nd	ns	ns	ns	ns	ns	ns	ns	0.1	0.5	ns	ns
Traditional *Quercus* [71]																		
France	nd	ns	ns	0.1	2.0	ns	0.0	ns	ns	ns	ns	ns	ns	ns	2.0	9.3	ns	ns
Seasoned in open air (36 months)																		
Alternative woods [64]																		
Q. pyrenaica (Alava)	0.1	0.0	0.5	2.0	2.3	0.4	0.3	20	1.5	0.3	3.9	4.6	18	3.7	11	15.	0.7	2.4
Q. faginea (Alava)	0.3	0.2	0.5	1.1	2.0	0.4	1.6	18	1.8	0.4	1.5	1.7	16	11	11	10	1.5	6.6
Traditional *Quercus* [64]																		
Q. petraea	0.1	0.1	0.1–0.4	1.0–1.1	0.6–3.2	0.2–0.3	0.2–0.3	10–20	1.5–1.7	0.2–0.4	0.5–2.6	0.1–7.8	0.4–12	3.5–5.0	14–19	17–19	0.9–1.2	1.9–2.3
Q. robur	0.1	0.1	0.2–0.7	1.0–1.3	1.1–1.6	0.3	0.2	8.9–11	1.1–2.0	0.3–0.4	0.8–2.7	3.4–4.0	2.8–23	4.0–7.0	9.3–16	14–18	0.7–1.0	1.7–2.5
Q. alba	0.1	0.0	0.7	0.5	5.7	0.3	0.2	4.0	0.3	0.2	1.8	3.5	33	16	7.9	16	0.5	1.6

Acronyms: 4-EG: 4-Ethylguaiacol; 4-MG: 4-Methylguaiacol; 4-VG: 4-Vinylguaiacol; *trans* WL: *trans* lactone (*trans*-β-Methyl-γ-octalactone); *cis* WL: *cis* lactone (*trans*-β-Methyl-γ-octalactone); ns: not studied; ni: not identified; nd: not detected.

There is much variability among the studies carried out, although, in general, it could be said that the toasted wood of *Q. pyrenaica* is rich in certain compounds, such as *cis* lactone, eugenol, 4-VG and furanic compounds. The rest of the compounds are usually present in similar concentrations to traditional woods, as is the case of most volatile phenols, phenolic aldehydes and phenyl ketones (Table 4 and Figure 1). Figure 1 shows that the lactone content in *Q. pyrenaica* is similar to (Figure 1c) or higher (Figure 1d,e) than *Q. alba* and always higher than *Q. petraea*. Furthermore, regardless of toasting, a higher content of furanic compounds was observed in the wood of *Q. pyrenaica* than in the traditional ones (Figure 1).

Quercus faginea Lam

Only one work was found on the volatile composition of *Q. faginea* wood [64], studied both after seasoning and toasting. This wood showed the same compounds and in similar concentrations to the wood of traditional oaks, although butyrolactone, hydroxybenzaldehyde and 1H-pyrrole-2-carboxaldehyde were not detected in the seasoned wood, but were detected in the toasted wood. The seasoned wood of *Q. faginea* showed higher concentrations of some aromas including: volatile phenols, such as guaiacol, 4-EG, phenol, syringol; some phenolic aldehydes, such as 2-(4-hydroxy-3-methoxyphenyl) acetaldehyde, acetovanillone, 1-(4-hydroxy-3-methoxyphenyl)-2-propanone, butyrovanillone, 2-(4-hydroxy-3,5-dimethoxyphenyl) acetaldehyde, acetosyringone, 1-(4-hydroxy-3,5-dimethoxyphenyl)-2-propanone, propiosyringone, benzaldehyde and the minor ones of 2-furanyl-1-ethanone, methyl vanillyl ether, syringaldehyde, coniferaldehyde and sinapaldehyde [64]. Figure 1b shows how this wood after seasoning stands out for its content of furanic compounds (21.3 µg/g).

During toasting, at 160–170 °C for 35 min, the *cis* and *trans* lactone contents decreased by about 80% and 40%, respectively, whereas in traditional woods they increased during toasting. Therefore, the toasted wood of *Q. faginea* is probably a lactone-poor wood among the *Quercus* woods (Table 4 and Figure 1c). The concentrations of the other volatile compounds studied after toasting were between those found in *Q. petraea* and *Q. alba*, with some exceptions, such as the higher content of 4-methylsyringol, benzaldehyde, benzothiazole, 2-phenoethanol and ethyl vanillyl ether and the lower content of isomaltol, 1-(4-hydroxy-3-methoxyphenyl)-2-butanone, butyrovanillone and methyl vanillyl ether. Furthermore, as shown in Figure 1c, this wood showed a low content of furanic compounds, the *Quercus* wood having the lowest content (185 µg/g) and the one with the highest average content of phenolic aldehydes/phenyl ketones (521.97 µg/g).

Table 4. Volatile compounds expressed as μg/g of wood found in extracts of toasted woods of different botanical origins.

Species	Seasoning Time (m: months)	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	trans WL	cis WL	cis/trans Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
		Volatile Phenols							**Furanic Compounds**				**Lactones**			**Phenolic Aldehydes/Phenyl Ketones**			
Heat treatment: light																			
***Alternative woods** as staves and chips* [66] *Q. pyrenaica*		0.4	0.0	0.5	0.6	5.1	0.1	1.3	368	44	5.2	198	8.2	47	5.7	28	83	1.5	ns
***Traditional Quercus** as staves and chips* [66]	24 m open air																		
French oak		0.3	0.1	1.0	0.3	1.2	0.1	1.4	78	17	5.2	37	12	11	1.0	120	196	3.3	ns
American oak		0.4	0.1	0.7	0.2	1.6	0.1	1.3	41	6.7	2.0	15	3.4	25	7.4	27	57	0.9	ns
Heat treatment: 190 °C for 10 min																			
***Alternative woods** Q. pyrenaica from Navarra* [40]																			
staves	24 m open air	0.7	ns	0.6	ns	6.6	2.3	1.5	548	49	1.2	196	4.2	34	8.1	29	101	1.5	ns
	Accelerated	0.2	ns	0.4	ns	2.2	0.9	0.6	462	51	3.3	247	2.5	69	27	19	84	1.0	ns
chips	24 m open air	0.2	ns	1.0	ns	3.9	1.7	0.6	71	11	11	84	8.3	36	4.3	42	74	1.4	ns
	Accelerated	0.2	ns	0.7	ns	6.0	0.5	0.7	79	13	10	76	4.5	20	4.4	33	74	1.1	ns
Heat treatment: 160–170 °C for 20 min																			
***Alternative woods** Q. pyrenaica of Portugal* [63]																			
Gerês forest		1.6	ns	2.5	ns	0.6	0.5	ns	2177	328	ns	3344	4.8	14	2.9	23	82	ns	ns
Guarda forest	24 m open air	2.5	ns	2.5	ns	1.4	0.7	ns	2670	465	ns	5078	7	3.6	0.5	11	88	ns	ns
Traditional Quercus [63]																			
Q. petraea		2.9–3.4	ns	nd-1.6	ns	1.7–4	0.5–0.8	ns	723–723	199–258	ns	1204–1722	5.4–11	14–19	1.6–2.6	6.9–8.3	49–60	ns	ns
Q. alba		3.7–7.3	ns	2.6–5.1	ns	6.2–12	1.3–1.9	ns	358–960	91–487	ns	1678–3221	6.4–7.4	27–46	4.1–6.2	7.7–11	24–35	ns	ns
Heat treatment: 160–170 °C for 35 min																			
Alternative woods																			
Q. pyrenaica from Álava [64]	36 m open ai	0.4	0.3	1.5	1.9	1.9	1.3	2.6	170	30	1.6	56	3.4	14	4.4	210	280	4.6	16
Q. faginea from Alava [64]		0.4	0.3	1.5	2.5	2.4	1.0	2.6	96	30	1.5	58	1.1	3.3	3.6	258	243	5.3	16
Robinia pseudoacacia l [65]		0.5	ni	0.2	ni	0.4	3.8	1.3	21	7.5	6.5	6.7	ni	ni	ni	19	57	1.0	3.0
Castanea sativa [65]	24 m open air	0.5	ni	2.6	ni	3.2	2.1	1.4	431	29	4.3	67	ni	ni	ni	72	114	1.7	14
Prunus avium [65]		0.9	ni	0.6	ni	0.7	1.3	2.1	88	14	3.5	42	ni	ni	ni	45	115	1.5	4.56
Fraxinus excelsior from Europe [65]		6.5	ni	3.7	ni	1.6	8.3	7.5	27	15	19	51	ni	ni	ni	76	98	4.2	9.1
Fraxinus americana from American [65]		6.5	ni	3.7	ni	1.6	8.3	7.5	27	15	19	51	ni	ni	ni	76	98	4.2	9.1
Traditional Quercus [64]																			
Q. Petraea	36 m open air	0.2–0.4	0.2–0.6	0.8–2.1	1.1–7.4	0.9–3.3	0.4–4.2	1.3–3.3	59–186	26–30	1.2–1.5	44–52	0.1–15	0.3–20	1.3–2.9	119–370	160–452	2.7–7.9	16–25
Q. Robur		0.2–0.5	0.2	0.9–1.0	1.5–1.9	1.0–1.4	0.3–1.8	1.2–3.0	103–340	26–81	1.4–1.6	41–112	0.3–4.1	0.3–5.0	1.6–4.5	130–172	162–216	3.0–3.9	13–18
Q. Alba		1.2	0.5	1.5	0.5	5.3	3.8	2.4	346	85	3.4	103	4.4	44	19	40	102	4.3	22

Table 4. *Cont.*

Species	Seasoning Time (m: months)	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
		Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Heat treatment: medium																			
Alternative woods *as staves and chips* [66]	24 m open air																		
Q. pyrenaica		1.3	0.1	1.6	0.6	5.0	0.3	3.4	919	135	18	322	11	47	4.2	54	135	3.4	ns
Traditional *Quercus* *as staves and chips* [66]																			
French oak		1.7	0.3	4.4	1.2	1.4	0.3	7.3	357	42	16	58	9.7	12	1.3	172	443	12	ns
American oak		2.7	0.4	3.0	1.6	2.5	0.4	8.4	681	95	14	75	6.6	31	4.7	120	34	7.2	ns
Heat treatment: 200 °C for 15 min																			
Alternative woods *Q. pyrenaica from Navarra* [40]																			
staves	24 m open air	0.6	ns	0.5	ns	3.8	1.2	1.4	1133	165	8.7	400	3.4	23	6.8	43	147	2.8	ns
	Accelerated	0.4	ns	0.6	ns	3.3	1.3	1.7	1536	249	16	567	7.5	87	12	31	115	1.9	ns
chips	24 m open air	0.4	ns	2.0	ns	3.3	1.2	1.2	118	22	26	122	11	44	4.1	79	123	3.4	ns
	Accelerated	0.4	ns	1.7	ns	4.8	1.1	1.5	201	29	28	115	5.4	25	4.6	83	129	3.3	ns
Heat treatment: 180 °C for 45 min																			
Alternative woods	24 m open air																		
Q. pyrenaica from Salamanca [23]		4.0	0.4	7.2	0.4	2.1	0.8	6.9	494	56	37	29	9.8	30	3.1	114	250	9.5	17
Robinia pseudoacacia [23]		5.4	0.6	1.5	0.6	2.4	12	21	840	94	20	113	nd	nd	-	77	272	11	45
Robinia pseudoacacia [65]		6.1	ni	1.7	ni	2.2	7.6	21	714	91	19	94	ni	ni	-	106	420	9.6	42
Castanea sativa [23]		5.1	0.8	6.9	0.6	2.1	2.0	13	1505	76	18	103	nd	nd	-	142	311	18	159
Castanea sativa [65]		5.3	ni	7.2	ni	2.3	2.0	14	1675	76	18	103	ni	ni	-	143	311	18	160
Prunus avium [23]		1.7	0.4	1.9	0.2	1.5	0.6	5.0	23	31	14	48	nd	nd	-	68.3	455	9.4	19
Prunus avium [65]		1.6	ni	1.9	ni	1.5	0.6	5.0	175	29	15	46	ni	ni	-	91.7	535	8.6	18
Fraxinus excelsior from Europe [23]		6.0	0.3	2.3	0.5	2.2	11	20	59	11	31	60	nd	nd	-	119	334	13	14
Fraxinus excelsior from Europe [65]		12	ni	3.4	ni	3.0	12	23	64	15	32	59	ni	ni	-	160	376	15	22
Fraxinus americana from American [23]		14	0.4	2.6	1.2	3.2	17	21	82	20	31	90	nd	nd	-	162	311	19	31
Fraxinus americana from American [65]		13	ni	2.6	ni	3.1	11	24	62	17	33	82	ni	ni	-	187	351	17	29
Traditional *Quercus* [23]																			
Q. Petraea		2.4	0.4	7.2	0.2	1.8	0.8	5.5	430	35	18	23	15	21	1.5	117	221	9.1	15
Q. Alba		4.9	0.4	5.9	0.2	1.3	1.3	9.7	395	38	21	21	3.4	32	9.5	102	226	9.0	113

Table 4. *Cont.*

Species	Seasoning Time (m: months)	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
		Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Heat treatment: 210 °C for 20 min																			
Alternative woods *Q. pyrenaica from Navarra* [40]																			
Staves	24 m open air	1.0	ns	1.5	ns	5.9	1.7	2.7	1415	185	16	275	8.7	92	11	55	184	4.8	ns
	Accelerated	1.6	ns	2.3	ns	5.6	3.8	6.5	2820	301	25	540	8.2	106	13	39	186	3.9	ns
Chips	24 m open air	1.0	ns	4.3	ns	1.9	1.2	3.7	161	30	38	91	9.8	40	4.1	177	373	13	ns
	Accelerated	1.2	ns	3.9	ns	3.6	1.8	4.6	345	49	41	118	4.9	21	4.3	125	338	9.1	ns
Heat treatment: 200 °C for 35 min																			
Alternative woods *Q. pyrenaica from Salamanca* [6]																			
staves	36 m natural seasoning	2.7	0.2	2.4	0.2	6.8	0.5	4.1	1636	193	20	182	8.3	32	3.9	40	79	2.2	ns
chips		3.8	0.4	6.9	0.3	2.1	0.2	6.8	458	54	37	29	9.9	32	3.2	113	229	8.9	ns
Traditional Quercus [6]																			
Q. petraea		2.3–2.5	0.3–0.4	3.8–7.2	0.13–0.16	0.8–2.3	0.2–0.7	5.1–5.7	437–963	36–148	19	22–100	0.0–13	0.1–23	1.8–5.0	53–113	102–213	3.6–8.8	ns
Q. alba		4.2–4.5	0.2–0.4	2.1–5.9	0.15–0.18	1.3–4.2	0.3–0.9	7.1–9.5	372–1539	38–237	17–21	21–122	3.3–6.3	21–32	3.3–9.7	42–99	86–229	2.3–8.4	ns
Heat treatment: 210 °C for 45 min																			
Alternative woods [7]																			
Q. humboldtii	semi-accelerated	3.7	ns	ns	0.7	3.3	7.2	10	534	45	ns	463	0.0	0.3	5.0	22	ns	ns	ns
Traditional Quercus [7]																			
Q. petraea	30 m natural seasoning	0.4–0.6	ns	ns	0.5	1.6–5.6	1.7–2.1	1.4–1.9	924–1150	23–28	ns	579–1192	2.1–20	13	0.7–6.2	23	ns	ns	ns
Q. alba		0.9	ns	ns	0.5	2.1	1.5	3.4	1363	17	ns	804	3.5	27	7.8	57	ns	ns	ns
Heat treatment: medium plus																			
Alternative woods *as staves and chips* [66]																			
Q. pyrenaica	24 m open air	2.6	0.3	2.6	1.4	6.1	1.1	11	1140	169	28	494	20	76	3.9	80	206	8.9	ns
Traditional Quercus *as staves and chips* [66]																			
French oak		2.3	0.4	3.6	0.6	1.7	0.3	8.1	301	38	16	54	6.1	6.1	1.0	145	731	9.3	ns
American oak		4.1	0.6	4.6	1.0	2.7	0.5	12.3	825	71	18	66	6.6	17	2.6	143	632	10	ns

Table 4. *Cont*.

Species	Seasoning Time (m: months)	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
		Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
Heat treatment: 250–260 °C for 27 min																			
Alternative woods Q. pyrenaica from Portugal [63]																			
Gerês forest	24 m natural seasoning	1.9	ns	1.7	ns	nd	0.9	ns	1635	173	ns	2977	7.2	9.6	1.3	34	69	ns	ns
Guarda forest		1.6	ns	0.8	ns	0.5	0.8	ns	2155	329	ns	2307	5.0	2.9	0.6	22	89	ns	ns
Traditional Quercus [63]																			
Q. petraea		1.7–2.6	ns	nd-0.6	ns	1.6–2.2	0.5–0.6	ns	118–613	244–250	ns	654–981	5.3–12	7.4–18	1.4	3.0–6.3	85–118	ns	ns
Q. alba		3.3–5.3	ns	2.8–4.6	ns	5.1–7.9	0.8	ns	353–788	167–363	ns	782–922	4.2–7.4	16–24	3.2–3.8	7.5–8.8	32–21	ns	ns
Heat treatment: heavy																			
Alternative woods as staves and chips [66]																			
Q. pyrenaica	24 m open air	3.1	0.4	3.0	0.8	4.4	0.6	9.8	1126	130	31	214	8.7	52	6.0	73	241	8.2	ns
Traditional Quercus as staves and chips [66]																			
French oak		1.7	0.4	3.5	0.7	0.9	0.1	11	170	25	16	44	4.4	7.6	1.7	262	721	15	ns
American oak		2.1	0.4	1.6	0.4	1.0	0.1	16	61	11	12	30	2.8	15	5.3	244	768	14	ns

Acronyms: 4-EG: 4-Ethylguaiacol; 4-MG: 4-Methylguaiacol; 4-VG: 4-Vinylguaiacol; *trans* WL: *trans* lactone (*trans*-β-Methyl-γ-octalactone); *cis* WL: *cis* lactone (*trans*-β-Methyl-γ-octalactone); ns: not studied; ni: not identified; nd: not detected.

Quercus humboldtii **Bonpl**

This wood seems to be of great interest in ageing, especially for rums. It has only been studied after toasting, so more studies would be necessary to know how drying and toasting really affect the volatile composition of this wood. The toasted wood of *Q. humboldtii* showed significant contents of 5-MF (386 μg/g), guaiacol (25.5 μg/g), 4-VG (13.6 μg/g), *cis* isoeugenol (34.3 μg/g) and syringol (58 μg/g), higher than those found in the wood of traditional species. Of these compounds, 4-VG showed the least difference between this wood and the traditional ones. However, 5-MF found in *Q. humboldtii* wood had twice the concentration found in traditional woods, *cis* isoeugenol and syringol three times and guaiacol four times. Therefore, the average volatile phenols content of this wood was higher than that of the traditional woods (Figure 1d; 377 μg/g versus 209 μg/g for *Q. petraea* and 291 μg/g for *Q. alba*). However, it is a wood poor in furfural, 5-HMF, *trans* and *cis* lactones. Due to the very low concentrations of lactones found in this wood, it could be said that this wood lacks the typical coconut aroma that can be transmitted to wines by these molecules (Figure 1d), especially since the *cis* isomer (0.3 μg/g) is 42 and 95 times lower than traditional woods (12.7–27.1 μg/g).

Robinia pseudoacacia **(Acacia)**

The volatile composition of acacia wood has been studied both when dried and toasted, for cooperage purposes and its use with alcoholic beverages, especially wines and vinegars. Flamini et al., 2007 [71] found the Italian seasoned wood interesting, especially for its content of benzoic aldehydes, such as hydroxybenzaldehyde, anisaldehyde, vanillin and syringaldehyde. The last two, known for their contribution with vanilla notes, were of the order of those found by other authors [23,65]. However, when comparing the concentrations of vanillin and syringaldehyde found in *Quercus* [23], it was found that the seasoned acacia wood had similar or even lower contents. Furthermore, Table 3 shows that seasoned acacia wood is poor in eugenol, furanic compounds, especially furfural, and phenyl ketones. Therefore, Figure 1 b shows how this wood stands out for its low content of furanic compounds and phenolic aldehydes/phenyl ketones next to cherry and the absence of lactones as all non-*Quercus* woods. After light toasting, this wood still shows low amounts of these compounds compared to *Quercus* woods (Table 3 and Figure 1c). However, after toasting at 180 °C for 45 min, it showed interesting contents of guaiacol, eugenol, isoeugenol, syringol, furanic compounds, especially furfural, syringaldehyde and acetovanillone (Table 3). Thus, Figure 1d shows that this wood has a higher content of volatile phenols than *Quercus*, 607 μg/g compared to 290–209 μg/g, of the order of the furanic compounds content of traditional woods (993 to about 1100 μg/g), and phenolic aldehydes/phenyl ketones higher than *Quercus* woods and of the order of non-*Quercus* woods.

In seasoned and toasted acacia wood, the compounds not found in *Quercus* were: catechol, 3-methylcatechol, cyclone, 3,4-dimethoxyphenol and 2,4-dihydroxybenzaldehyde [23]. The last two compounds were only found in acacia wood, presenting contents of 1.24–1.83 and 14.90–16.7 μg/g, respectively, in seasoned wood and 0.72–1.17 and 89.3–91.7 μg/g in toasted wood, so it could be said that they are characteristic of this wood [23,65]. In addition, resorcinol, a compound never detected in wood, was detected in acacia [65]. However, acacia wood both after seasoning and toasting does not possess certain volatile compounds found in *Quercus* [23] such as methyl benzoate, methyl homovanillate, methyl vanillate, methyl syringate, isobutyrovanillone, *trans* and *cis* lactones, these lactones being of special interest for providing aromatic notes of coconut to the wines. As in other non-*Quercus* wood (cherry, chestnut and ash), the contents of most of these compounds increased during toasting, as well as those of phenyl alcohols, while in *Quercus* wood they decreased or did not change [23]. However, other compounds decreased in concentration during toasting in acacia wood such as: 3,4-dimethoxyphenol, 3,4,4-trimethoxyphenol, acetic acid, hexanoic acid, hexadecanoic acid and 1-hexanal [23,65].

Castanea sativa (Chestnut)

This wood has been widely used for oenological purposes in the Mediterranean area in the past due to its wide availability and low cost. Moreover, it is the only non-*Quercus* species accepted for use by the OIV. This wood, after being seasoned, is distinguished by its phenolic aldehydes/phenyl ketones content (Figure 1b) and has the same or even higher contents of volatile phenols and furanic compounds than traditional woods. Like the other non-*Quercus* woods, they lack lactones. The compounds generally increase during toasting; the higher the toasting, the higher the content. These increases during toasting are very significant in acacia, chestnut and ash wood, especially in chestnut wood, which is the richest as a whole, in compounds derived from lignin, lipids and carbohydrates [23]. Chestnut wood showed higher contents than *Quercus* wood, especially when toasted at 180 °C for 45 min, in compounds such as volatile phenols (guaiacol, 4-VG, eugenol, isoeugenol and syringol), furanic compounds (furfural, 5-MF, 5-HMF, 5-acetoxymethyl-2-furfural, 1-methoxy-2-ethoxyethyl-1-furan) and phenolic aldehydes/phenyl ketones (vanillin, syringaldehyde, acetovanillone, butyrovanillone, propiovanillone, propiosyringone, butyrosyringone, isoacetovanillone, isopropiovanillone, isoacetosyringone, isopropiosyringone, methyl homovanillate and acetophenone) [23]. All this indicates that it is a very rich wood aromatically after toasting, especially after medium toasting (Figure 1c). This figure shows how this wood is more aromatic than traditional and other woods in furanic compounds and phenolic aldehydes/phenyl ketones, and the content of volatile phenols is higher than *Quercus*, but it is not the richest wood in these compounds. However, coconut notes would not be contributed or would play an insignificant role with these woods, since in their composition, according to some authors, neither of the two lactone isomers were found [23], and according to others, they were found in low concentrations (<0.7 μg/g) [65].

Prunus avium (Cherry)

The composition of cherry was studied after 24 months of seasoning and after light and medium toasting [23,65]. In cherry wood, p-anisaldehyde, p-anisylacetone, p-anisyl alcohol, 7,8-dihydro-3-oxo-α-ionol, 7,8-dihydro-4-oxo-β-ionol and benzyl salicylate, not found in any other woods, were found, so these compounds could be considered characteristic of cherry wood. Of these compounds, p-anisaldehyde and benzyl salicylate were the ones found in the highest concentrations. The p-anisaldehyde increased significantly during toasting from 0.18–0.33 μg/g in dry wood to 0.45 μg/g after light toasting to 4.36–4.41 μg/g after medium toasting, while benzyl salicylate decreased during this process from 4.46–7.67 μg/g in dry wood to 0.61–0.68 μg/g in wood after medium toasting. In seasoned cherry wood, the three most abundant compounds were 3,4,5-trimethoxyphenol, methyl syringate, and benzoic acid and in toasted wood they are syringaldehyde and sinapaldehyde.

Cherry wood after seasoning and toasting was the poorest in vanillin, followed by acacia, with almost less than half the concentration of *Quercus* wood. However, especially after medium toasting the syringaldehyde content of cherry wood was higher than that of traditional woods 455–535 μg/g compared to 221–226 μg/g, so the phenolic aldehydes/phenyl ketones content was high (Figure 1d). The furfural content in seasoned wood was very low and the increase during toasting was very small compared to that of the other woods, which makes toasted cherry wood very poor in this compound, and generally in furanic compounds (Figure 1b–d). In general, the volatile phenols presented in Tables 3 and 4 show a behaviour during toasting similar to *Quercus*, presenting contents similar to traditional woods, although the wood after medium toasting presents lower contents of guaiacol, 4-MG and syringol.

Fraxinus excelsior (European ash) and *Fraxinus americana* (American ash)

Ash wood did not show any unique volatile compounds, as all compounds present in ash wood were detected in at least one other wood, be it acacia, chestnut, cherry or *Quercus*. However, quantitative differences can clearly be used to identify toasted

ash wood, with tyrosol being the most interesting, since, although in seasoned wood it is found in this wood and in oak wood, after toasting it was only found in ash wood and in high concentrations, 24.6 and 26.4 μg/g in the European and American species, respectively. Furthermore, this wood is quantitatively different and with higher contents in certain volatile compounds than all the woods compared (acacia, cherry, acacia, *Q. pyrenaica*, *Q. petraea* and *Q. alba*), especially after toasting, including: catechol, 3-methylcatechol, homovanillyl alcohol, coniferaldehyde, 2-phenoxyethanol, 1-hydroxy-2-butanone, 1-acetyloxy-2-butanone, γ-butyrolactone, solerone, 3,5-dimethylcyclotene, 4,5-dimethyl-2-cyclohexen-1-one, 2-furanmethanol, 3-ethylcyclotene, α-methylcrotonolactone, solerone and 3-hydroxybenzaldehyde. Focusing on volatile compounds sought after by consumers, it was observed that ash wood also had high contents of guaiacol, isoeugenol, syringol and maltol, as well as vanillin, syringaldehyde and acetovanillone, when subjected to medium toasting (Table 4). Therefore, after light and medium toasting it is a wood with more volatile phenols (Figure 1c,d) and after medium toasting more phenolic aldehydes/phenyl ketones than *Quercus* (Figure 1d). However, the wood is rather low in furfural (Table 4) with very low contents of furanic compounds after all cooperage treatments (Figure 1b–d). There are compounds that are not detected in ash wood but are in traditional woods, such as *trans* and *cis* lactones, which are of great interest. American toasted ash wood appears to be more aromatic than European ash wood in most of the compounds [23,65], as well as in the compounds represented in Table 4.

Morus alba (mulberry)

The volatile composition of this wood has been little studied, and no studies were found that focused on its toasting, a very important process in the formation of aromas. After seasoning, mulberry wood seemed to be the poorest in volatile benzene compounds, and certain compounds of great aromatic interest, such as eugenol, methoxyeugenol, vinylguaiacol and syringol, were not detected [71]. The concentrations of vanillin and syringaldehyde found were very low; however, it presented important extraction percentages, especially of vanillin, which differed considerably from those of oak wood, probably due to the different porosity of the wood [71].

3. Influence of Ageing with Alternative Woods on the Volatile Composition of Wine: Comparison with Traditional Oak Woods

In this section, we have compiled the existing data from the scientific literature on the effects of the use of different types of wood, traditional and alternative, on the volatile composition of wines. Data are included both from studies carried out with barrels (Table 5) and those carried out with chips and staves (Table 6).

3.1. Ageing in Barrels with Traditional and Alternative Woods

The compiled bibliography studies the ageing of wines from 4 months (short ageing) to 21 months (long ageing) in alternative barrels and compares them with traditional barrels. The most common wine ageing was with medium-long wood contact time (between 9 and 21 months) (Table 5). It is expected that, as the ageing time increases, the variety and the content of volatile compounds in the wine increase. However, this will also depend on the factors mentioned above (degree of toasting, toasting temperature, type of wine, etc.).

Table 5. Volatile compounds in wines after ageing in barrels from woods of different botanical origins expressed as µg/L.

Heat Treatment	Time (months)	Wine	Species	Volatile Phenols							Furanic Compounds				Lactones			Vanillin	Phenolic Aldehydes/ Phenyl Ketones		
				Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio		Syringaldehyde	Acetovanillone	Butyrovanillone
100 °C for 60 min	4	White [72]	*Alternative woods*																		
			Robinia pseudoacacia	0.8	0.7	0.3	3.0	0.6	ns	1.5	9.2	0.1	ns	0.8	ns	ns	ns	1.2	1.0	35	ns
nontoasted	6	Red [73]	*Castanea sativa*	35	134	24.5	41	139	63	285	9.7	64	2.4	3.3	ns	ns	ns	157	108	136	57
160–170 °C for 45–50 min	6	Red [73]	*Castanea sativa*	35	124	30	40	162	92	242	15.7	184	3.3	6.2	ns	ns	ns	241	253	155	58
°C offire for 40 min	9	Red [63,74]	*Alternative woods*																		
			Robinia pseudoacacia	ns	3250	ns	ns	21	ns	ns	30	30	ns	ns	ns	ns	ns	310	ns	ns	ns
			Castanea sativa	ns	1840	ns	ns	26	ns	ns	70	40	ns	ns	ns	ns	ns	430	ns	ns	ns
			Prunus avium	ns	2790	ns	ns	7	ns	ns	nd	nd	ns	ns	ns	ns	ns	120	ns	ns	ns
			Morus alba	ns	1840	ns	ns	6	ns	ns	nq	nq	ns	ns	ns	ns	ns	80	ns	ns	ns
			Traditional Quercus																		
			Q. petraea	ns	2900	ns	ns	18	ns	ns	600	320	ns	ns	ns	ns	ns	360	ns	ns	ns
165 °C for 35 min	12	Red [29]	*Alternative woods*																		
			Q. pyrenaica	31–76	5.3–45	17–37	93–315	81–116	42–111	241–736	134–3575	94–2477	111–282	757–3533	184–231	718–1096	3.9–5.1	342–574	553–1748	121–223	897–1164
			Traditional Quercus																		
			Q. petraea	25–40	5.6–105	17–48	68–409	23–44	27–120	194–631	110–1543	51–869	92–163	986–1611	125–735	396–1174	1.6–3.2	357–854	735–2244	102–309	417–981
			Q. alba	27–55	5.0–77	16–66	109–269	50–63	30–82	185–724	187–5256	42–1543	159–197	713–2723	141–236	992–1313	5.6–7.0	437–806	1378–2274	128–286	488–995
185 °C for 45 min	12	Red [75]	*Alternative woods*																		
			Robinia pseudoacacia	60	20	14	26	19	54	217	238	450	300	248	nd	nd		233	768	61	105
			Castanea sativa	59	49	52	24	118	36	153	509	241	125	689	21	31	1.5	456	1189	92	226
			Prunus avium	43	73	25	23	11	19	169	101	32	133	145	nd	nd	nd	304	1877	75	132
			Fraxinus excelsior	75	92	35	31	13	37	198	66	58	354	339	nd	nd	nd	696	1090	111	150
			Traditional Quercus																		
			Q. petraea	44	24	32	21	101	53	178	40	842	142	703	99	577		408	1305	62	193

Table 5. *Cont.*

Heat Treatment	Time (months)	Wine	Species	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
							Volatile Phenols					**Furanic Compounds**				**Lactones**				**Phenolic Aldehydes/ Phenyl Ketones**		
Medium	12	White [76]	*Alternative woods* *Robinia pseudoacacia* from Medjimurje	31	2.6	ns	ns	8.0	33	ns	1236	251	ns	ns	0.3	0.5		0.03	0.3	ns	ns
			from Istria	2.7	0.7	ns	ns	2.5	8.6	ns	83	4.3	ns	ns	0.2	0.4		0.02	0.3	ns	ns
			Traditional Quercus *Q. petraea*	4.9–9.2	0.6–1.3	ns	ns	4.4–6.6	3.6–7.9	ns	740–1796	93–173	ns	ns	0.5–39	11–43		0.02–0.05	0.1	ns	ns
Medium	21	Red [77,78]	*Alternative woods* *Q. pyrenaica*	20	ns	ns	ns	42	ns	ns	49	15	78	49	67	229	3.4	78	75	ns	ns
			Q. faginea	22	ns	ns	ns	41	ns	ns	44	13	72	26	103	352	3.4	74	64	ns	ns
			Traditional Quercus *Q. petraea*	24–27	ns	ns	ns	35–48	ns	ns	90–93	26–28	118–135	49–75	28–150	66–347	2.3–2.4	80–91	135–150	ns	ns
			Q. robur	23–28	ns	ns	ns	37–54	ns	ns	60–67	13–26	98–117	20–56	101–185	331–407	1.8–4.1	59–84	72–136	ns	ns
			Q. alba	43	ns	ns	ns	89	ns	ns	124	96	172	85		788	8.8	145	168	ns	ns

Barrel volume = 225 L. Acronyms: 4-EG: 4-Ethylguaiacol; 4-MG: 4-Methylguaiacol; 4-VG: 4-Vinylguaiacol; *trans* WL: *trans* lactone (*trans*-β-Methyl-γ-octalactone); *cis* WL: *cis* lactone (*trans*-β-Methyl-γ-octalactone); ns: not studied; nd: not detected.

Table 6. Volatile compounds in wines after alternative ageing with woods of different botanical origin expressed as µg/L.

Heat Treatment	Dosage	Contact Time Days	Wine Type	Species	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	trans WL	cis WL	cis/trans Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
												Volatile Phenols				Furanic Compounds			Lactones			Phenolic Aldehydes/Phenyl Ketones	
Chips																						
				Alternative woods																		
	1 g/L			*Robinia pseudoacacia*	ns	ns	ns	1295	2	ns	ns	1746	329	ns	ns	nq	3	nq	2	nq	ns	ns
	1.5 g/L			*Robinia pseudoacacia*	ns	ns	ns	1734	3	ns	ns	2233	413	ns	ns	nq	20	nq	16	72	ns	ns
	1 g/L			*Prunus avium*	ns	ns	ns	1485	2	ns	ns	1350	281	ns	ns	nq	1	nq	39	74	ns	ns
	1.5 g/L			*Prunus avium*	ns	ns	ns	1704	3	ns	ns	1557	400	ns	ns	nq	7	nq	39	117	ns	ns
Medium		20	Rosé [79]	*Traditional Quercus*																		
	1 g/L			*Q. petraea*	ns	ns	ns	1484	4	ns	ns	2403	1435	ns	ns	nq	13	nq	392	572	ns	ns
	1.5 g/L			*Q. petraea*	ns	ns	ns	1819	5	ns	ns	1722	1439	ns	ns	13	29	2.23	722	860	ns	ns
	1 g/L			*Q. alba*	ns	ns	ns	1347	4	ns	ns	1788	1265	ns	ns	nq	49	nq	309	489	ns	ns
	1.5 g/L			*Q. alba*	ns	ns	ns	1914	5	ns	ns	2715	1919	ns	ns	nq	70	nq	748	1110	ns	ns
Nontoasted	7 g/L	25	Red [80]	*Alternative woods*																		
				Castanea sativa	116	nd	nd	115	44	18	655	4.4	nd	nd	nd	ns	ns	ns	41	37	66	53
100 °C for 60 min	4 g/L	30	White [72]	*Robinia pseudoacacia*	0.8	0.9	0.5	27	0.6	ns	1.3	8.7	0.2	ns	4.9	ns	ns	ns	3	2.1	34	ns
				Alternative woods																		
				Q. pyrenaica	12	0.2	ns	6.7	8	3.6	15	1660	464	ns	ns	124	92	0.7	246	694	42	ns
				Q. pyrenaica	12	0.4	ns	8.4	8.2	4.2	16	2722	758	ns	ns	13	31	2.38	364	959	48	ns
Medium	4 g/L	60	Red [31]	*Traditional Quercus*																		
				Q. petraea	18	0.3	ns	9.1	33	7.4	21	1848	1005	ns	ns	37	86	2.3	220	505	41	ns
				Q. petraea+ Q. robur	12	0.5	ns	7.7	9.4	5.9	16	168	169	ns	ns	30	66	2.2	774	1449	56	ns
				Q. alba	18	0.9	ns	10	14	9.8	38	90	179	ns	ns	27	188	7.0	988	2541	82	ns

Table 6. *Cont.*

Heat Treatment	Dosage	Contact Time Days	Wine Type	Species	Volatile Phenols							Furanic Compounds				Lactones			Phenolic Aldehydes/Phenyl Ketones			
					Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
210 °C for 45 min	3 g/L	90	Red [7]	*Alternative woods* *Q. humboldtii*	26	ns	ns	14	14	34	58	511	386	ns	319	8.3	8.3	1.0	62	ns	ns	ns
				Traditional Quercus *Q. alba*	3.9	ns	ns	13	7.6	6.9	8.7	1422	181	ns	702	33	3267	9.9	149	ns	ns	ns
				Q. petraea	3.3–3.8	ns	ns	12–13	4–16	6	10	1485–2192	190–260	ns	693–958	43–99	43–99		256–360	ns	ns	ns
190 °C for 10 min	225 L barrel surface	120	Red [40]	*Alternative woods* *Q. pyrenaica* traditional seasoning	6.9	0.2	5.1	7.9	24	8.6	29	61	66	87	683	74	363	4.9	120	61	ns	ns
				accelerated seasoning	6.1	0.3	3.9	6.3	42	8.7	28	134	74	84	351	55	180	3.3	83	76	ns	ns
200 °C for 15 min				traditional seasoning	8.2	0.4	10	5.9	19	11	35	120	100	178	659	80	396	5.0	293	203	ns	ns
				accelerated seasoning	7.7	0.5	10	6.5	34	17	35	337	181	205	692	56	189	3.4	228	186	ns	ns
210 °C for 20 min				traditional seasoning	11	0.9	20	7.1	13	15	56	148	143	273	468	85	413	4.9	706	794	ns	ns
				accelerated seasoning	13	1.2	22	6.6	23	27	68	240	252	338	727	55	223	4.1	530	811	ns	ns
200 °C for 35 min	225 L barrel surface	180	Red [6]	*Alternative woods* *Q. pyrenaica*	22	3.3	38	53	22	55	181	437	104	232	182	87	351	4.0	819	2393	ns	ns
				Traditional Quercus *Q. alba*	27	2.8	38	36	20	44	201	374	89	149	173	67	229	3.4	797	2533	ns	ns
				Q. petraea	22	2.9	45	45	17	46	156	715	145	144	240	122	289	2.4	811	2530	ns	ns

Table 6. *Cont.*

Heat Treatment	Dosage	Contact Time Days	Wine Type	Species	Guaiacol	4-EG	4-MG	4-VG	Eugenol	Isoeugenol	Syringol	Furfural	5-MF	Maltol	5-HMF	*trans* WL	*cis* WL	*cis/trans* Ratio	Vanillin	Syringaldehyde	Acetovanillone	Butyrovanillone
				Volatile Phenols								**Furanic Compounds**				**Lactones**			**Phenolic Aldehydes/Phenyl Ketones**			
Staves																						
				Alternative woods																		
				Q. pyrenaica																		
190 °C for 10 min	225 L barrel surface	120	Red [40]	traditional seasoning	16	76	13	15	51	31	92	48	146	127	2491	73	662	9.1	225	523	ns	ns
				accelerated seasoning	19	13	16	14	75	33	68	98	207	136	3982	109	1442	13	188	432	ns	ns
200 °C for 15 min				traditional seasoning	24	45	22	13	45	27	78	136	622	250	4296	84	703	8.3	415	965	ns	ns
				accelerated seasoning	33	1.6	29	24	76	41	153	13667	2135	323	7822	140	2342	17	326	918	ns	ns
210 °C for 20 min				traditional seasoning	33	31	33	16	38	38	146	232	473	446	4224	90	314	3.5	584	1456	ns	ns
				accelerated seasoning	42	1.9	36	11	68	45	150	990	993	452	6177	215	2445	11	504	1234	ns	ns
200 °C for 35 min	225 L barrel surface	180	Red [6]	*Alternative woods* *Q. pyrenaica*	43.4	2.84	41	54	54	72	192	14262	2163	377	2485	99	588	5.9	740	1912	ns	ns
				Traditional Quercus																		
				Q. alba	44.3	2.68	34	31	36	71	184	13582	1802	305	1602	64	466	7.24	613	1716	ns	ns
				Q. petraea	36.5	3.39	55	40	29	64	184	8981	2063	372	1846	12	26	2.11	938	2304	ns	ns

Dosage: 225l barrel surface= The amount of oak chips and staves required to reproduce the surface/volume ratio of a barrel of 225 L Acronyms: 4-EG: 4-Ethylguaiacol; 4-MG: 4-Methylguaiacol; 4-VG: 4-Vinylguaiacol; *trans* WL: *trans* lactone (*trans*-β-Methyl-γ-octalactone); *cis* WL: *cis* lactone (*trans*-β-Methyl-γ-octalactone); ns: not studied; nd: not detected; nq: not quantified.

De Rosso et al., 2009 [74] studied the volatile composition of red wines aged in barrels of different alternative woods (acacia, chestnut, cherry and mulberry) and *Q. petraea* for 9 months and observed significant differences in some of the compounds. In the case of volatile phenols, it was found that the wines aged in acacia barrels had a higher content of 4-EG (3250 µg/L), which contributes phenolic, smoky and leathery notes, than the rest of the wines aged in the other barrels. Wines aged in acacia and chestnut barrels were characterised by a higher eugenol content (21 µg/L and 26 µg/L, respectively), which contributes clove, honey, spicy and cinnamon aromas, compared to wines aged in *Q. petraea* barrels (18 µg/L). These results are consistent with the analysis of toasted wood, where it was observed that chestnut and acacia wood had higher contents of this compound than *Q. petraea*. However, wines aged in *Q. petraea* barrels were characterised by a higher content of certain compounds, such as furfural and 5-MF. In contrast, the use of chestnut barrels contributed more vanilla to the wines than *Q. petraea* barrels. In addition, they observed that wines aged in mulberry barrels showed a significant decrease in fruity notes such as ethyl esters and other compounds, and yielded compounds considered aroma defects such as ethylphenol to the wine. In this study, they concluded that the wines studied could be differentiated quantitatively and qualitatively [74]. Thus, wines aged in *Q. petraea* barrels carried aromas of caramel and toasted almonds and wines aged in acacia and chestnut barrels gave more woody and spicy aromas, such as clove, smoke and vanilla. Therefore, it can be said that the aromas mostly found in the wines were the same as in the wood.

The number of literature references found was more abundant for 12-month ageing [29,75,76]. Kozlovic et al., 2010 [76] evaluated the aromatic composition of white wines aged in acacia barrels from two different geographical areas (Medjimurjey and Istria) against wines aged in *Q. petraea* barrels. The results showed a significant increase after 12 months in the content of furfural, 5-MF, guaiacol, eugenol and *trans* isoeugenol in all Malvasia white wines aged in acacia and oak barrels. After 12 months of ageing, clear differences were observed between the wines aged with these two types of wood. Thus, it was found that wines aged in acacia wood barrels were characterised by significantly higher guaiacol amounts than wines aged in *Q. petraea* barrels. In addition, other volatile phenols such as o-cresol, p-cresol and m-cresol, not found in wines aged in *Q. petraea* barrels, were also found in wines aged in acacia wood. On the other hand, the wines aged in *Q. petraea* barrels had more lactones. From the sensory analysis they were able to extract that the wines aged in acacia barrels were the best scoring wines.

In general, wines aged in *Q. pyrenaica* barrels were characterised by high levels of eugenol, guaiacol and other volatile phenols [29]. Regarding compounds such as *cis* lactone or maltol, the behaviour of *Q. pyrenaica* wood was very similar to that of *Q. alba*. As for phenolic aldehydes and ketones, the levels of *Q. pyrenaica* wines were intermediate between those aged in *Q. petraea* and *Q. alba*, with few significant differences. Another 2014 study by this group [75], very similar to that of De Rosso et al., 2009 [74], but after 12 months of ageing, evaluated wines aged in *Q. petraea*, acacia, chestnut, cherry and ash barrels. They found that phenolic aldehydes in wines aged in ash barrels, as in the studies on wood chips, had higher vanillin content than wines aged in the other barrels. Similarly, wines aged in ash barrels, together with those aged in chestnut barrels, were the richest in acetovanillone. Therefore, these wines were characterised by a higher content of volatile compounds that can provide vanilla aromas. Wines aged in chestnut barrels were also richer in butyrovanillone, and those aged in cherry were richer in syringaldehyde. As far as lactones are concerned, the results obtained in wines were similar to those found in the works discussed above, with wines aged with *Q. petraea* having the highest lactone content, as expected from the results observed in wood. In terms of furanic compounds, the chestnut barrels were the ones that contributed the most furfural (Table 5), as well as high 5-HMF contents in this compound similar to the *Q. petraea* barrels. In contrast, acacia and *Q. petraea* barrels contributed higher 5-MF contents, although much higher in the traditional barrels, 450 and 842 µg/L, respectively. Finally, the wines aged in ash and acacia barrels had more than twice the maltol content, around 300 µg/L, than the other

wines. Furthermore, from the sensory analysis, it was observed that the wines aged in cherry barrels for more than 6 months were the ones with the worst scores, so this wood was more suitable for short ageing times [75].

There are also studies of the aromatic compounds of red wines aged in *Q. pyrenaica* and *Q. faginea* barrels compared to traditional barrels for 21 months, showing that in general, the wines aged in *Q. alba* barrels had higher aroma content than the rest of the wines aged in *Q. pyrenaica*, *Q. faginea*, *Q. robur* and *Q. petraea* barrels [77,78]. Therefore, for longer ageing, it seems that American oak barrels are more optimal, if a higher contribution of spicy aromas (due to guaiacol and eugenol), toasted nuts and caramel (due to furanic compounds), coconut and wood aromas (*cis* lactone) and vanilla aromas (vanillin and syringaldehyde) is sought. The *Q. pyrenaica* and *Q. faginea* woods were chemically similar to each other and to the traditional woods. However, from a sensory point of view, the wines aged in *Q. faginea* barrels were the worst evaluated and therefore seem to lack cooperage interest.

3.2. Aging of Wines with Chips and Staves from Traditional and Alternative Woods

The use of chips and staves to accelerate the ageing processes of wines, through a faster release of wood compounds, is a technique that has been widely used for years. As with barrels, the use of oak chips and staves, as well as other alternative woods, was studied in different studies with the aim of identifying those compounds that allow wines to be differentiated according to the volatile compounds and their concentration released by each type of wood. Fernández de Simón et al., 2010 [40] observed that wines aged in contact with staves provided a higher concentration of volatile compounds than wines aged with chips, although the release of the compounds from the wood into the wine was slower in the case of staves. This study was carried out on *Q. pyrenaica* wood, and the greatest differences were observed in *trans* isoeugenol, guaiacol, *cis* and *trans* lactones, eugenol, syringol, vanillin and maltol. Another study carried out by Santos et al., 2019 [79], in which chips from *Q. petraea* and *Q. alba* oak wood and alternative acacia and cherry woods were added, showed differences in the volatile composition of the different wines after 20 days in contact with the chips. The greatest differences were seen in the phenolic aldehyde group, where the wines to which oak chips were added had higher vanillin and syringaldehyde contents than the wines to which alternative wood chips were added. Differences were also seen in other compounds, although minor, such as *cis* lactone, furfural and 5-methylfurfural.

Rodríguez-Bencomo et al., 2009 [31] evaluated the volatile composition of red wines aged for 2 months with chips of *Q. pyrenaica*, *Q. petraea*, *Q. petraea* and *Q. robur* and *Q. alba*. These authors observed that wines aged with *Q. pyrenaica* had a higher content of furanic compounds (furfural and 5-methylfurfural) and eugenol than wines aged with traditional oak chips. In contrast, wines aged with *Q. alba* chips differed from the rest by having higher *cis* lactone, vanillin and syringaldehyde content. Fernández de Simón et al., 2010 [6] also studied the effect of using *Q. pyrenaica*, *Q. alba* and *Q. petraea* chips but aged for 6 months on the volatile composition of red wines. The results obtained showed that the volatile composition was very similar in the three types of wines, with only small differences in the content of *cis* lactone and eugenol, the content of both compounds being higher in the wines with *Q. pyrenaica* than those macerated with *Q. alba* and *Q. petraea*. These authors carried out the same study with staves, where the differences in *cis* lactone and eugenol content were greater than in the chips.

Q. humboldtii wood in contact with wine was studied after 3 months with chips in red wines and compared with *Q. petraea* and *Q. alba* chips [7], showing that the aromas of wines aged with this alternative wood differed quantitatively from those aged with traditional woods. Wines macerated with *Q. humboldtii* were found to have higher contents of 5-MF, guaiacol, isoeugenol and syringol. In contrast, these wines were lower in 5-HMF, *cis* and *trans* lactone and vanillin than wines macerated with *Q. alba* and *Q. petraea* oak. These differences in the chemical analysis were also observed in the sensory analysis, where it

was found that the wines macerated with Colombian oak were characterised by woody and smoky aromas compared to the other wines.

4. Conclusions

The volatile composition of *Quercus* alternative woods compared to traditional oak species only differs quantitatively, as the same compounds have been found. The volatile composition concentration of *Q. pyrenaica* varies widely depending on cooperage treatments, origin and other factors. The volatile composition of *Q. pyrenaica* wood can be considered similar to traditional oak species used in winemaking and is probably very interesting for its contribution of coconut, spice, clove, caramel to almond and clove notes due to its higher content of *cis* lactone, eugenol, 4-VG and furanic compounds. These results have also been confirmed in studies carried out on wines aged in barrels and with pieces of wood with *Q. pyrenaica*. The volatile composition of *Q. faginea* wood and of the wines aged seems to be qualitatively and quantitative similar to that of the traditional oak species. However, the wines aged with *Q. faginea* were the worst evaluated from a sensory point of view, so that wood seems to be of no interest for wine aging. *Q. humboldtii* wood seems to be an interesting wood due to its high contents of 5-MF, guaiacol, 4-VG, *cis* isoeugenol and syringol, but poor in furfural, 5-HMF, *cis* and *trans* lactones. Wines aged with this wood corroborated the results of the wood.

Acacia, chestnut, cherry and ash show differences not only quantitatively but also qualitatively, presenting compounds that are not found in *Quercus* woods and not having in their composition compounds as important as *cis* and *trans* lactones. All these woods except ash show some compounds that are not found in any other woods. Toasting causes an increase in the concentrations of most of the volatile compounds, and this increase is especially important in acacia, chestnut and ash woods. Thus, toasted acacia wood shows high contents of guaiacol, eugenol, isoeugenol, syringol, furanic compounds, syringaldehyde and acetovanillone. Chestnut wood after medium toasting is rich in volatile phenols, furanic compounds and phenolic aldehydes/phenyl ketones. In addition, ash wood after medium toasting has high contents of guaiacol, isoeugenol, syringol, maltol, vanillin, syringaldehyde and acetovanillone; however, it is rather low in furfural. American ash appears to be more aromatic than European ash. Acacia, chestnut, cherry and ash woods after medium toasting have higher lignin derivatives than *Quercus* wood. In addition, acacia and chestnut woods are also richer in lipid and carbohydrate derivatives than traditional oaks woods, while cherry and ash woods are relatively poor in these compounds. In the case of wines, those made from acacia and chestnut wood are richer in eugenol. In addition, those made from chestnut wood also stand out for their high vanillin content and those made from acacia wood for their higher 4-EG content. On the other hand, wines aged in ash wood are characterised by being richer in vanillin and acetovanillone. Mulberry wood does not seem to be of great interest for the aging of wines, since it decreases the fruity notes and increases the compounds that contribute negative notes.

Author Contributions: Conceptualization, A.M.M.-G. and M.d.A.-S.; formal analysis, A.M.M.-G., M.d.A.-S., I.N. and R.d.B.-G.; investigation, A.M.M.-G., M.d.A.-S., I.N. and R.d.B.-G.; writing—original draft preparation, A.M.M.-G.; writing—review and editing, A.M.M.-G., M.d.A.-S., I.N. and R.d.B.-G.; supervision, M.d.A.-S. and I.N.; project administration, M.d.A.-S. and I.N.; funding acquisition, M.d.A.-S. and I.N. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: For data request, the contact of the corresponding author is present in the affiliation part of each referenced manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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