applied sciences

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Review

The Application of Wood Species in Enology: Chemical Wood Composition and Effect on Wine Quality

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Abstract: Aging wine is a usual practice in winemaking, as the wine quality improves due to the compounds extracted from wood barrels or chips, cubes, blocks, or staves used. The wood species used are traditionally oak, namely from *Quercus petraea*, *Q. alba*, or *Q. robur* species. In the last years, the increasing request for oak wood has caused a significant increase in environmental and production costs. Therefore, heartwood from several alternative species has been considered a potential wood source for winemaking and aging. Thus, the main purpose of this review is the application of these alternative wood species on wine production and to discuss the advantages and disadvantages of its use compared with the traditional wood species, namely oak wood. In addition, a brief chemical characterization of several wood species with possible application in enology is also discussed in this review.

Keywords: wood species; oak; wine; aging; volatile compounds; phenolic compounds; sensory characteristics

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Citation: Jordão, A.M.; Cosme, F. The Application of Wood Species in Enology: Chemical Wood Composition and Effect on Wine Quality. *Appl. Sci.* **2022**, *12*, 3179. https://doi.org/10.3390/app12063179

Academic Editor: Ana María Martínez Gil

Received: 17 January 2022
Accepted: 16 March 2022
Published: 21 March 2022

1. Introduction

Over the centuries, numerous wood species were used to manufacture wood barrels with mahogany, chestnut, pine, and false acacia wood as the most used species [1]. Nevertheless, oak has been one of the key wood species for this purpose, as it has diverse characteristics, which differentiate it from the other wood species, such as flexibility, ease to handle, resistance, and it has low permeability [2]. However, it is essential to remind that in the mid-twentieth century, there was a strong rejection of wood for enological purposes due to the incremented application of materials like concrete and stainless steel. From the 1990s onwards, the application of wood for cooperages, mainly from diverse oak wood species, reemerged rather significantly and became one of the main choices, for example, in aging wine [3,4].

The most oak wood species employed by cooperages are *Quercus alba*, *Q. garryana*, *Q. macrocarpa*, and *Q. stellate* in the U.S.A., while other different oak species, specifically *Quercus petraea* and *Q. robur*, but also other oak species, such as *Quercus cerris*, *Q. suber*, *Q. lyrata*, *Q. bicolor* and *Q. lanuginose* are used in Europe [5,6]. However, are *Quercus alba*, *Q. petraea*, and *Q. robur*, the key oak species employed in the wine sector. Currently, several studies also described the application of other European and non-European oak species with remarkable use in winemaking, such as *Quercus faginea* [7,8], *Q. pubescens* [9,10], *Q. pyrenaica* [11–20], and also *Q. humboldtii* from Colombia [21,22].

Actually, chestnut and oak wood species are permitted only by the Resolution OENO 4/2005 of Organization of Vine and Wine for enological use [23]. Nevertheless, in recent years, heartwood from other species has been considered for winemaking, especially for the aging process, such as false acacia, cherry, European and American ash, and mulberry.

Additionally, scarce studies described the possible application of other wood species in enology like *Juglans regia* [24].

The main purpose of the wood barrels in enology is to enhance the wine with compounds extracted from the wood (such as phenolic compounds), stimulate reactions between wine and wood compounds, allow the air diffusion through the wood barrels' pores, and improve chemical reactions that happen gradually in wines and therefore increase wine's quality [25,26]. Thus, in the last decades, the scientific literature contains a considerable quantity of study associated with the employment of oak wood barrels in enology, mainly its effect on wine chemical and sensory characteristics. The majority of research has focused on red wine, the use of oak barrels [15,16,20,27–31], or the application of oak fragments, like chips, staves, blocks, or powders [10,14,28,31–35]. Moreover, for rosé wines, a few recent works report results about using diverse wood species, comprising oak, false acacia, and cherry [36,37]. Finally, for white wines, there are also several works published concerning the application of diverse wood species, especially from oak and false acacia [38–45].

A comparative analysis between oak and non-oak wood species on wine chemical composition and sensory characteristics was the key objective of this review work. The chemical composition of diverse wood species with potential application in enology and the main factors determining their composition were also addressed. The review will be particularly useful for wine producers and winemakers, and all those who study this subject, as it shows a large amount of data on the use of different woods in enology, summarizing much of the information that has been published in the last twenty years.

2. Chemical Composition of Wood Species

A high quantity of studies has been published concerning oak wood chemical composition. The extractable wood compounds, ellagitannins, ellagic acid, gallic acid, several aldehydes, and aromatic compounds are the key compounds with interest for wine production and the aging process. According to several works [46–49], volatile phenols and benzoic aldehydes play a very important role in the wines sensory profile. Other authors [48–51] describe hydrolysable tannins as having particular importance as they give astringency, as well as being involved in the stabilization of wine compounds and demonstrating important antioxidant properties. According to Vivas and Glories [52,53], ellagitannins have a significant role in the wine oxidation processes because they quickly absorb dissolved oxygen and facilitate the hydroperoxidation of wine compounds. In addition, they also demonstrate an essential role in the proanthocyanidin and anthocyanins condensation rate, avoiding their degradation and precipitation.

For oak wood species studied with enological use, in general, the content of these extractives compounds is influenced by several factors, namely, the forest origin [11,13,54–56], species [11,13,54,56–58], heartwood age [59,60], and most importantly, heat treatment which happens in cooperage during barrel and wood fragment production [11–13,58,60,61]. Several works [13,53,57,58,61–63] also describe that European and American species contain dissimilar levels of ellagitannin, with lower levels for American oak (*Q. alba*) compared to European species (*Q. robur*, *Q. petraea*, and *Q. pyrenaica*).

Table 1 shows examples of several individual phenolic compounds detected in untoasted and toasted wood species (oak, cherry, and false acacia). Generally, the ranges for the most individual phenolic compounds, especially for ellagitannins in the same oak species, are broad due to factors such as the toasting process that occurs in cooperage and also variability within the species. According to several authors, false acacia and cherry do not contain ellagitannins in their composition [64–68].

Alañón et al. [69] detected in *Castanea sativa* Mill (chestnut) a very low quantity of the two main ellagitannins, vescalagin and castalagin. The outcomes also show that its heartwood has the greatest comparable polyphenolic profile to oak wood. Nevertheless, there were also some dissimilarities. Thus, in agreement to Comandini et al. [70], 1-*O*-galloyl castalagin, which was for the first time detected in chestnut wood samples, might originate from the esterification of castalagin or vescalagin with a gallic acid residue. For Vivas et al. [53], *Q. frainetto* is distinguished particularly from the other species by its greater concentration of pentosylated dimers and a monomer level that is similar to the rest of the *Quercus* species, which makes it the species designated with the high concentration in ellagitannins. Ellagic acid could also be detected in diverse wood species, including oak, cherry, false acacia, and chestnut [68,71].

According to several authors [65,67,72], cherry wood is characterized by a richness of procyanidins and (+)-catechin. This species also contains some phenolic acids and their esterification products (*p*-hydroxybenzoic acid, *p*-coumaric acid, benzoic acid, methylsyringate, 3,4,5-trimethylphenol, and methylvanillate), and flavonoids (naringenin, isosakuranetin, aromadendrin, and taxifolin). Jordão et al. [68] detected low values of naringenin for cherry woods. However, Chatonnet [73] also reported the existence of an extremely low content of procyanidins in oak woods.

Fernández de Simón et al. [74] showed that the false acacia heartwood enclosed a greater quantity of flavonoids, namely, robinetin and dihydrorobinetin at values up to 100 µmol/g. These compounds are specific markers of false acacia wood as they have not been found in other woods used for cooperage, such as oak, chestnut, cherry, and mulberry. On the other hand, Jordão et al. [68] detected several compounds characteristic of false acacia wood, like fustin, robinetin, and butin, that were not found in the cherry and oak woods. Other researchers described only a few procyanidins and no hydrolysable tannins [65,66,74]. Other wood species with very limited enological applications, such as ash wood, the occurrence of phenylethanoid glycosides, secoiridoids, or di- and oligolignols could be a good identifier for the application of this wood species. [65,66]. Lastly, for mulberry wood, mainly for the two species that have been studied by Kozlovi et al. [75], high antioxidant activity and polyphenolic concentration were achieved in wood extracts from *Morus nigra* L. and *Morus alba* L. in contrast with the phenolic concentration achieved for extracts of *Robinia pseudoacacia* L and. *Quercus robur.*

Table 1. Individual phenolic compounds are found in different wood species.

Phenolic Compounds	Wood Species					Reference
	Oak Species			Fabaceae	Cherry	
	Quercus petraea	*Quercus alba*	*Quercus pyrenaica* **Willd.**	*Robinia pseudoacacia* **L.**	*Prunus avium* **L.**	
Total polyphenols (1)	1269	–	–	786	898	[76] (2)
Total polyphenols (3)	61.39	61.51	65.03	51.23	46.82	[77,78] (7)
Protocatechuic aldehyde (4)	nd	nd	nd	1.40	nd	[68] (7)
Gallic acid	1.25	nd	1.44	nd	nd	
Vanillic acid	0.14	0.33	0.128	nd	nd	
Syringic acid	0.44	0.83	0.22	nd	nd	
(+)-Catechin	nd	nd	nd	nd	18.51	
Robinetin	nd	nd	nd	118.94	nd	
Fustin (5)	nd	nd	nd	0.86	nd	
Butin (5)	nd	nd	nd	3.52	nd	
p-Coumaric acid	153.4	nd	84.3	nd	172.5	
Quercetin	5.45	5.49	2.48	nd	nd	
Naringenin	nd	nd	nd	nd	5.54	
Vescalagin (6)	19.21	6.21	25.74	nd	nd	
Castalagin (6)	24.97	5.43	32.45	nd	nd	
Ellagic acid	3.49	1.17	4.91	0.049	0.72	
Vescalagin (8)	9.87–10.6	5.41–8.24	–	–	–	[58] (9)
Castalagin (8)	12.56–19.8	2.34–3.54	–	–	–	
Ellagic acid	6.91–12.56	2.34–3.42	–	–	–	

Table 1. *Cont.*

Phenolic Compounds	Wood Species					Reference
	Oak Species			Fabaceae	Cherry	
	Quercus petraea	*Quercus alba*	*Quercus pyrenaica* Willd.	*Robinia pseudoacacia* L.	*Prunus avium* L.	
Vescalagin (8)	12.6–17.6	1.23–5.28	11.3–14.6	–	–	[13] (9)
Castalagin (8)	20.1–22.7	0.37–0.44	15.2–19.7	–	–	
Ellagic acid	2.60–4.42	1.90–3.62	3.9–20.5	–	–	
Total ellagitannins (10)	–	–	–	–	nd-0.04	[64,66,69]
Gallic acid (11)	70.75	–	–	9.61	nd	[79]
Vanillic acid (11)	2.34	–	–	nd	1.86	
Syringic acid (11)	3.78	–	–	0.82	3.05	
Ellagic acid (11)	32.68	–	–	nd	nd	
Protocatechuic (11) aldehyde	nd	–	–	0.19	7.90	

(1) (+)-catechin equivalents; (2) mg/L and data obtained after 30 extraction days by the use of model wine solutions 12 % with 60 g/L of wood chips without toasting process; (3) gallic acid equivalents; (4) protocatechuic acid equivalents; (5) naringenin equivalents; (6) ellagic acid equivalents; (7) mg/L and data obtained after 30 extraction days by the use of model wine solutions 12% with 4 g/L of wood chips; (8) mg/g dry wood gallic acid equivalents; (9) obtained after 160 min by the use of extraction solution (water/acetone); (10) mg/g untoasted wood and the sum of castalagin, vescalagin, granidin, and A, B, C, D, and E roburins; (11) mg/L of toasted wood and data obtained after 35 extraction days by the use of model wine solutions.

Table 2 shows the content of some of the most typical volatile compounds quantified in oak, false acacia, and cherry wood species. In oak wood species existent, a high quantity of volatile compounds with a significant influence on the wine sensory profile, especially in olfactive wine characteristics and also in some descriptors of the wine taste profile. Generally, wood belonging to genus *Quercus* has β-methyl-γ-octalactones (*cis* and *trans* forms), frequently in higher quantities in American species, like *Quercus alba*. Nevertheless, also in European oak species, it is possible to find these compounds. The lactones are related to sensory descriptors such as coconut and fresh oak. The literature describes that the *cis* isomer is more aromatic than the *trans* isomer [11,80,81]. Rendering to numerous authors [82,83], the *cis* to *trans*-oak lactone ratio is specific to the wood's source, where this ratio is greater for American oak wood species than European oak species. Jordão et al. [11] reported values of *cis/trans* ratio of 5.7, 4.2, and 0.63 for *Q. alba*, *Q. petraea*, and *Q. pyrenaica*, respectively. These authors also quantified twelve distinct volatile compounds, comprising *cis*- and *trans*-β-methyl-γ-octalactones, in toasted oak woods from these species and diverse geographical origins. Rendering to the outcomes achieved the highest concentration for β-methyl-γ-octalactones were detected in *Q. alba*, followed by *Q. petraea*. For all of these oak species, the *cis* form was the most abundant β-methyl-γ-octalactone. As shown in Table 2, generally, woods not belonging to genus *Quercus* do not have either *cis* or *trans*-β-methyl-γ-octalactone in their composition. Nevertheless, some researchers [68,84] already found very low concentrations of lactones in false acacia and cherry woods. Furthermore, Caldeira et al. [85] also detected small quantities of *cis* and *trans* forms in chestnut wood.

De Rosso et al. [76] investigated the chemical compounds extracted from oak, chestnut, false acacia, and mulberry woods used to manufacture barrels. According to these researchers, chestnut, false acacia, and oak extracted quantities between 1 and 10 µg/g wood of coniferaldehyde, while very low quantities for mulberry wood were found. Furthermore, higher quantities were quantified for syringaldehyde for the wood species considered (chestnut, false acacia, and oak). For cherry wood, only quantities between 1 and 10 µg/g wood were detected. Lastly, benzaldehyde was only found in cherry woods. These results follow an analogous trend showing by Fernández de Simón et al. [86]. According to these authors sinapaldehyde, coniferaldehyde, and syringaldehyde were found in false acacia, oak, and cherry woods (Table 2).

Table 2. Individual volatile compounds are found in different wood species.

Volatile Compounds	Wood Species					Reference
	Oak Species			Fabaceae	Cherry	
	Quercus petraea	*Quercus alba*	*Quercus pyrenaica* Willd.	*Robinia Pseudoacacia* L.	*Prunus avium* L.	
Furanic aldehydes (1)	397.19	–	–	8.26	70.18	[84] (1)
Volatile phenols (1)	941.58	–	–	197.84	334.63	
Phenolic aldehydes (1)	1563.62	–	–	170.38	1208.42	
Phenyl ketones (1)	55.33	–	–	57.04	72.21	
Lactones (1)	14.77	–	–	nd	3.95	
Guaiacol (2)	4.46	0.91	–	0.10	0.16	[87,88]
Eugenol (2)	1.05	3.44	–	0.92	0.11	
Furfural (2)	12.09	5.79	–	0.56	nd	
Vanillin (2)	45.69	70.37	–	4.70	4.68	
Trans-β-methyl-γ-octalactone (2)	2.14	1.64	–	nd	nd	
Cis-β-methyl-γ-octalactone (2)	6.12	39.37	–	nd	nd	
Guaiacol (3)	2.41	4.89	3.98	5.36	1.71	[86]
Eugenol (3)	1.83	1.29	2.12	2.36	1.50	
Furfural (3)	430	395	494	804	23.3	
5-Hydroxymethylfurfural (3)	22.9	21.1	28.9	113	47.6	
5-Methylfurfural (3)	35.1	38.3	56.3	94.2	31.3	
Vanillin (3)	117	102	114	77.1	68.3	
Trans-β-methyl-γ-octalactone (3)	14.6	3.36	9.77	nd	nd	
Cis-β-methyl-γ-octalactone (3)	21.1	31.8	30.0	nd	nd	
Benzaldehyde (3)	0.8	0.74	0.96	0.25	0.91	
Syringaldehyde (3)	221	226	250	272	455	
Coniferaldehyde (3)	106	96.2	174	227	145	
Sinapaldehyde (3)	263	239	439	912	804	
Guaiacol (4)	4.20×10^{-3}	12.52×10^{5}	4.12×10^{-3}	12.8×10^{-3}	8.22×10^{-3}	[68] (7)
Eugenol (4)	3.39×10^{-3}	59.39×10^{4}	12.01×10^{-3}	0.60×10^{-3}	1.29×10^{-3}	
Vanillin (4)	71.77×10^{-3}	31.5×10^{6}	169.45×10^{-3}	120.8×10^{-3}	1.64×10^{-3}	
Furfural (4)	134×10^{-3}	20.69×10^{6}	5.75×10^{-3}	13.7×10^{-3}	3.24×10^{-3}	
β-Methyl-γ-octalactones (4)	119.6×10^{-3}	199.8×10^{5}	521.8×10^{-3}	16.5×10^{-3}	18.12×10^{-3}	
Ethyl cinnamate (4)	nd	nd	nd	nd	1.77×10^{-3}	
Ethyl hexanoate (4)	nd	nd	nd	nd	2.21×10^{-3}	
Benzaldehyde	11.44	12.68	7.93	nd	nd	
Coniferaldehyde (5)	1.42	1.35	0.90	nd	nd	
Syringaldehyde (6)	0.109	nd	0.11	nd	nd	

(1) mg/100 g toasted wood in 3-octanol equivalents and oak *Quercus robur* specie was studied; (2) µg/g of untoasted wood; (3) µg/g toasted wood and data obtained after 15 extraction days by the use of model wine solutions 12% with 20 g/L of wood chips; (4) average peak area expressed in relative peak area in relation of internal standard and data obtained after 30 extraction days by the use of model wine solutions 12% with 4 g/L of wood chips; (5) sinapaldehyde equivalents; (6) syringic acid equivalents; (7) data obtained after 30 extraction days by the use of model wine solutions 12% with 4 g/L of wood chips; nd—not detected.

False acacia could be defined by an important concentration of benzene aldehydes, oak, and chestnut, by a great concentration of eugenol, vanillin, methoxyeugenol, syringaldehyde, and α-terpineol [76]. Furthermore, chestnut is also characterized by a great number of fatty acids and volatile compounds. In addition, mulberry wood contains a very low number of volatile compounds.

Vanillin, eugenol, and guaiacol are compounds with a significant role in numerous wine sensory descriptors. These compounds are related to sensory descriptors such as vanilla, smoky, and cloves aromas, respectively. Generally, vanillin is existent in different oak, chestnut, cherry, false acacia, and ash species. Nevertheless, lower values are also found in false acacia and cherry woods [86–89]. For Martínez-Gil et al. [22], the guaiacol concentrations in medium-toasted ash woods are considerably higher than those found in the other toasted woods. Other researchers [68,86] revealed similar concentrations of eugenol detected between different toasted oak wood species and other wood species (false acacia, cherry, and ash). Fernández de Simón et al. [86] described for false acacia, cherry, ash, and chestnut toasted woods average concentrations of eugenol between 1.50 and 3.21 µg/g.

After wood toasting, the main volatile compounds formed are furfural, 5-hydroxymethylfurfural, and 5-methylfurfural. They resulted in hemicellulose thermodegradation during the toasting process. These compounds are related to caramel, toasted and bitter almonds sensory descriptors. Some wood species are characterized by a few different profiles concerning these compounds. Therefore, *Quercus humboldtti* for toasted wood shows a higher level of 5-methylfurfural and lower furfural and 5-hydroxymethylfurfural than other oak wood species, such as *Quercus petraea* and *Q. alba* [22]. In addition, Martins et al. [84] described a low concentration of furfural, 5-methylfurfural, and, 5-hydroxymethylfurfural in false acacia and cherry toasted woods when compared with oak and chestnut woods. Even for untoasted woods, other works described low concentration of 5-methylfurfural and furfural in false acacia, while for no toasted cherry, it was not detected furan derivatives [87,89].

In Table 3, through various examples, the contents found of some of the volatile compounds quantified from several oak wood species as a function of the toasting intensity are shown.

Table 3. Influence of toasting level on volatile composition of different oak wood species.

	Toasting Level					
Volatile Compounds	**Without Toasting**	**Light Toasting**	**Medium Toasting**	**Strong Toasting**	**Oak Species**	**References**
Vanillin	1.6–2.5 6.8–7.5 2.0–3.4	nd nd nd	10.5–23.4 24.1–34.5 48.5–60.0	22.0–33.6 7.5–8.8 3.0–6.3	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	27.4 120.0	120.0 172.0	244.0 262.0	*Q. alba* *Q. petraea*	[16] (2)
	nd n.d.	nd 12.86	14.59 16.77	nd 24.76	*Q. alba* *Q. petraea*	[90] (3)
Syringaldehyde	14.9–16.5 16.3–20.2 12.5–14.8	nd nd nd	82.0–88.4 24.1–34.5 48.5–60.0	69.0–88.8 20.5–31.5 85.0–118.0	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	57.4 196.0	343.0 443.0	768.0 721.0	*Q. alba* *Q. petraea*	[16] (2)
	nd 50.5	nd 72.2	40.0 63.4	nd 75.2	*Q. alba* *Q. petraea*	[90] (3)
Furfural	3.9–4.5 1.2–1.8 3.4–7.0	nd nd nd	2176–2670 357.5–960.0 723.0–772.5	1635–2155 353.5–787.5 118.0–613.0	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	41.0 78.0	681.0 357.0	61.0 170.0	*Q. alba* *Q. petraea*	[16] (2)
	nd 7.1	nd 14.3	2.61 4.1	nd 28.6	*Q. alba* *Q. petraea*	[90] (3)
5-Hydroxymethyl-furfural	0.0–1.3 0.4–0.7 0.3–0.5	nd nd nd	3344–5078 1678–3221 1203–1722	2306–2976 781.9–922.3 654.2–980.6	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	14.6 37.2	74.5 58.3	30.2 44.2	*Q. alba* *Q. petraea*	[16] (2)
	nd 5.73	nd 7.9	10.7 6.13	nd 12.66	*Q. alba* *Q. petraea*	[90] (3)

Table 3. *Cont.*

Volatile Compounds	Toasting Level: Without Toasting	Light Toasting	Medium Toasting	Strong Toasting	Oak Species	References
Trans-β-methyl-γ-octalactone	nd-8.3 4.0–5.0 5.0–6.7	nd nd nd	4.8–7.0 6.4–7.4 5.4–11.3	5.0–7.2 4.2–7.4 5.3–11.5	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	3.35 11.5	6.63 9.65	2.78 4.43	*Q. alba* *Q. petraea*	[16] (2)
Cis-β-methyl-γ-octalactone	5.3–10.0 22.3–23.1 14.0–21.3	nd nd nd	3.6–13.7 26.5–45.5 14.1–18.5	2.9–9.6 16.1–23.6 7.4–18.2	*Q. pyrenaica* *Q. alba* *Q. petraea*	[11] (1)
	nd nd	24.9 11.4	31.1 12.1	14.6 7.59	*Q. alba* *Q. petraea*	[16] (2)

(1) mg/g dried wood; (2) µg/g wood; (3) mg/100g wood; nd—not detected.

3. Impact of Wood Species on Wine Chemical Composition

During the wine aging in wood, numerous chemical and physical changes occurred, such as transferring volatile and phenolic compounds from wood to wine to improve the wine's quality [91]. However, reactions including only wine compounds and evaporation of volatile compounds can also take place. The key wood extractives are phenolic compounds [92], lactones (*cis*- and *trans*-β-methyl-γ-octalactones), aldehydes [76], and furfuryl compounds (5-methylfurfural, furfural, and furfuryl alcohol) [90]. Moreover, wines aged in wood are also continually exposed to small quantities of atmospheric oxygen (for oak barrels, it has been estimated at 10–45 mg/L per year) through the stave pores. This natural micro-oxygenation enhanced the condensation and polymerization reactions between flavonoid compounds (tannin–tannin and tannin–anthocyanin), which positively influenced the evolution of wine phenolic composition, by the formation of new stable anthocyanin and tannin derivatives, with consequent color stabilization and loss of astringency [53,76,93]. On the other hand, the wine compounds can also be fixed on the wood and by wine lees [94,95], so this factor will also impact the volatile composition of wine. Therefore, the wine aged in wood undergoes important modifications that influence the wine volatile profile (a potential more complex aroma), color stability, and clarification; however, these changes are dependent on numerous factors, such as the wood species, initial wine composition, and the aging time.

The type and quantity of wood extractives are highly dependent on the aging time and on the number of compounds that are potentially extractable from the wood to the wine, which is influenced by the wood species employed [76], geographical origin, wood grain [13,15] drying and the toasting methods [16,96,97] and on barrel utilization time [43,98]. Nevertheless, the wine to be aged in wood needed to have a good initial structure and body to balance the adverse influence of oxygen.

Ortega-Heras et al. [99] studied the concentration of the volatile compounds removed from the wood, namely the syringaldehyde, *cis*- and *trans*-whiskylactones, vanillin, furfural, 5-methylfurfural, guaiacol, eugenol, *p*-ethyl-phenol, and *p*-ethylguaicol in twelve red monovarietal wines aged in new American oak barrels. These authors conclude that the removal of these compounds was quicker during the first 4 or 9 months of aging time in wood. Moreover, the wine alcohol content influences the removal process of the compounds from the wood. Thus, Maga [100] studied the removal of *cis*- and *trans*-oak lactones, from American oak (*Q. alba*) in model wines with diverse ethanol levels (0%, 10%, 20%, 40%, and 60%), showing that the maximum levels of oak lactones were achieved in the samples with 40% ethanol. The removal of volatile compounds from wood barrels throughout the wine's aging process with diverse alcohol content and pH (Cabernet Sauvignon, 12.3% *v*/*v*, pH, 3.45; Merlot, 13.6% *v*/*v*, pH, 3.7) was studied by Garde-Cerdán et al. [101]. These authors described that in Merlot wine, with higher alcohol content, the removal of volatile compounds from wood barrels was higher than in Cabernet Sauvignon wine with lower alcohol content. These authors also observed that the alcohol degree has a higher effect on the removal process than the wine pH. Jordão et al. [11], using model wine solutions, studied the influence of temperature, pH, alcoholic level, and aging time on the removal of some ellagic tannins (castalagin, vescalagin, grandinin, roburin D and E) and ellagic acid from *Q. pyrenaica* wood chips (*Quercus pyrenaica*). In the removal conditions studied, the temperature was the key factor influencing ellagic acid and ellagic tannins evolution. The results suggest that a decrease/degradation of these compounds is less perceptible at low temperatures (12 °C).

Another factor to have in consideration is the number of barrel utilization, as the extraction decreases with the increased number of uses [83,102,103]. In the experiment performed by Towey and Waterhouse [102], fifteen barrels (7 American, 6 French, and 2 Hungarian) were used with Chardonnay wines in three successive vintages. These authors showed that the extraction rates were lesser in the one-year-old barrels than in the new barrels and lower in two-year-old barrels than in one-year-old barrels and that the levels of the compounds associated with toasting reduced significantly in the second year. Pérez-Prieto et al. [104] showed that the compounds removed from the wood, no significant differences were detected in furfuryl compounds and 4-methylguaicol, between new and 3 times used barrel (French or American oak); however, the number of lactones, which are essential compounds for the sensory wine characteristics, were significantly decreased in used barrels.

Moreover, Garde-Cerdán et al. [103] studied the effect of the barrels' utilization time on the red wine volatile composition and showed that wood compounds such as syringaldehyde, vanillin, and *trans*-β-methyl-γ-octalactone, which are essential for the red wine aroma, were smaller than their perception threshold in barrel with 5 to 6 utilization times. This author also detected differences between the wines aged in used French and American oak barrels, so the wines aged in American oak presented levels of *cis*-β-methyl-γ-octalactone greater than its perception threshold, which was not observed in the wines aged in French oak. On the other hand, the wine aged in used French oak barrels presented a superior quantity of syringaldehyde, vanillin, acetovanillone, and ethyl lactate. Table 4 summarizes some results obtained by several authors on the volatile composition of some wines aged in French and American oak barrels, with different utilization times.

Table 4. Wine volatile compounds (µg/L) aged in oak barrels with different utilization times.

Volatile Compounds	Wine Characteristics	French Oak	American Oak	Reference
New oak barrels				
Alcohols × 10^{-3}	Monastrell wine aged for 6 months	~325	~325	[104]
Acids × 10^{-1}		~200	~200	
Esters × 10^{-2}		~40	~40	
Furfuryl × 10^{-1}		~140	~120	
Guaiacol		~10	~10	
4-Methyl guaiacol		~10	~25	
4-Ethyl phenol		~300	~320	
4-Ethyl guaiacol		~25	~10	
Trans-oak lactone		~40	~25	
Cis-oak lactone		~125	~400	
Vanillin		~200	~175	

Table 4. *Cont.*

Volatile Compounds	Wine Characteristics	French Oak	American Oak	Reference
Oak barrels used twice				
Furfural	Blend wine of Tempranillo (60%), Cabernet Sauvignon (20%), and Garnacha (20%) aged for 12 months	771		[105]
5-Methyl furfural		135		
5-Hydroxymethyl furfural		0.02		
Furfuryl alcohol		3714		
Cis-oak lactone		79		
Trans-oak lactone		73		
γ-Nonalactone		2.6		
γ-Butyrolactone		49,930		
Syringaldehyde		312		
Coniferaldehyde		40		
Vanillin		89		
Acetovanillone		114		
β-Ionone		0.16		
Eugenol		20		
Guaiacol		8.8		
4-Methyl guaiacol		0.06		
Phenol		15.52		
m-Cresol		0.8		
p-Cresol		0.19		
4-Ethyl phenol		656		
4-Ethyl guaiacol		87		
2-Phenyl ethanol		2051		
Ethyl butyrate		517		
Ethyl hexanoate		206		
Ethyl octanoate		246		
Ethyl decanoate		9		
Ethyl lactate		31,198		
Oak barrels used 3 times				
Alcohols $\times 10^{-3}$	Monastrell wine aged for 6 months	~350	~325	[106]
Acids $\times 10^{-1}$		~240	~225	
Esters $\times 10^{-2}$~		~40	~40	
Furfuryl $\times 10^{-1}$		~125	~120	
Guaiacol		~10	~10	
4-Methyl guaiacol		~10	~10	
4-Ethyl phenol		~60	~175	
4-Ethyl guaiacol		nd	~5	
Trans-oak lactone		~20	~5	
Cis-oak lactone		~75	~100	
Vanillin		~60	~75	
Oak barrels used 5 times				
Furfural	Blend wine (Tempranillo 41% and Cabernet Sauvignon 59%) aged for 12 months	89–206	70–110	[103]
5-Methyl furfural		4.0–5.0	5–13	
Furfuryl alcohol		516–620	115–447	
Cis-oak lactone		44–89	100–151	
Trans-oak lactone		28–51	20–37	
γ-Butyrolactone		18,200–19,300	17,900–18,100	
γ-Nonalactone		1.6–2.6	1.8–2.6	
Ethyl butyrate		225–270	246–272	
Ethyl hexanoate		264–294	292–313	
Ethyl octanoate		349–353	345–355	
Ethyl decanoate		85–89	91–106	
Isoamyl acetate		276–296	245–338	
Ethyl lactate		26,200–34,500	14,700–17,500	
Vanillin		25–35	9–25	
Syringaldehyde		5–7	1–4	
Coniferaldehyde		17–20	15–18	

Table 4. *Cont.*

Volatile Compounds	Wine Characteristics	French Oak	American Oak	Reference
Acetovanillone		145–177	113–116	
β-Ionone		0.20–0.30	0.20–0.30	
Guaiacol		5–6	5–7	
4-Methyl guaiacol		0.030–0.030	0.04–0.05	
Eugenol		13–22	17–25	
4-Ethyl guaiacol		271–306	209–274	
4-Ethyl phenol		1540–1850	1160–1590	
Phenol		5–7	5–8	
p-Cresol		0.05–0.06	0.05–0.06	
m-Cresol		1–2	0.1–1.0	
2-Phenyl ethanol		3170–3470	2780–3320	

nd—not detected.

Besides oak wood, other species like cherry (*Prunus avium*), false acacia (*Robinia pseudoacacia*), mulberry (*Morus alba* L. and *Morus nigra* L.), or ash (*Fraxinus excelsior*) are increasingly considered for winemaking, and they are investigated in numerous studies [65,66,74,76,77], due to their lower costs, or due to their distinctive sensory contribution [85]. In the case of cherry wood, several authors reported that this wood species contribute to a faster red wine pigment stabilization, preserving the maximum red color intensity and the best wine chromatic characteristics [106]. On the other hand, the red wines aged in contact with mulberry wood barrels showed significant reductions in fruity-note ethyl esters and ethylguaiacol and also higher ethylphenol content. In addition, wines aged in cherry wood barrels presented higher polyphenol oxidation, being cherry wood not appropriate for long-time aging [76,77]. If the aging of the red wine in cherry wood chips is compared with the aging in oak wood chips, it seems to be a quicker evolution of the wine phenols [10,34]. During the wine aging in cherry wood barrels, a decrease in flavonols and flavanols was observed (involved in condensation phenomena capable of stabilizing wine color) [107]. Chinnici et al. [106] proposed that red wine aged in cherry wood barrels presented a high quantity of flavanols that may possibly be involved in acetaldehyde-mediated condensation, increasing pigments stabilization. As shown in Table 5, the wines aged in cherry wood barrels are distinct from the wine aged in oak wood barrels due to the existence of five additional phenolic compounds, namely, eriodictyol, a flavanone derivative, sakuranetin, pinocembrin, and chrysin [107]. For wines aged in contact with chestnut wood barrels, the presence of valoneic acid dilactone was observed, which could be considered a phenolic marker for a wine aged in contact with this wood species [74]. In these wines, a higher concentration of gallic and ellagic acids was also quantified [71,74,108]. Wines aged in contact with false acacia wood presented dihydrorobinetin, robinetin, and 2,4-dihydroxybenzaldehyde in higher concentrations, but also other compounds were identified in wines aged in contact with false acacia wood barrels such as 2,4-dihydroxybenzoic acid, pentahydroxydihydroflavonol, tetrahydroxydihydroflavonol, fustin, trihidroxymethoxy dihydroflavonol, robtin, butin, tetrahydroxyaurone, and butein [65,66,74], as shown in Table 5. Phenolic acids present in oak wood also have important functions in aged wines as they influence factors associated with an antioxidant capacity [69,109–113]. Wine increases its antioxidant capacity in contact with the wood due to an increase in the concentration of *p*-coumaric, gallic, caffeic acids, ferulic, protocatechuic, and protocatechuic aldehyde during wine wood aging [69,109,112]. Therefore, the wood composition in phenolic acids used in wine aging could determine the increase in antioxidant capacity of wood-aged wines [113], and consequently, it will be dependent on botanical species used in the wood aging process. Alañón et al. [69] observed that the minimum antioxidant capacity was found in extracts from *P. avium*, the extracts from *Q. pyrenaica*, *Q. alba*, and *Q. petraea* showed middle antioxidant capacity, and the maximum antioxidant capacity was found in extracts from *Q. robur* and *C. sativa*, these authors also showed that the antioxidant capacity observed was related with the wood phenol composition of these species.

Table 5. Red wine (Sangiovese (85%) and Merlot (15%)) phenolic compounds (mg/L) aged in oak and cherry wood with 225 L capacity during 2 and 4 months Adapted from [107] and Syrah red wines aged in cherry, chestnut, false acacia, ash, and oak wood barrels with 225 L capacity (D.O. Cataluña aged 6 months) Adapted from [74].

Compound	**2 Months**		**4 Months**		**6 Months**				
	Oak	**Cherry**	**Oak**	**Cherry**	**Cherry**	**Chestnut**	**False Acacia**	**Ash**	**Oak**
Protocatechuic acid	4.20	4.27	3.74	2.72	1.02	0.24	0.9	0.82	0.73
Vanillic acid	1.63	1.37	1.81	1.14	3.59	3.25	nq	4.88	3.62
Syringic acid					5.16	3.95	3.32	4.09	3.56
Caffeic acid	6.72	6.46	6.16	5.82	22.66	15.62	20.21	21.28	24.82
p-Cumaric acid	1.46	1.34	0.89	1.08	0.82	0.32	0.33	0.38	0.41
Caftaric acid	38.8	36.9	36.6	36.3	0.07	0.54	0.71	0.41	0.07
GRP	7.08	6.92	6.17	5.96					
Cis p-Coumaric acid					4.01	1.27	4.31	4.2	4.25
Trans p-Coumaric acid					46.68	9.45	40.14	41.89	47.13
Ferulic acid					0.56	1.02	1.41	1.29	1.07
Cis-Coutaric acid	2.51	2.57	2.39	2.44	0.03	0.11	0.06	0.03	nd
Trans-Coutaric acid	7.90	7.82	7.97	7.63	0.04	0.36	0.17	0.13	nd
Fertaric acid	13.1	12.6	13.2	12.2	0.16	0.19	0.91	0.05	nd
Ethyl cumarate	0.10	0.12	tr	tr					
(Epi)catechin gallate					4.52	4.36	nq	4.06	5.12
(+)-Catechin	56.1	53.0	42.7	21.4	47.7	38.88	35.34	37.5	40.13
(−)-Epicatechin	52.0	45.2	38.6	20.5	10.81	9.81	9.32	9.17	10.35
Procyanidin B1	82.8	75.6	66.5	26.7					
Procyanidin B2	86.9	73.9	68.4	27.7	11.14	5.78	4.92	7.54	9.11
Isorhamnetin-3-glucoside	2.07	1.83	2.06	1.74	7.82	6.11	6.28	7.73	6.59
Syringetin-3-galactoside					nd	0.54	2.49	0.82	2.37
Isorhamnetin	1.20	1.16	1.40	1.21					
Kaempferol	1.33	1.43	1.60	1.28	1.05	1.02	0.67	0.56	0.56
Myricetin-3-glucoside	4.91	2.88	4.93	3.43	5.11	4.28	4.66	4.62	4.69
Myricetin	5.37	5.77	4.47	3.14	1.91	1.53	1.81	2.55	1.37
Quercetin	14.6	16.7	14.6	8.55	27.82	23.99	23.72	23.41	26.24
Quercetin-3-glucoside	1.39	1.23	0.79	0.64	3.48	4.38	3.14	2.97	2.93
Quercetin-3-glucuronide	7.28	6.57	6.75	4.44	0.84	1.39	0.74	0.72	0.57
Laricitrin-3-glucoside					13.70	11.96	12.62	13.07	13.42
Tyrosol	57.1	49.4	55.5	52.6	0.82	0.73	0.84	1.01	0.84
Trans-Resveratrol	1.01	0.94	1.04	0.69	1.35	1.18	1.77	1.38	1.57
Trans-Resveratrol glucoside	4.10	5.01	5.49	5.33	1.72	1.45	2.35	1.61	2.01
cherry wood wines aged phenolic markers									
Eriodictyol	nd	nd	nd	0.09	0.63				
Flavanone derivative	nd	0.31	nd	0.51					
Sakuranetin	nd	0.86	nd	2.21					
Pinocembrin	nd	1.44	nd	1.72					
Chrysin	nd	0.11	nd	0.71					
Taxifolin					3.64				
Prunin					0.76				
Aromadendrin					5.56				
Naringenin					5.57				
Isosakuranetin					3.98				
chestnut wood wines aged phenolic markers									
Gallic acid	66.7	64.1	68.0	64.7	21.38	43.91	33.09	27.77	30.46
Ellagic acid	4.53	1.39	7.66	3.44	5.94	20.41	4.54	5.54	11.61
Ethyl gallate	47.0	33.1	25.9	14.1	8.99	11.73	7.95	8.11	9.16
Valoneic acid dilactone						1.69			

Table 5. *Cont.*

Compound	2 Months		4 Months		6 Months				
	Oak	Cherry	Oak	Cherry	Cherry	Chestnut	False Acacia	Ash	Oak
false acacia wood wines aged phenolic markers									
2,4-Dihydroxybenzoic acid							2.19		
2,4-Dihydroxybenzaldehyde							16.48		
Dihydrorobinetin							79.24		
Pentahydroxydihydroflavonol							1.75		
Tetrahydroxydihydroflavonol							5.69		
Fustin							4.33		
Trihidroxymethoxy dihydroflavonol							2.78		
Robtin							1.49		
Butin							3.41		
Robinetin							30.01		
Tetrahydroxyaurone							3.28		
Butein							2.63		

nd—not detected; tr trace; nq = not quantified, interference by other peaks.

Fernández de Simón et al. [114] also identified several volatile compounds that could be used as chemical markers for red wines aged in false acacia (2,4-dihydroxybenzaldehyde) and cherry wood barrels' (ethyl-2-benzoate).

Regarding the evolution of bottled red wines with previous wood chips contact, Costa et al. [10] focused on the study, over a time of 18 months of aging, of several phenolic parameters of bottled Touriga Nacional red wines that had before been in contact with toasted wood chips from two oak species and cherry. Throughout 18 months of aging, the results indicated less reduction in the phenolic compounds and red color of wines which had previous interaction with oak chips, as well as a less developed brown color throughout bottle storage, compared to the wine previously in contact with cherry chips and the wine without contact with wood chips. Furthermore, wine previously in contact with cherry wood chips always presented an evolution similar to the wine without contact with wood chips. Previously, Tavares et al. [34] also reported the evolution of phenolic compounds of a Portuguese red wine aged for 90 days in contact with wood chips from false acacia (*Robinia pseudoacacia*), cherry (*Prunus avium*), and oak species. According to these authors, the diverse wood chip species studied had no clear effect on the evolution of the majority of the red wine phenolic compounds. Nevertheless, from a sensory point of view, the use of diverse wood species induced higher distinction, particularly for aroma descriptors.

Wood aging is also applied in some white wines, mostly by fermentation in barrels but also for aging to increase the quality of white wines [31,38–43,75,115–120]. Studies performed by Nunes et al. [43] to understand the effect of the application of diverse oak wood barrel sizes and utilization time on a white wine characteristic showed that the wines aged in new oak wood barrels presented a higher number of phenolic compounds, for instance, gallic and ellagic acid, independently of the oak wood barrel capacity. On the other hand, Sánchez-Palomo et al. [42] studied the influence of the application of wood chips at different stages of the vinification process on the volatile composition of Verdejo white wines. This study showed that higher concentrations of oak lactones, benzene compounds, and furanic compounds were presented in white wines in contact with oak chips. Moreover, in white wines, the application of other wood chip species, besides oak, was investigated in numerous studies such as cherry chips [44] and false acacia chips [44,75,88,89]. These innovations aim to enhance and improve white wines, searching for new sensory characteristics/sensations to satisfy the consumers. Tables 5 and 6 show several examples of compounds detected in wines aged in wood barrels from different wood species.

Table 6. Red wine (Syrah) aged 12 months in cherry, chestnut, false acacia, ash, and oak wood, white wine (Malvazija) aged in false acacia and oak wood, and Chardonnay aged in false acacia volatile compounds (µg/L) Adapted from [75,89,114].

Compound	Red wine (12 Months)					White Wine		
	Cherry	Chestnut	False Acacia	Ash	Oak	False Acacia (12 Months)	Oak (12 Months)	False Acacia (1 to 4 Months)
Furfural	101	509	238	66.2	39.8	82.8–1236.3	740.2–1795.8	24–9.2
5-Methyl furfural	31.8	241	450	57.8	842	4.3–250.6	93–173.3	5.2–0.1
5-Hydroxymethylfurfural	145	689	248	339	703			1.4–0.8
5-Acetoxymethyl-2-furfural	1.81	5.51	4.85	2.58	2.09			
2-Furanmethanol	1550	14,120	3415	878	6248			
Methyl-2-furoate	13.7	10.4	43.0	28.8	31.9			
Ethyl-2-furoate	28.3	53.4	54.9	48.1	57.0			
1-(2-Furanyl)-ethanone	62.1	299	161c	76.8	420			
1-Methoxy-2-ethoxyethyl-1-furan	38.7	169	39.3	24.8	20.5			
3-Ethylcyclotene	nd	1.22	6.73	26.3	8.28			
4,5-Dimethyl-2-cyclohexen-1-one	0.45	nd	10.5	14.7	10.0			
γ-Butyrolactone	4240	4419	4307	4007	4334			0.1
Whiskylactone *trans*	nd	21.3	nd	nd	99.4	0.2–0.3	0.5–38.7	
Whiskylactone *cis*	nd	31.2	nd	nd	577	0.4–0.5	1.2–42.7	
Phenol	0.9	8.47	9.06	10.8	9.07	1.8–3.1	1.6–2.1	
o-Cresol	2.20	2.04	2.56	5.75	2.28	0.3–1.3		
p-Cresol	13.2	2.84	3.27	4.50	2.53	0.3		
m-Cresol	1.79	1.36	0.59	2.24	1.04	0.5–0.9		
4-Ethylphenol	431	415	48.1c	479	274	0.4–0.7		6.2–3.3
Catechol	4.70	4.65	nd	nd	nd			
4-Methylcatechol	10.4	11.4	3.81	14.2	nd			
Guaiacol	42.8	59.3	59.8	75.1	43.8	2.7–31.4	4.9–9.2	3.1–0.8
4-Methylguaiacol	24.6	51.5	14.1	34.8	31.5			0.9–0.3
4-Ethylguaiacol	73.3	49.1	19.9	91.5	24.2	0.7–2.6	0.6–1.3	1.4–0.7
Eugenol	10.5	118	19.3	12.8	101	2.5–8	4.4–6.6	0.9–0.6
Cis-isoeugenol						0.5–1.6	0.6	
Trans-isoeugenol						8.6–33.1	3.6–7.9	
2,4-Dihydroxybenzaldehyde	nd	nd	1248	nd	nd			
p-Anisaldehyde	4.42	nd	0.29	nd	nd			
Vanillin	304	456	233	696	408	0.02–0.03	0.02–0.05	38.1–1.2
Syringaldehyde	1877	1189	768	1090	1305	0.25–0.29	0.12–0.13	43.1–1.0
Acetovanillone	75.1	92.4	61.3	111	62.4			59.5–30
Methyl benzoate	94	nd	nd	0.43	nd			
Ethyl benzoate	29.16	nd	nd	nd	nd			

nd—not detected.

A study carried out by Kozlovic et al. [75] indicated differences in the volatile composition between wines aged in contact with oak and false acacia wood barrels. These authors reported an increase in oak lactones, simple volatile phenol, furfural, 5-methylfurfural, eugenol, guaiacol, and *trans*-eugenol during 12 months of aging time. Moreover, Délia et al. [44] studied the influence of aging in an Encruzado white wine in contact with diverse wood chips species (false acacia, cherry, and oak) during 28 days. The results showed that the wine stored in contact with false acacia wood chips revealed a rise in total phenols, non-flavonoid and flavonoid phenolic compounds, and also color intensity. Alañón et al. [88,89] studied the volatile composition of young white wine from the *V. vinifera* grape variety Chardonnay aged in wood barrels of false acacia. After 4 months of barrels aging, it was observed that the quantity of vanillin, syringaldehyde, ferulic acid, and furfural reduced significantly. This reduction is related to the false acacia wood's porosity that induced higher oxidation.

There have been studies on the use of different woods in rosé winemaking. Nunes et al. [37] investigated the influence of the application of cherry and oak wood chips (throughout the alcoholic fermentation and aging process) on rosé wine characteristics. Rosé wines vinified and aged in contact with wood chips showed greater levels of colored anthocyanins, while also presenting an increase in color intensity compared to the rosé wine without wood chips contact. Moreover, Santos et al. [35] observed the influence of the application of diverse wood chip species (false acacia, cherry, and oak) in rosé wines throughout a short aging period. Costa et al. [24] also studied the potential use of toasted wood chips from walnut (*Juglans regia* L.) in enology. This study focused on comparative evolution during 30 days of the phenolic composition and sensory profile of a Touriga Nacional red wine kept in contact with toasted walnut (*Juglans regia* L.) chips and oak (*Quercus petraea* L.) wood chips. The results obtained in this research revealed that the wine stored in contact with *Quercus petraea* L. chips showed, in general, the highest concentration for the majority of the phenolic compounds studied. At the same time, the wine stored in contact with *Juglans regia* L. chips presented significantly higher concentrations for oligomeric proanthocyanidins.

4. Influence of Wood Species on the Wine Sensory Profile

Aged wines show a distinctive sensory feature that is acquired throughout the aging process. In the last years, winemakers from outside of Europe began to make wines with potential new sensory profiles, and therefore, the application of diverse wood species for wine aging constituted a potential increasingly valid and widespread option.

Wood barrel-aged wine is complex and its sensory perception results from the interaction of many compounds. However, only a few of the compounds extracted from the wood to the wine during barrel aging have a significant impact on the wine sensory characteristics (Table 7). The main volatile compounds released from wood with wine sensory impact are phenolic aldehydes and phenyl ketones, furanic compounds (furfural, hydroxymethylfurfural, furfuryl alcohol, and 5-methylfurfural), volatile phenols (guaiacol, 4-methylguaiacol, ethylguaiacol, vinylguaiacol, and eugenol), and β-methyl-γ-octalactones [121,122]. Phenolic aldehydes and ketones give the characteristic vanilla aroma of oak wood-aged wines, with vanillin being the main compound, characterized by low sensory thresholds (0.3 ppm) in wine [30,123]. Siringaldehyde, sinapaldehyde, and coniferaldehyde do not have a great sensory impact, although their perception thresholds are clearly higher and, therefore, at their usual concentration.

Furanic compounds are responsible for the characteristics and pleasant aromas of almonds and toasted almonds [122], with an olfactory detection threshold in red wines of 20 mg/L for furfural and 45 mg/L for 5-methyl furfural [123]. Maltol and other oxygenated heterocycles provide the aromas of caramel and notes of toast that also characterize wood-aged wines. Guaiacol contributes with a smell of toast and sweet smoke aroma, with an olfactory detection threshold as low as 0.05 ppm [124]; methyl-4-guaiacol and ethyl-4-guaiacol have the smell of burnt wood, while phenol has an ink odor. Eugenol is also of great importance for wine sensory characteristics as it gives a spicy aroma of clove with a sensory threshold of 0.5 ppm [124]; however, all the others give smoked/toasted notes [125]. β-methyl-γ-octalactones (*cis* and *trans* forms) are responsible for the coconut flavor, two isomers, *cis* (−) and *trans* (+), have been described [63,126]. It is necessary to point out that the *cis* isomer presents a perception threshold between 4 and 5 times less than the *trans* isomer making its contribution to coconut perception much more important [125], namely 460 μg/L for the *trans*-isomer and 92 μg/L for the *cis*-isomer [127]. Phenol has a medicinal smoky aroma but a slight sensory effect as its olfactory detection threshold is nearby 40,000 μg/L; *o*-cresol and *p*-cresol have a medicinal aroma, with an olfactory detection threshold of 300 and 60 μg/L, respectively [75,124]. Ethyl-4-phenol has an unpleasant animal smell, described as leather and even a horse odor. The presence of the latter compound is considered, as long as it exceeds its threshold perception, as a serious wine defect [124]. Wood also releases some nonvolatile compounds such as phenolic acids, coumarins, and especially ellagitannins into the wine [92], which contribute to wine texture and taste sensations, such as body and astringency [128].

Fernández de Simón et al. [114] showed that each wood species added a diverse intensity of aromatic and gustative descriptors, emphasizing the main intensity of caramel/almond, vanilla, and toasty notes in red wines aged in oak wood barrels, of smoky, spicy, and fruity notes in red wines aged in false acacia wood barrels, and of balsamic descriptors in the red wines aged in ash wood barrels. Moreover, Hale et al. [129] referred that throughout wine aging in a barrel, volatile compounds extracted from oak wood contribute with aromatic notes of smoke, vanilla, and spices.

Table 7. Wood compounds and their sensory descriptors and olfactory detection threshold (ODT).

Compounds	ODT (µg/L)	Sensory Descriptors	Reference
Furfural	15,000–20,000	Toasted nuts, burnt almonds, caramel, dried fruit	[122,129–131]
5-Methyl furfural	16,000–45,000	Toasted nuts, toasty, sweet, spicy	[123,129–131]
Vanillin phenols	60–320	Vanilla	[123,131]
Syringaldehyde	50,000	Vanilla	[123]
Eugenol	5–500	Spice cloves, cinnamon, smoke character	[123,129–131].
Guaiacol	15–75	Spicy, toasty, smoky/burnt	[123,131,132]
4-Methylguaiacol	65	Burnt	[123]
β-Methyl-γ-octolactones		Coconut	[123]
Isomer *cis*	35–46-92	Vanilla, oaky, clove, coconut	[125,130,131,133]
Isomer *trans*	122–460	Vanilla, oaky, clove, coconut	[127,130,131]
4-Ethylphenol	620	Horse sweat	[125]
4-Ethylguayacol	140	Toasted bread, smoky, clove, burnt	[125,130]
Acetovanillone	1000	Vanilla	[134]
Maltol	5000	Caramel, toasted	[135]

In the literature, several research works studied the impact of aging red wine in oak wood barrels on the wine sensory characteristics [14,32,33,96,104]. In this sense, it was shown that in the case of red wines aged for 12 months in oak wood barrels that the kind of oak wood barrels used and the barrel toasting process influenced the wine sensory characteristics [96]. The descriptors vanilla aroma, astringency sensation, and bitterness taste are significantly influenced by the barrel toasting process. These researchers also showed that the wood origin influenced the sensory characteristic of the wine, as it was shown that the concentration of the extractable compounds is different, mainly on whiskey lactone and eugenol concentration. Moreover, differences were observed if the wines were aged in new or used barrels. Pérez-Prieto et al. [104] showed that all sensory descriptors of wines aged in new oak barrels are significantly different from wines aged in used oak barrels. The wines aged in new barrels were higher scored in the descriptors woody, vanilla, spicy, and cedar notes, and the wines aged in used barrels were higher scored for the descriptors pharmaceutical, herbaceous and horsy notes.

Fernández de Simón et al. [74] assessed the sensory profile of Syrah wines aged twelve months in barrels from diverse wood species. It was shown that each wood species contributed with diverse intensities of practically all gustative and aromatic descriptors. Regarding the olfactory descriptors, these authors showed that the wines aged in oak barrels presented the highest intensity of vanilla (4.6), almond/caramel and toasty notes, wines aged in false acacia wood barrels of spicy, smoky, and fruity notes, and the wines aged in ash wood barrels of balsamic notes. The scores for a vanilla descriptor for the wines aged in ash wood was 1.8 and for the wines ages in chestnut wood, 1.6. However, these authors pointed out that the levels of vanillin were higher in wines aged in ash, followed by those aged in chestnut and oak wood and those aged in cherry and false acacia wood barrels. According to these researchers, the results showed that the olfactory descriptors for vanilla need to be enriched by the existence of other compounds, such as whisky lactones, compounds that are only found in wines aged in oak wood barrels. Previously, Spillman et al. [136] showed that the olfactory descriptor vanilla in red wines correlated strongly with the level of *cis*-β-methyl-χ-octalactone. On the other hand, the wines aged in false acacia wood barrels showed higher spiced, toasted, and fruited notes [74], which could be, according to these authors, correlated to their high level in mono and dimethoxyphenols, acetosyringone, and ethyl vanillate [125]. Fernández de Simón et al. [74] also observed that wines aged in chestnut wood barrels presented middle scores of all olfactory descriptors, and the wines aged in cherry wood barrels presented the lowest scores for the olfactory descriptors toasty, almond, caramel, vanilla and smoky. The wines aged in oak wood were the higher scored wines regarding global wine valuation and the wines aged in the cherry wood barrels were the worst scored. Moreover, other researchers have previously shown that the cherry wood barrels are only suggested in red wines for short aging times [76,77,106].

More recently, Tavares et al. [34] studied the sensory characteristics of a red wine aged in contact with chips from cherry, false acacia, and oak woods. It was shown that the wine aged in contact with French oak chips presented significantly higher scores for the aroma descriptors (vanilla, boisé, and coconut), while the red wine aged with Portuguese oak wood chips presented significantly higher scores for other aroma descriptors such as sawdust. However, these last wines showed lesser scores for fruity and floral aroma descriptors. The red wines aged in false acacia and cherry wood chips showed lower scores for all aroma descriptors. These differences observed in the wines aged in contact with the different oak wood chips are related to greater extraction of β-methyl-γ-octalactone (mainly *cis*-β-methyl-γ-octalactone), furfural, vanillin, and 5-methylfurfural from oak chips [32,40].

Ortega-Heras et al. [137] observed that wine aged with wood chips would give a similar sensory characteristic of wines aged in a new oak wood barrel for a short aging period (about three months); however, if the aging in a new oak wood barrels will be for a long period of time, differences in the sensory characteristics were detected. Nevertheless, the application of oak wood chips could be a good option for the production of young red wines with few gustative and olfactory wood notes

For white wines, Herrero et al. [119] associated the volatile compounds removed from oak wood with diverse toasting degrees with the sensory characteristics of varietal wines from Chardonnay and Sauvignon Blanc grapes. For these researchers, guaiacol, eugenol, vanillin, 4-methylguaiacol, furfuryl alcohol, and furfural were positively correlated to aroma quality perceived by specialists of Sauvignon Blanc wines. For Chardonnay wines, the highest aroma scores were positively correlated with the 4-vinylguaiacol and isoeugenol and negatively correlated with the existence of lactones and 4-vinylphenol in wines. Spillman et al. [122] established the role of some oak wood-extractable compounds in Chardonnay wines aged in new oak barrels, for example, the correlation between the volatile compounds of the wood manufactured during the toasting process and the "smoky" aroma. Herjavec et al. [117] reported a positive effect of the use of new Croatian oak barrels during the alcoholic fermentation on the sensory characteristics of Chardonnay and Sauvignon Blanc wines, in comparison with those fermented in stainless steel vats. Therefore, Gutiérrez-Afonso [138], also using white wines, considered the influence of wood (in the form of oak chips or in oak barrels) on the sensory proprieties during the fermentation. The outcomes indicated that American oak chips induce a higher intensity of coconut and vanilla notes and an increase in the degree of astringency and bitterness sensations than barrels.

Other research works studied the application of non oak wood species on the sensory profile of white wines. Thus, Young et al. [139] carry out the aging of Chardonnay wines in contact with numerous diverse wood species from New Zealand, such as Feijoca, Matai, Cherry beech, Silver beech, Macrocarpa, Manuka, Pohutukawa, Radiata pine, Totara, Kahikatea, and Rimu, in comparison with American oak wood during 2 weeks. The outcomes found by these researchers showed that only Chardonnay wine aged in contact with Macrocarpa wood presented analogous flavors with oak white wine. Loupassaki et al. [140] reported results about a comparative study between the application of oak (*Q. petraea* and *Q. alba*) and false acacia wood barrels on the sensory characteristics of white wine aged for 9 months. The outcomes showed that wines aging in barrels manufactured with *Quercus alba* wood had the higher average scores, with more intense aromatic profiles and notes of "oak". Kozlovic et al. [75] reported after 12 months of aging that Malvazija wines aged in false acacia barrels presented higher finer textures and with more marked vanilla and spicy character than the wines aged in oak barrels. Other authors [88,89] also indicate that wines aged in false acacia barrels may have new sensory descriptors related to nutty, honeyed, and toasted notes.

Délia et al. [44] reported the positive influence of false acacia wood chips on the sensory characteristics of aged white wines. The outcomes showed significantly higher persistence in white wines aged with false acacia and French oak wood chips compared to other wines aged with cherry and American oak chip species. Jordão et al. [141] studied likewise the influence of toasted oak and cherry wood chips on sensory properties of numerous monovarietal white wines produced from Viosinho, Alvarinho, Loureiro, and Sauvignon Blanc grape varieties. The results showed that the influence of the application of cherry wood chips was mainly detected by the tasters for the wine vinified from the grape variety Viosinho with a rise of fruity aroma.

Finally, Del Galdo et al. [45] considered the application of diverse blends of toasted oak and cherry wood chips to develop numerous sensory descriptors of white wine. The authors reported a significant reduction of scores attributed to the panel taste during the aging time, although the white wine aged with cherry wood chips alone and control wine presented not as much of a marked decrease.

5. Final Remarks

In the last two decades, for numerous wood species, including oak species, a diversity of chemical compounds has been identified and quantified. However, only oak and chestnut species are authorized by the O.I.V. for enological application. Consequently, these two wood species are usually applied throughout the winemaking and aging process. Nevertheless, it is important to note that according to the O.I.V., the option for the application of wood chips is only possible for the *Quercus* genus. Nevertheless, more recently, the increasing request for oak wood has triggered significant growth in manufacturing and environmental concerns. In this way, other wood species have been pointed for winemaking, especially in non-European countries. However, the understanding of the effect of the application of non-oak wood species on wine quality is still new. Thus, the application of diverse wood species to the wine may be an alternative to produce wines with different sensory profiles. In this context, additional investigation is needed to increase the understanding of the potential effect of the different non-oak wood species on wine quality.

Author Contributions: A.M.J. and F.C. contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FCT-Portugal and COMPETE (grant number UIDB/00616/2020 and UIDP/00616/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Chemistry Research Center-Vila Real (CQ-VR) and Polytechnic Institute of Viseu for their financial support.

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

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