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Review

Different Woods in Cooperage for Oenology: A Review

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Abstract: Contact of wine with wood during fermentation and ageing produces significant changes in its chemical composition and organoleptic properties, modifying its final quality. Wines acquire complex aromas from the wood, improve their colour stability, flavour, and clarification, and extend their storage period. New trends in the use of barrels, replaced after a few years of use, have led to an increased demand for oak wood in cooperage. In addition, the fact that the wine market is becoming increasingly saturated and more competitive means that oenologists are increasingly interested in tasting different types of wood to obtain wines that differ from those already on the market. This growing demand and the search for new opportunities to give wines a special personality has led to the use of woods within the *Quercus* genus that are different from those used traditionally (*Quercus alba*, *Quercus petraea*, and *Quercus robur*) and even woods of different genera. Thus, species of the genus *Quercus*, such as *Quercus pyrenaica* Willd., *Quercus faginea* Lam., *Quercus humboldtti* Bonpl., *Quercus oocarpa* Liebm., *Quercus frainetto* Ten, and other genera, such as *Robinia pseudoacacia* L. (false acacia), *Castanea sativa* Mill. (chestnut), *Prunus avium* L. and *Prunus cereaus* L. (cherry), *Fraxinus excelsior* L. (European ash), *Fraxinus americana* L. (American ash), *Morus nigra* L, and *Morus alba* L. have been the subject of several studies as possible sources of wood apt for cooperage. The chemical characterization of these woods is essential in order to be able to adapt the cooperage treatment and, thus, obtain wood with oenological qualities suitable for the treatment of wines. This review aims to summarize the different species that have been studied as possible new sources of wood for oenology, defining the extractable composition of each one and their use in wine.

Keywords: traditional oaks; different oaks; other woods; ellagitannins; low molecular phenols; volatile compounds

1. Introduction

The wine trade controlled mainly by Greeks and Romans (2000 BCE) used earthenware jars and amphora, although these containers were fragile, heavy, and difficult to handle. Faced with this problem of transporting wines from the production to the consumption areas, wooden containers were created. The study of archaeological findings and written testimonies allows us to establish how wooden barrels displaced clay amphorae for wine transport and storage: a revolution. There are many references to the use of wooden containers for wine. The best-known reference is possibly that of Julius Caesar in "The Gallic Wars" (51 BCE) [1,2]. From the 5th century onwards, the term 'barrel' was used to designate these wooden containers. Since then, oak has been one of the main woods for this purpose, being a resistant, flexible, easy to handle, and not very permeable material. Specifically, the European species, mainly *Quercus petraea* and *Quercus robur*, were used as they were abundant near the areas where wine was made.

In the mid-twentieth century, the use of wood was notably abandoned due to the proliferation of other materials (cement and stainless steel). However, from the 1990s onwards, the use of wooden barrels re-emerged rather significantly and became a world fashion [2–4]. In addition, this resurgence also led to a change in their use. Nowadays, wine ageing has changed with the use of newer oak barrels because with their use the extractability of the oak compounds decreases. For this reason, in recent years, an imbalance between the amount of oak available and the number of barrels produced has been detected in France [5]. Moreover, the price of cooperage logs is increasing steadily with a concomitant decrease in the quality/price ratio. Given the growing demand for French oak barrels (*Quercus petraea* and *Quercus robur*) and the increase in price, some cooperages also work with oak from Eastern Europe (Romania, Hungary, Russia), as it is the same species with characteristics similar to those of French oak. Many oenologists have used barrels of this type of oak, as the results obtained are comparable to those of ageing wine in French oak. For these reasons, over the last few years, there has been a proliferation of studies on European oaks of the same species but of different origins. In recent years, the literature has offered studies about Slovenian oak [6], Spanish oaks [7–11], Hungarian oaks [12,13], Russian oaks [13,14], Romanian, Ukrainian, and Moldavian oaks [15], Romanian oak [16,17], among others. These studies of the same species but different origin showed similar characteristics to American and French oaks, suggesting that they are suitable for barrel production for quality wines. Some authors even state that these origins have intermediate characteristics between French and American oaks [7,9,15].

Singleton mentions different woods within cooperage, from both the United States (white oak, red oak, chestnut oak, red or sweet gum, sugar maple, yellow or sweet birch, white ash, Douglas fir, beech, black cherry, sycamore, redwood, spruce, bald cypress, elm, and basswood) and Europe (white oak, chestnut, fir, spruce, pine, larch, ash, mulberry), and a number of additional species imported from Africa, South America, and Australia (acacia, karri: *Eucalyptus diversicolor*; jarrah: *Eucalyptus marginata*; stringybark: *Eucalyptus obliqua* and *Eucalyptus gigantea*; and she oak: *Casuarina fraseriana*). However, this long list of woods rapidly diminishes when considering only those that are suitable for ageing different alcoholic beverages [18]. As the number of wood species declined, oak and chestnut became the most widely used varieties in barrel-making and so were already those most used from the 16th century onwards [19–21]. They were chosen because they modified the gustatory and olfactory characteristics of the different wines and spirits favourably [21]. These two woods (*Quercus* and *Chestnut*) are the only ones approved today by the Organzation of Vine and Wine (OIV) (Resolution OENO 4/2005).

The typical anatomy of oak offers greater resistance, flexibility, easy handling, and low permeability in relation to those provided by other woods [22]. At present, oak (*Quercus*) is the preferred material for the manufacture of barrels for ageing alcoholic beverages, especially wines. Oak belongs to the genus *Quercus*, which is made up of more than 250 species, although this figure is controversial as some authors cite up to 600 [21,23]. Most of these are to be found in the temperate zones of the northern hemisphere as far as south to Central America and Ecuador. The number of species increases from East to West, from Europe and Africa to the North American Pacific coast, Mexico being the country with the greatest diversity of species. The *Quercus* genus is subdivided into two subgenera, Cyclobalanopsis and Euquercus: the first includes tropical species and some from Asia and Malaysia not used in the manufacture of barrels for oenological use, while those within the subgenera Euquercus are used in cooperage [21]. Within these species, few meet all of the requirements, and those most used belong to the group of white oaks [5]. According to Vivas [21], some of the species used in cooperage in the USA and Europe are *Quercus alba*, *Quercus garryana*, *Quercus macrocarpa*, and *Quercus stellata*, and only in Europe *Quercus cerris*, *Quercus suber*, *Quercus coccifera*, *Quercus lanuginosa*, *Quercus petraea*, and *Quercus robur*. The main species used for wine ageing belong to the genus *Oersted* (formerly Lepidobalanus): *Quercus petraea* L. (*Quercus sessilis*) and *Quercus robur* (*Quercus pedunculata*) growing in Europe and *Quercus alba* growing in different areas of the United States.

In America, white oak has only been associated with *Q. Alba* for years; however, strictly speaking, the classification of "white oak" includes many other species, such as: *Q. alba*, *Q. garryana*, *Q. macrocarpa* M., *Q. stellata* Wan., *Quercus lyrata* Walt., *Quercus prinus*, *Quercus muehlenbergii* E., *Quercus michauxi* Nutt, *Quercus bicolor* Willd., *Quercus lobata Née*, *Quercus montana* Willd, and *Quercus virginiana* L. [24,25]. Thus, in cooperage, *Q. alba*, a majority species in the eastern United States, has been associated with numerous species resulting in confusion, as is the case for: *Q. prinus*, *Q. muehlenbergii*, *Q. bicolor*, *Q. stellata*, *Q. macrocarpa*, *Q. lyrrata*, and *Quercus durandii* [18,26].

In Europe, the largest forests producing high-quality oaks are found in France. Forests cover 27% of the total area of France, and approximately 9% of these are oak forests. The regions of Le Fôret du Centre, Nevers, Tronçais, Allier, and Limousin in the Massif Central and Vosges in the northeast of the country are particularly important producers. Although French oak is the most highly valued in Europe, other producer regions include Hungary, Poland, Russia, Italy, and, in the Iberian Peninsula, the Basque Country. In fact, until the 1930s, the oak that was most widely used in the châteaux of Bordeaux came from Russia rather than France. However, *Q. petraea* and *Q. robur* are associated with France and not the rest of Europe.

In general, American oaks differ from European species because they have higher density and resistance and lower porosity and permeability than European species [25]. In addition, American woods have larger tylosis, which allows this wood to be cut by sawing without compromising the watertightness, which leads to a better use of wood. Heartwood of *Quercus* is composed of macromolecules that are polymers of cellulose, hemicellulose, and lignin, representing 90% of dry wood. In addition, there is an extractable fraction that are soluble compounds released to wine during aging; this part represents approximately 10% of dry wood and is variable depending on species. The extractable fraction (ellagitannins, low molecular weight compounds and volatile compounds) in wood depends not only on variety but also on many other factors, such as sylvocultural factors, geographic origin, and individual tree and cooperage processing, with high variability in content (Tables 1 and 2). In general, *Q. robur* has the highest content of ellagitannins followed by *Q. petraea* and finally *Q. alba*. In addition, *Q. alba* also tends to have lower content of low molecular weight compounds (Table 1) and *Q. robur* lower aromatic compounds (Table 2).

Table 1. The range of ellagitannins and low molecular weight phenolic (LMWP) compounds found in green, seasoned, and toasted wood. * sum of castalagin, vescalagin, granidin, and A, B, C, D, and E roburins; ** sum of acids (ellagic, gallic, syringic, vanillic, and ferulic), aldehydes (coniferaldehyde, sinapaldehyde, syringaldehyde, and vanillin) and cumarins (scopoletin and aesculetin); *** sum of gallic acid and elagic acids.

Treatment	Species	Concentration Range Ellagitannins (mg/g) *	References	Concentration Range LMWP (μg/g) *	References
Untreated (green wood)	*Quercus pyrenaica* Willd.	28.12–32.72	[27–29]	265–1061	[23,27,28,30]
	Quercus faginea Lam.	32.51	[28,29]	407	[28,30]
	Quercus frainetto Ten.	-	-	-	-
	Quercus oocarpa Liebm.	-	-	-	-
	Quercus humboldtti Bonpl.	1.94	[16]	365	[16]
	Castanea sativa Mill.	-	-	-	-
	Robinia pseudoacacia L.	-	-	-	-
	Prunus avium L.	-	-	-	-
	Prunus cereaus L.	-	-	-	-
	Fraxinus americana L	-	-	-	-
	Fraxinus excelsior L.	-	-	-	-
	Quercus petraea	8.65–32.10	[16,28,29]	225–752	[16,28,30]
	Quercus robur	28.41–44.01	[28,29]	310–647	[28,30]
	Quercus alba	3.48–5.96	[16,29]	237–486	[5,16]
Seasoned	*Quercus pyrenaica* Willd.	2.81–77.9	[8,31–33]	475–4304	[7,28,31,33–35]
	Quercus faginea Lam.	24.11–26.97	[8,28]	760–1422	[7,28]
	Quercus frainetto Ten.	108	[36]	3800 ***	[36]
	Quercus oocarpa Liebm.	33.9	[36]	5500 ***	[36]
	Quercus humboldtti Bonpl.	1.61	[17]	832	[17]
	Castanea sativa Mill.	4.74–76.3	[31,33,36–38]	1155–14,430	[31–34,36–41]
	Robinia pseudoacacia L.	nd	[42,43]	41–408	[40,42]
	Prunus avium L.	nd–0.04	[31,43,44]	6–620	[31,44]
	Prunus cereaus L.	-	-	228	[40]
	Fraxinus americana L.	nd	[43,45]	98	[45]
	Fraxinus excelsior L.	nd	[43,45]	53	[45]
	Quercus petraea	1.98–80.62	[8,17,28,31,32,36,38]	368–3400	[7,17,28,31,34,38]
	Quercus robur	3.93–87.4	[8,31,32,36]	647–4166	[7,28,31,34,45]
	Quercus alba	0.88–35.64	[8,17,31,32,36]	469–1064	[7,17,31]

Table 1. *Cont.*

Treatment	Species	Concentration Range Ellagitannins (mg/g) *	References	Concentration Range LMWP (μg/g) *	References
Toasted	*Quercus pyrenaica* Willd.	4.32–47.05	[8,32,33,46]	607–20,500	[7,33,35]
	Quercus faginea Lam.	9.34	[8]	2132	[7]
	Quercus frainetto Ten.	-	-	-	-
	Quercus oocarpa Liebm.	-	-	-	-
	Quercus humboldtti Bonpl.	0.12	[17]	2464	[17]
	Castanea sativa Mill.	0.66–10.51	[33,37]	1353–35,282	[7,33,35,37,40,47,48]
	Robinia pseudoacacia L.	nd	[42,49]	6–2496	[40,42,44,46]
	Prunus avium L.	nd	[43,46]	90–3378	[44,46,48]
	Prunus cereaus L.	-	-	445–1578	[40]
	Fraxinus americana L.	nd	[43,45]	1915–3062	[45]
	Fraxinus excelsior L.	nd	[43,45]	1922–3585	[45]
	Quercus petraea	3.53–56.76	[8,17,32,46]	856–4420	[7,17,32,46]
	Quercus robur	7.72–11	[8]	2067–8225	[7,40,47,48]
	Quercus alba	nd–5.89	[8,17,32,46]	460–3620	[7,17,32,46,47]

nd: not detected.

Table 2. The range of volatile compounds expressed as μg/g wood found in green, seasoned, and toasted wood.

Treatment	Species	Guaiacol	Eugenol	Furfural	Trans-β-Methyl-γ-Octalactone	Cis-β-Methyl-γ-Octalactone	Vanillin	References
Untreated (green wood)	*Q. pyrenaica* Willd.	0.16–0.24	1.47–5.71	1.35–2.56	0.84–29.37	14.35–59	3.42	[27,50]
	Q. petraea	0.09	2.05	1.19	18.4	36.9	2.19	[50]
Seasoned	*Q. pyrenaica* Willd.	nd–1.25	nd–7.28	1.94–19.7	nd–33.8	5.3–68.2	1.6–25.24	[27,51–55]
	Q. faginea Lam.	0.29	1.98	17.6	1.74	15.5	10.6	[51]
	Q. humboldtti Bonpl.	0.1	2.65	nd	nd	0.02	1.97	[17]
	Castanea sativa Mill.	nd–0.38	0.71–4.47	2.27–6.72	nd–0.23	nd–0.34	2.90–24.40	[53,55–57]
	Robinia pseudoacacia L.	nd–0.86	nd–0.21	0.45–0.92	nd	nd	1.65–3.48	[55–57]
	Prunus L.	nd–0.53	nd–0.11	0.49–0.66	nd	nd	0.13–2.42	[55–57]
	Fraxinus americana L.	0.08–0.13	0.19–0.57	0.54–0.8	nd	nd	7.25–10.3	[55,57]
	Fraxinus excelsior L.	0.11–0.22	0.44–0.94	1.21–1.31	nd	nd	1.39–14.7	[55,57]
	Q. petraea	nd–1.3	0.57–6.5	3.4–19.9	0.09–14.7	0.42–55.9	2.0–18.8	[50,51,53–55]
	Q. robur	0.08–0.11	1.01–1.58	4.51–10.8	2.87–3.98	2.83–22.9	1.21–15.9	[51,53]
	Q. alba	0.04–3.3	1.38–5.9	1.2–4.68	2.52–5.0	22.3–32.5	6.8–7.9	[51,54,55]
Toasted	*Q. pyrenaica* Willd.	0.11–8.91	nd–14.6	19.6–4082	nd–58.6	0.10–212	8.69–235	[51,54,55,58–60]
	Q. faginea Lam.	0.36	2.35	96	1.08	3.25	258	[51]
	Q. humboldtti Bonpl.	3.74	3.34	533.53	0.06	0.3	22.36	[17]
	Castanea sativa Mill.	0.46–5.30	2.13–3.23	431–1675	nd	nd	7.15–143	[55,57]
	Robinia pseudoacacia L.	0.52–6.05	0.40–2.36	20.7–840	nd	nd	19.2–106	[55,57]
	Prunus L.	0.91–1.71	0.74–1.50	23–175	nd	nd	45–91.7	[55,57]
	Fraxinus americana L.	5.97–11.9	1.58–3.00	26.5–63.6	nd	nd	76.1–160	[55,57]
	Fraxinus excelsior L.	6.47–14.07	1.59–3.21	26.5–82	nd	nd	76.3–187	[55,57]
	Q. petraea	0.17–3.4	0.83–4.0	10.3–963	0.01–14.6	0.05–22.8	3.0–370	[51,54,55,60]
	Q. robur	0.17–0.53	1.01–1.37	8.90–10.8	3.41–3.98	2.83–22.9	130–172	[51]
	Q. alba	1.22–7.3	1.29–11.6	4.04–1539	3.29–7.4	16.1–45.5	7.5–102	[51,54,55,60]

Furthermore, the use of oak barrels in the production of quality wines implies long periods and a high economic cost for wineries. For this reason, alternative techniques to ageing in oak barrels have been used for over 15 years and these were developed to give wood characteristics to the wine in a faster, cheaper, and simpler way. They are based on the addition to the wine of pieces of wood of very different sizes and shapes (splinters, cubes, staves). These alternative products have been widely used for a long time in the producing countries of the New World, but their use has spread, above all, since the main wine producer, Europe, changed its legislation to admit their use. This maturation practice was approved by the International Oenological Codex of the International Organization of Vine and Wine (OIV) (OENO 9/2001) and by the Official Journal of the European Union (CE 1507/2006).

2. Oak Species Not Traditionally Used in Cooperage

The use and/or study of alternative oaks (other species of the genus *Quercus*) is proposed as a solution to the search for new sources of quality wood for cooperage that provide wines with differentiated notes appreciated by the consumer. For this reason, a market opportunity has arisen for oak species not traditionally used in cooperage, such as *Quercus pyrenaica*, *Quercus faginea*, *Quercus frainetto*, *Quercus oocarpa*, and *Quercus humboldtii* and others that are less well-known, such as *Quercus serrata*, *Quercus mongolica* or *Quercus denta* (Figure 1).

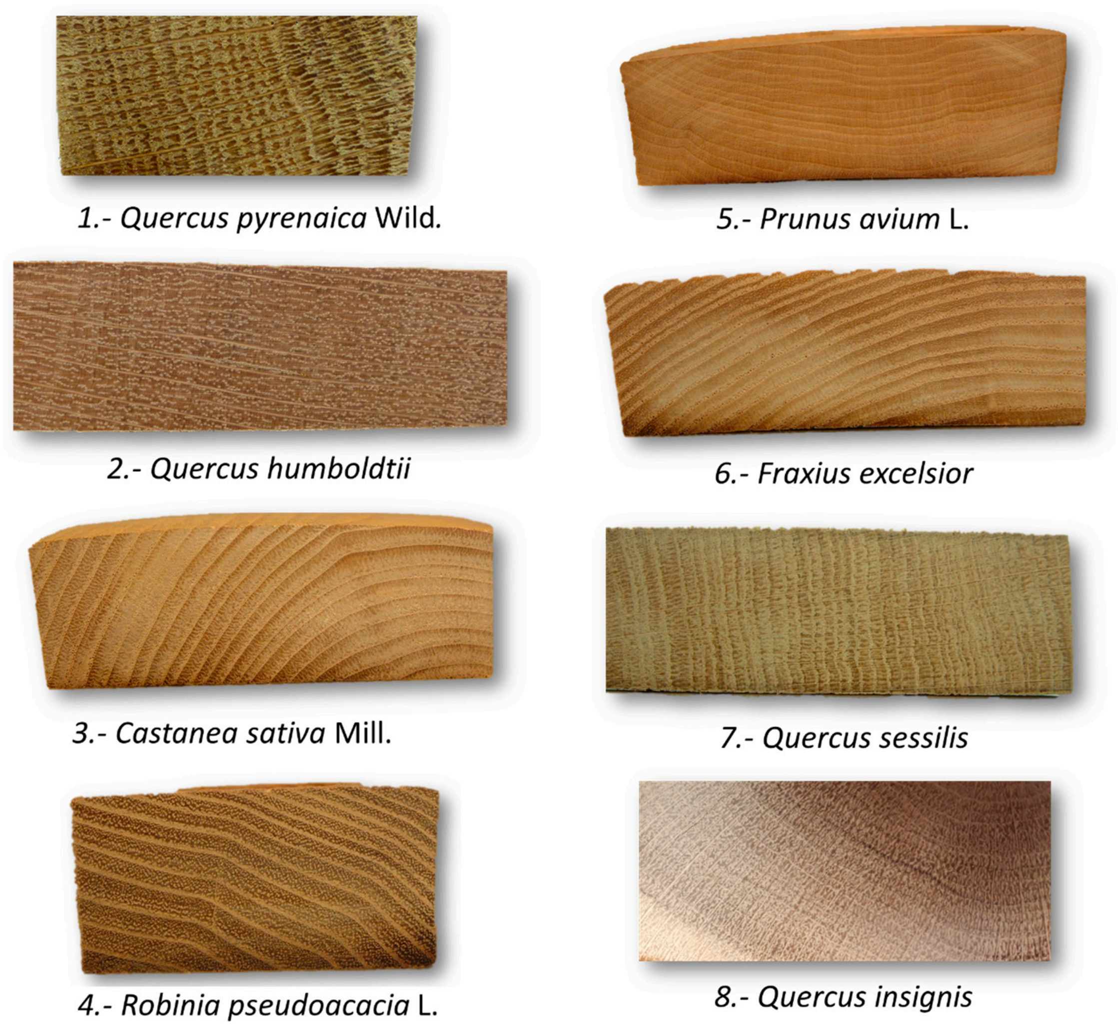

Figure 1. Cross-sections of some of the non-standard species in cooperage in comparison with *Q. sessilis*.

2.1. Pyrenaica Oak (Quercus Pyrenaica Willd)

It is distributed throughout the western Atlantic–Mediterranean regions (West France, Portugal, Spain, and North Morocco) through a wide range of altitudes, from sea level to over 2000 m. This wood is known as "rebollo" or "melojo", and is mostly located in Spain (Allué, 1995) with a forest mass of 1,090,716 ha, the majority of which is found in the region of Castilla y León [61] (Figure 2). Traditionally, this wood has been used in Spain for railway sleepers and ships and, in recent years, especially as firewood from low forest cover, an arboreal mass composed of feet coming from buds or roots. This has resulted in a progressive degradation of the characteristics of some of these forest areas, such as a high percentage of trees with a diameter of <40 cm and knotty, twisted, or short-boled trees. Therefore, their use for manufacturing barrels is very limited due to the high number of poor quality trees for cooperage. However, its structural properties (mesh, grain, density, and permeability) are also appropriate for oenological use [27].

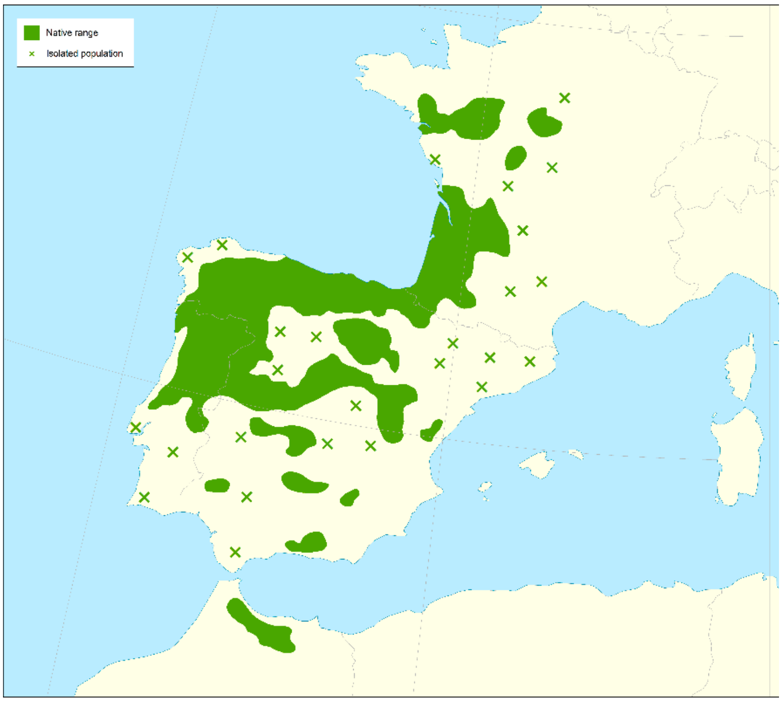

Figure 2. *Quercus pyrenaica* Willd distribution map [62]. https://commons.wikimedia.org/wiki/File:Quercus_pyrenaica_range.svg.

Various studies from 1996 to the present place value on this wood's content of ellagitannins, low weight, and aromas [7,8,27–32,34,35,46,50–53,55,58,59,63–65], as well as its use for containers of alcoholic drinks, such as brandy and other spirits [66–70] and wines [9,10,58,60,71–79]. However, the supply of quality wood for the manufacture of barrels is insufficient, so this wood can be used for the manufacture of alternative products in the short and medium term. With proper management, these forests could supply wood for the manufacture of barrels in the future. Consequently, most studies on the behaviour of this wood during wine ageing have been carried out with alternative products (in particular chips or staves) [58,60,71–77,79], observing that wines aged with this wood present good final characteristics. The resulting wines are closer to those aged with French oak than those aged with American oak, thus meaning this wood is suitable for producing quality wines [9,10,74]. In addition, peculiarities have been reported, such as that wines aged with barrels of this oak species had high levels of eugenol, guaiacol, and other volatile phenols, while the contents of cis-β-methyl-γ-octalactone or maltol are similar to those of wines aged with *Q. alba* [76]. However, Fernandez de Simón et al. [60] observed that the Tinta del País variety, in addition to having a higher concentration of eugenol, also had a higher content of cis-β-methyl-γ-octalactone than the same wine treated with French and

American oak, especially when staves were used. In tasting, wines aged in *Q. pyrenaica* wood barrels are more appreciated than the same ones aged in American or French oak barrels [76]. Gallego et al. 2012 [79] also observed that the wines aged with chips and staves from *Q. pyrenaica* oak were better considered than American or French ones, showing higher aromatic intensity and complexity, and woody, balsamic, and cocoa notes. Connick et al. [77] carried out a sensorial analysis and found that wine aged in contact with *Q. pyrenaica* chips only differed to wine aged with *Q. petraea* for woody character and attained a higher score. However, a wine from two Portuguese red grape varieties (Tinta Roriz, 80% and Touriga Nacional, 20%), aged with chips of *Q. petraea* versus *Q. pyrenaica*, reported that, from a sensory point of view, the wine with French oak chips showed a tendency for higher aroma scores than those aged in contact with *Q. pyrenaica* oak [71]. As regards oxygen, a very important factor in the ageing of wines, Del Álamo et al. [73] reported that the same red Tempranillo variety aged with *Q. pyrenaica* required less oxygen than the same one aged with traditional oak species (*Q. petraea* and *Q. alba*). Similarly, Gonalves and Jordão 2009 [75] recorded that Syrah wines aged in contact with *Q. pyrenaica* oak species had higher antioxidant activity values than those aged in contact with the American oak species.

2.2. Quercus Faginea Lam

A wood studied from 1996 [30] to the present [80] for oenological purposes. This species is endemic to the Iberian Peninsula and North Africa. Its common name is Quejigo, with about 269,000 ha distributed mainly in Castilla-La Mancha, Castilla y León, Aragón, and Cataluña on the peninsula [61,81] (the protected surface area is under 4%, due to its dispersion and abundance in Spain [81]). It is a medium-sized deciduous or semi-evergreen tree growing to a height of 20 m and a diameter of 80 cm. This species once covered (during the 15th and 16th centuries) much of the Iberian Peninsula, and the wood was valued and intensively exploited for naval construction [82]. It was traditionally used for the production of charcoal, and it has also been used in the manufacture of beams for construction due to its strength and resistance. *Q. faginea* wood has a white yellowish sapwood and brown yellowish heartwood, high density, and considerable mechanical strength [80]. Its composition in ellagitannins, low molecular weight compounds, and volatile compounds in wood has been studied [7,8,10,28–30,51,63,80], as well as its interaction with wine [9,10,78]. The antioxidant activity is very high, with an IC50 of 3.3 μg/mL for heartwood, as compared to standard antioxidants (an IC50 of 3.8 μg/mL for Trolox) [80]. Miranda et al. [80] reported that *Q. faginea* is a very good candidate for cooperage due to it being a source of compounds with antioxidant properties. However, after studying the volatile composition of different species of Spanish oak, both in traditional species (*Q. robur* and *Q. petraea*) and new species (*Q. faginea* and *Q. pyrenaica*), Cadahía et al. [51] propose that, while *Q. pyrenaica* may be considered suitable for wine ageing, *Q. faginea* is not. In addition, a wine was in contact with this oak for 21 months and then compared with other species, especially traditional ones, and it was observed that wine aged with *Q. faginea* was the least preferred by the tasting panel and always the one that obtained the lowest scores in almost all descriptors [10]. Fernández de Simón et al. 2003 [9] studied the low molecular weight phenolic compounds in red Rioja wine aged during 21 months in barrels made of *Q. Faginea* oak and other woods (*Q. pyrenaica*, *Q. robur*, *Q. petraea*, and *Q. alba*), showing by means of a discriminant analysis that wines aged with *Q. faginea* could be discriminated from the rest by function 2, which was related to trans-resveratrol, p-hydroxybenzaldehyde, syringic acid, ellagic acid, and 5–HMF.

2.3. Quercus Frainetto Ten

This species is native to the Balkan Peninsula and also present in South Italy and Northwest Turkey (Figure 3). Despite also being known as Hungarian oak, its presence in Hungary is sporadic [83]. In Greece, it is a vital timber tree and frequently managed as coppice forest for both firewood and timber in combination with grazing. In the other countries in which it grows, it is most often used for firewood, although the quality of the wood is similar to *Q. petraea*. Because of the rather high durability of its wood, *Q. frainetto* has sometimes been used as construction material in civil engineering and mining. Vivas [21] is studying this species with the aim of using it in cooperage. This wood has an ultra-structure that is comparable to French oaks, and its lindens are similar to those of *Q. alba*. However, in the manufacture of barrels with *Q. frainetto*, the staves have been found to need longer heating during taming, which could be due to their high density [21]. This species also has a high content in ellagitannins [36]. As regards the gustatory quality of the wood extracts of this species, it has high bitterness and particular and indefinable aromas, but both attributes can be cushioned by the natural drying and toasting of the wood [21].

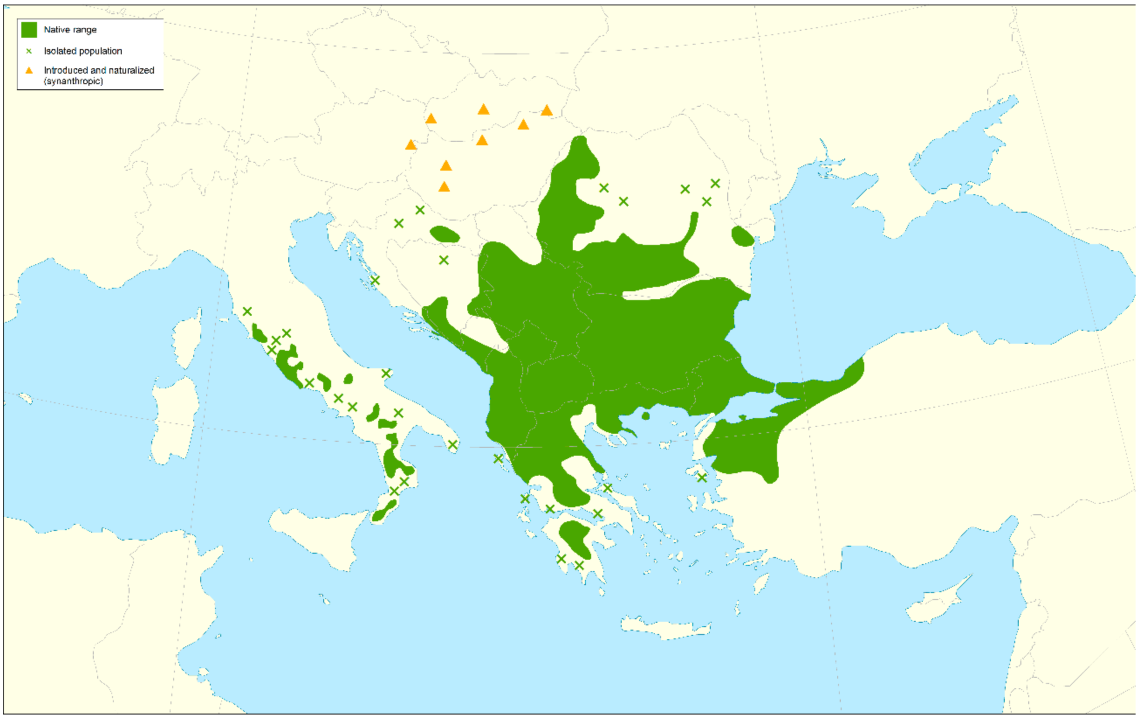

Figure 3. *Quercus frainetto* Ten. distribution map [62]. https://commons.wikimedia.org/wiki/File:Quercus_frainetto_range.svg.

2.4. Quercus Oocarpa Liebm

This species is also used in wine ageing [36] and extends naturally from Veracruz, Mexico, through Chiriquí, Panama, Guatemala, and Costa Rica, where it is found in Monteverde, Puntarenas; Cordilleras de Tilarán and Central; Escazú, San José; Muñeco, Cartago; and the Cordillera de Talamanca [84]. Vivas [21] proposes this as a new species when observing that it presents an ultra-structure that is comparable to French oaks with a clear succession of early and late wood, forming an annual growth and, with respect to its lime trees, observed that *Q. oocarpa* was comparable to *Q. alba*. This species presents only monomers of ellagitannins, since during its analysis no dimer was found [36]. Regarding the gustatory quality of the extracts of these woods, the quality of the *Q. oocarp* was similar to that of *Q. petraea* [21].

2.5. Quercus Humboldtii Bonpl

This is one of the main forest species in the woods of Colombia [85]. This white oak is a neotropical species found in the Three Mountains range, from 750 m to 3450 m above sea level, in 18 departments of the Colombian Andes (Antioquia, Bolívar, Boyacá, Caldas, Caquetá, Cauca, Chocó, Cundinamarca, Huila, Quindío, Risaralda, Nariño, North of Santander, Santander, Tolima, Valle del Cauca, Cesar, and Córdoba) [85]. The hardwood is hard, heavy, and easy to work and its density is 0.9–1 g/cm^3. Traditionally, it has been used for making posts, railroad ties, handles for tools, wooden rollers, charcoal, and firewood [86]. In addition, this species is normally used in barrel-making; specifically, it has been utilised by two companies since the middle of the 20th century. Cooperage products made from this "White oak" have normally been used to age alcoholic beverages, such as rum [87] or brandy. Recently, three studies on the composition of this oak when green and before and after toasting have been published [16,17,88]. The phenolic composition (ellagitannins and low molecular weight phenols) of green *Q. humboldtii* was characterized and compared to traditional oak wood species, with the most abundant phenolic acids, aldehydes, and ellagitannins being the same as in *Q. alba* and *Q. petraea*, and with a phenolic composition closer to that of the American ones [16]. The study on syringaldehyde and vanillin contents showed a similar vanillin concentration to *Q. Faginea* in toasted wood and a balanced syringaldehyde/vanillin relationship, a marker usually used to characterize oak wood quality [88], when seasoned and toasted. *Q. humbolditti* had comparable low molecular weight phenols to woods of *Q. petraea* and *Q. alba*. Its ellagitannin composition was similar to that in *Q. alba*, and its volatile composition differed from that of *Q. petraea* and *Q. alba*, since it had the highest concentration of 5-methyl furfural, furfuryl alcohol, guaiacol, 4-ethylguaiacol, 4-vinylguaiacol, cis and trans-isoeugenol, and syringol and the lowest furfural, 5-hydroxymethylfurfural, and *cis*-β-methyl-γ-octalactone concentrations [17]. When this wood is used as an alternative for ageing wines compared to traditional species, the wines macerated with *Q. humboldtii* chips showed higher concentrations of 5-methylfurfural, guaiacol, isoeugenol, trans-isoeugenol, and syringol and lower furfural, 5–HMF, *trans*-β-methyl-γ-octalactone, and *cis*-β-methyl-γ-octalactone content [89]. In the sensorial analysis, there were no negative comments from the tasters about the wine macerated with Colombian oak; in addition, few significant differences in the sensorial analysis were observed in these wines compared to those aged with traditional oaks. Therefore, *Q. humboldtii* oak has an interesting oenological potential as an alternative species for coopering [89].

3. Woods Not Traditionally Used in Cooperage Different to Oak

The growing demand for wood for cooperage and the search for new opportunities to give wines and their derivatives a special personality have led to the use of woods other than oak, some of which have been used for many years. This is how wood from species such as *Castanea sativa* Mill. (chestnut), *Robinia pseudoacacia* L. (false acacia), *Prunus avium* L. and *Prunus cereasus* L. (cherry), *Fraxinus excelsior* L. and *F. americana* L. (*European ash* and *F. americana* L.). (European and American ash, respectively), and *Morus alba* L. and *Morus nigra* L. (Mulberry) have been proposed as alternatives to oak (Figure 1). In addition to those mentioned above, experiments in wines have been made with other types of wood, such as *Juglans regia*, *Juniperus communis*, *Pinus heldreichii var. Leucodermis*, *Prunus armeniaca*, *Fagus Syvatica*, and *Alnus glutinosa* [48,90], but, to date, few trials have been carried out. Moreover, many producers prefer using local woods in order to reduce costs [43], and, recently, some wine cellars have ordered barrels with some non-oak staves included from cooperages.

3.1. *Castanea Sativa Mill*

This species of the Fagaceae family can be found in southern Europe and Asia (China) (Figure 4). Chestnut is widely cultivated for its tasty edible fruits. Its starch is used in industrial applications, such as paper, plastics, textiles, food, pharmaceuticals, and cosmetics, and its wood is of interest for the manufacture of stakes. Moreover, this species has been widely used for oenological purposes in the Mediterranean area in the past due to its widespread availability and low cost [91]. As mentioned above, it is the only species alongside *Quercus* that has been accepted for use by the OIV. It seems that there is a growing interest in the use of this wood in the ageing of different drinks, which is why numerous studies have been carried out on the characteristics of this wood [31,33,34,36–41,43,47,51,53,54,92,93] and its use for the purpose of ageing spirits [36,67–70,91,94–103], vinegars [53,104,105], and wines [57,106–113]. Chestnut wood barrels prove to be suitable for the ageing of wine liqueurs, as they improve the chemical composition and the sensory properties of the alcohol of the aged wine, showing higher content of total phenolics and of low molecular weight compounds and higher antioxidant activities [100]. The sensory properties found in spirits aged in chestnut wood demonstrate the potential of this wood for the ageing of alcoholic beverages [69], with the heat treatment in cooperage having a very significant influence on the majority of low molecular weight extractable compounds by brandies aged two years in chestnut barrels [39]. Chestnut wood proved to be a suitable alternative to Limousin oak for ageing brandies, showing a high quality, with a faster evolution of brandies and more economical ageing as the price is lower [91]. However, chestnut does not seem to be the most suitable for vinegar ageing, as the best results are found when oak or cherry are used [104,105]. Regarding the ageing of wine in barrels made of this wood, it has been observed that they are suitable for short periods, but not for prolonged ageing, due to the high porosity [108–113]. Thus, Rosso et al. [113] observed a low content of oxidizable polyphenols in wines aged with chestnut, indicating that this type of wood causes a more oxidative environment than oak and is, therefore, less suitable for prolonged ageing. Alañon et al. [108] reported that wines aged for long periods in chestnut present off-flavours (4-ethylphenol and 4-ethylguaiacol) and oxidation problems. However, chestnut is an excellent flavouring wood for short periods of ageing in barrels, as very balanced wines are obtained [108]. Arfelli et al. [106] observed that red Sangiovese wine aged in old chestnut barrels were more fruited and tannic than in Allier, while the latter were less astringent, more balanced, and had more vanilla notes.

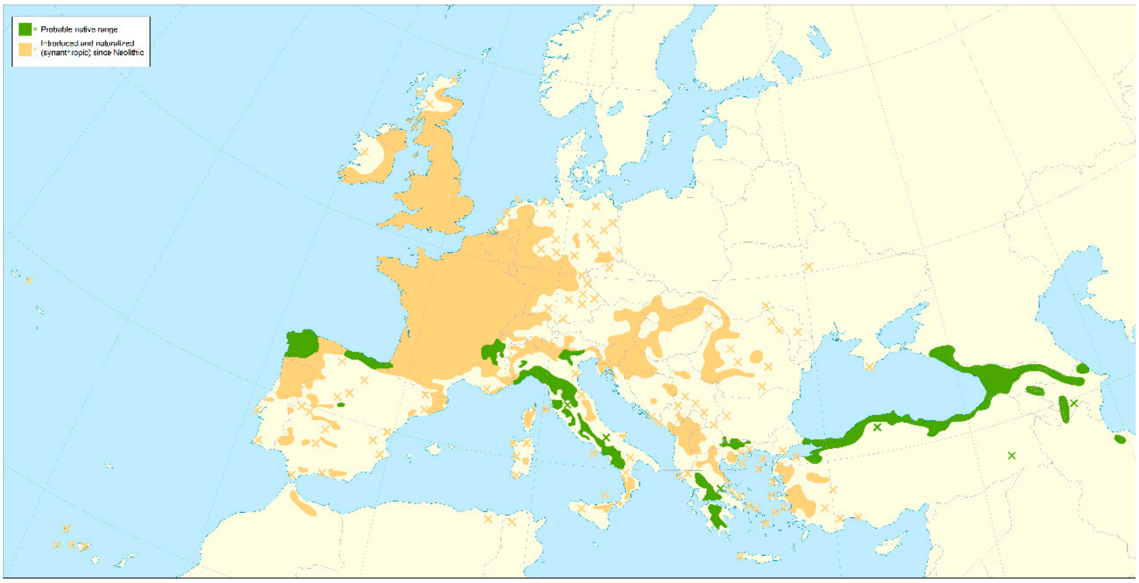

Figure 4. *Castanea sativa* Mill. distribution map [62]. https://commons.wikimedia.org/wiki/File:Castanea_sativa_range.svg.

3.2. *Robinia Pseudoacacia* L., *(False Acacia)*

This species, originating in the eastern United States and introduced into Europe, is often referred to as acacia, but its proper name is robinia [42] (Figure 5). It is considered a rapid-growth species with adaptive plasticity compared to others [114]. Traditionally, it has been used for the production of poles and pulp, as well as for other uses, such as erosion control and fodder. It has now been proposed for cooperage purposes, as robinia barrels are approximately 10% cheaper than French oak though still more expensive than American oak. Acacia wood is hard, with a low porosity [115]. In the last 10 years, research papers have been published focusing on the characterization of this wood for cooperage purposes and its use with alcoholic beverages, especially wines [71,110–113,116–119] and vinegars [104,105,120]. Red wines aged in acacia barrels have higher notes of smoky, spicy, and fruity, and may be related to their richness in mono and dimethoxyphenols, acetosyringone, and ethyl vanillate [111,121]. Fernández de Simón et al. [111] observed that, after the use of barrels of the species cherry, chestnut, acacia, ash, and oak, the wines with the highest scores were those aged with acacia and oak [111]. Acacia barrels also had a positive influence on the quality of Istria wines, as they were the best-rated with the highest amount of simple volatile phenol compounds [116]. In the case of white wines, the preference of this wood over others, such as cherry and even over American and French oak, was also observed [119]. The use of acacia for vinegar ageing is increasing due to the air transfer efficiency that favours a good rate of acetification [122], since, of all of the woods studied, the acacia barrels were observed to be those with the highest oxygen permeability. However, regarding the aromatic notes of the vinegars aged with wood, Callejon et al. [105] suggest that the best woods are cherry and oak, not acacia.

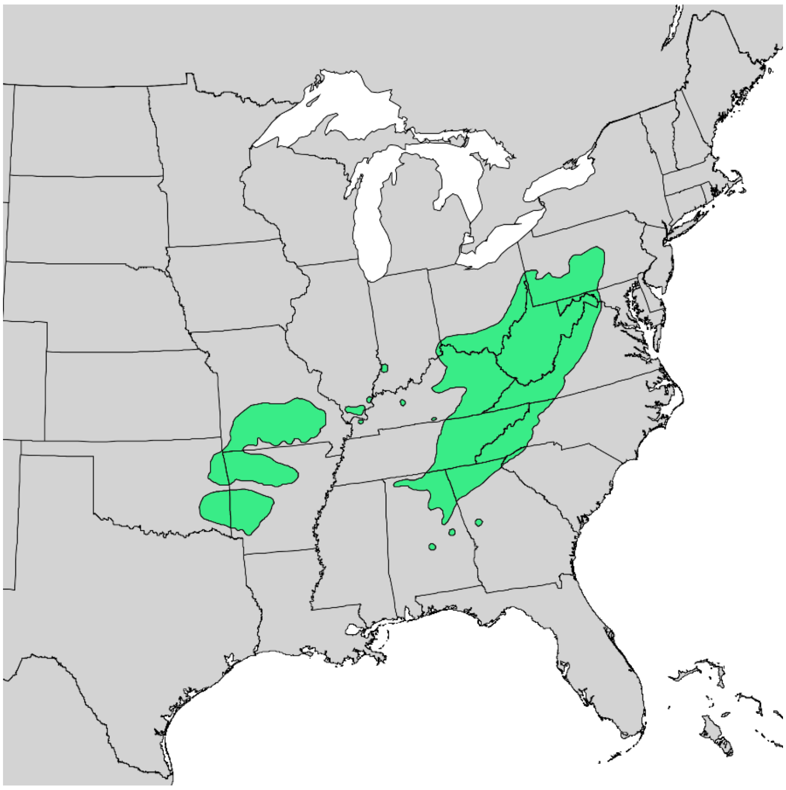

Figure 5. *Robinia pseudoacacia* L. distribution map [123]. https://commons.wikimedia.org/w/index.php?curid=29169867.

3.3. *Prunus*

The cherry species studied for this purpose are *Prunus avium* L. and *Prunus cerasus* L., related to each other and native to Europe and western Asia (Figure 6). The cherry has been extensively studied in recent years in order to know its characteristics [31,43,44,55–57,92,124] and the effect it provides during the ageing of different drinks, such as wine, distillates, and vinegars [40,48,71,105,110–113,117,119,125,126]. This wood has a high porosity and oxygen permeation, and is usually used for short ageing times [40]. Fernández de Simón et al. [110], after studying white, rosé, and red wines aged using barrels and chips, observed that 6 (aromadendrin, naringenin, taxifolin, isosakuranetin, eriodictyol, and prunin) of the 68 identified nonanthocyanic phenolic compounds were only identified in wines aged with cherry wood. Thus, the nonanthocyanic phenolic profile could be a useful tool to identify wines aged in contact with this wood. In addition, significant differences were found in certain compounds with respect to *Q. petraea* and *Q. alba*. Delia et al. [119] showed that the white wine aged in contact with cherry chips showed similar overall appreciation scores to those obtained for the wines aged with *Q. alba* and *Q. petraea* chips. De Rosso et al. [113] also found some special characteristics in wines aged in untoasted cherry barrels compared to other woods (acacia, chestnut, mulberry, and oak), suggesting that this wood allows for greater oxygen penetration through its staves. However, Torrija et al. [122] observed that the most permeable to oxygen was acacia. Cerezo et al. [104] observed that vinegars from red wines after their acetification with better scores in the sensory analysis were those from ageing with this wood together with oak, presenting better notes of global impression and red fruits. De Rosso et al. [113] also found some special characteristics in wines aged in a cherry-barrel compared to other woods (acacia, chestnut, mulberry, and oak), suggesting greater oxygen penetration through their staves; and, therefore, proposed their use for shorter ageing times.

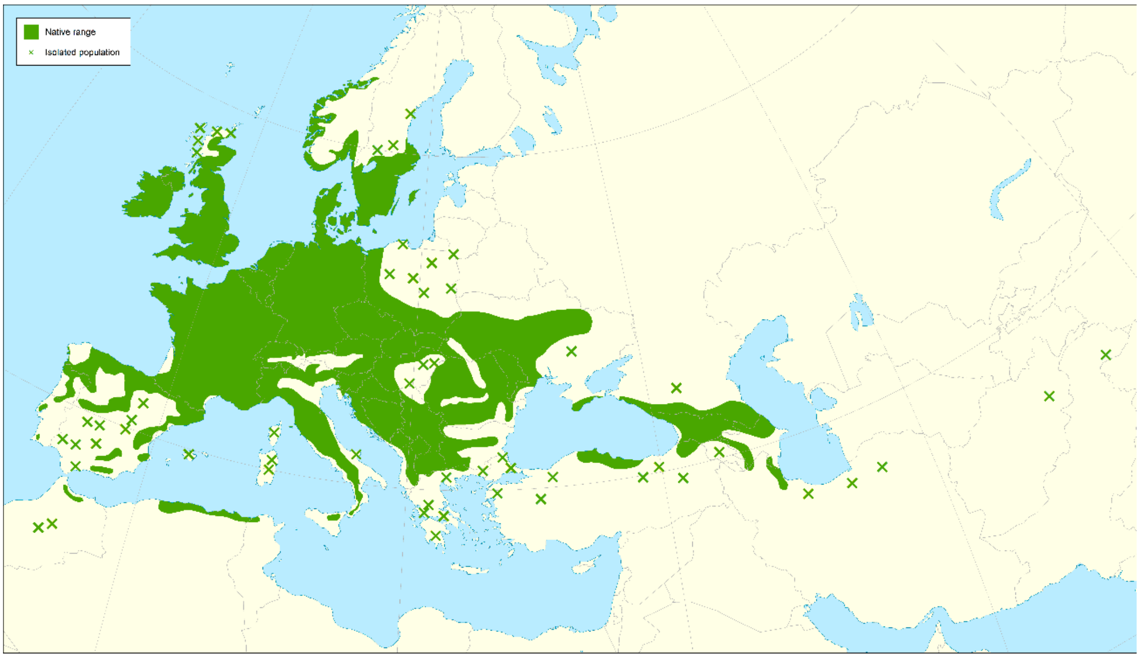

Figure 6. *Prunus avium* L. distribution map [62]. https://commons.wikimedia.org/wiki/File:Prunus_avium_range.svg.

3.4. Fraxinus

This genus of the family of oleaceae, generally known as ash, is found in the geographical area of the *Fraxinus excelsior* L. extending throughout Europe, Asia Minor, and North Africa, preferably in oceanic climates (Figure 7). It reaches heights of up to 40 m, and specimens from 20 to 30 m are common. This species only grows properly in areas where the climate and soil conditions provide a good water supply throughout the year. Ash is highly appreciated. The highest quality logs are destined for the veneer industry, where they reach their maximum price. Ash is also highly valued in the sawmill and cabinet-making industries. *Fraxinus americana*, L. a native of North America, is found mainly in the eastern United States and has been introduced in Cuba and Romania [127,128]. It is a large tree approximately 36 m high and 182 centimetres in diameter, and is highly appreciated thanks to the qualities of its wood, which is moderately heavy, strong, rigid, hard, and resistant to shocks. Because of these characteristics, it is mainly used for handles, ropes, oars, vehicle parts, baseball bats, and other sporting goods, as well as for veneers, sawn wood, and canoes. Heartwood from *Fraxinus*, both excelsior and American, has been considered as a possible source of wood for ageing wines [57,110,111], so its composition has been studied from the oenological point of view [43,45,48,124]. Wines aged in ash barrels differed from the rest due to their high content of 3-ethyl and 3,5-dimethylcyclotene, o-cresol, α-methylcrotonalactone, and vanillin and their low content of furanic derivatives, the latter like wines aged in cherry [111]. In spite of showing greater quantities of vanillin, after a sensorial analysis, the wine aged with oak had the highest scoring vanilla notes [111]. The polyphenolic profile of wines aged in contact with ash has not shown any specific polyphenols provided by this wood, with no unusual compounds being found when the wine was aged with oak [110], although ash has shown to have compounds not present in oak [45].

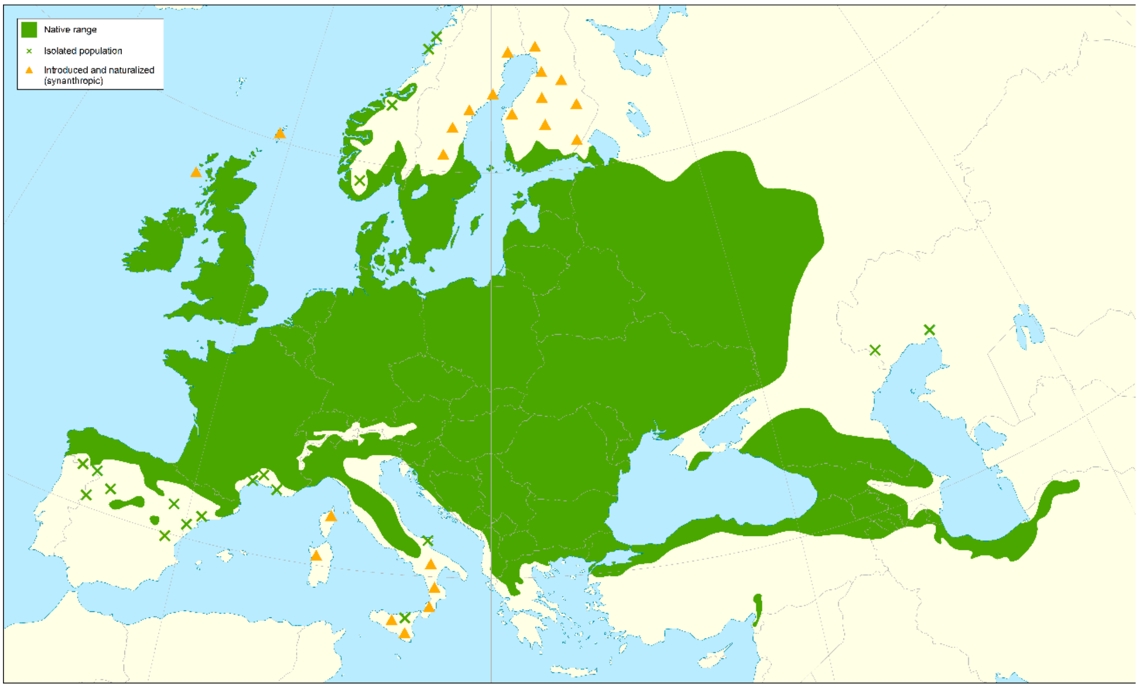

Figure 7. *Fraxinus excelsior* distribution map [62]. https://commons.wikimedia.org/wiki/File:Fraxinus_excelsior_range.svg.

3.5. *Morus (Mulberry)*

The mulberry species that have been considered as possible new woods in wine ageing have been *Morus alba* L. (known as white mulberry) and *Morus nigra* L. (known as black mulberry). *Morus alba* L. is a native of China but widely planted and naturalized in many warm temperate regions. *Morus nigra* L. is a native of western Asia but mostly cultivated in Europe and Asia [129]. In general, *Morus* L. (Moraceae) is found in Asia, Africa, Europe, and North, Central, and South America [130] and grows in various forest types from sea level up to 2500 m [131]. Morus species are economically important to the silk industry, as they are host plants for the silkworm (*Bombyx mori* L.) larvae [132]. Additionally, species have been cultivated in many parts of the world for their edible fruits and as ornamental trees. Moreover, *M. alba* is the main species for making traditional bowl-shaped musical instruments [133]. Karami et al. [133] studied the anatomical differences and similarities between these two species of wood, showing that small differences exist between them in vessel distribution and frequency and the existence of aliform axial parenchyma cells. The main differences reported by these authors were a semi-ring porous distribution of vessels in *M. alba*, and fewer vessels and a lower presence of aliform parenchyma in *M. nigra*. The wood of these species is tender and elastic, with medium porosity, and is characterized by the low release of compounds [134]. These species have been less-studied from the point of view of their characterization and use for the ageing of beverages than those previously mentioned. Rosso et al. [92] studied extracts (50% water/ethanol *v*/*v*) with 60 g/L of different woods (acacia, chestnut, cherry, mulberry, and oak) and observed that the lowest contents of volatile compounds were found in mulberry, with little eugenol and no methoxyeugenol though high (negative) fatty acids. Flamini et al. [56] extracted the compounds from the same woods and in the same dosage as in the previous study, not only with a 50% water/ethanol solution but also with model wine (12% ethanol with tartrate buffer pH 3.2), showing that the mulberry wood extract had a low presence of volatile benzene compounds and is probably more suitable for ageing wines.

Gortzi et al. [90] studied two Greek red wines (Syrah and Cabernet) aged with white Mulberry wood chips. They observed that the total polyphenol content (mg/L) in Syrah wines aged with *M. alba* was lower than those aged with *Q. alba* when the dosage of alternatives was 1 g and very similar when it was 2 g. The opposite occurred when the grape variety used was Cabernet. Gortzi et al. [90] saw that the concentration of resveratrol and catechin in all of the wines studied was much higher when aged with *M. alba* chips than when aged with *Q. alba*. The sensory test showed that, after 20 days' ageing with *M. alba*, Syrah wines presented better scores than the same ones aged with *Q. alba*; however, the scores of the Cabernet wines after ageing with these two woods were similar [90]. Mulberry extract (*M. nigra* heartwood) (2 g/L of wood in 40% water-ethanol) had higher a polyphenol content and antioxidant activity than the extracts from the *Quercus robur*, *Robinia pseudoacacia* L., and *Cotinus coggygria Scop* wood species [116]. Rosso et al. [113] observed that a red wine (Raboso Piave var.) aged during 9 months in blackberry (*M. alba*) 225-L barrels presented a significant decrease in fruity-note ethyl esters and ethylguaiacol and the high cession of ethylphenol (a horsey-odour defect). Therefore, these authors concluded that this wood is hardly suitable for wine ageing.

4. Chemical Composition of the Extractable Fraction of the Different Woods

The chemical composition, especially the extractable fraction, of oak wood can decisively condition its oenological quality, as it contributes to characteristics such as the colour, smell, flavour, and body of the final wine. Ellagitannins, low molecular weight compounds, and volatile compounds are the main constituents of this fraction in oak. Table 1 shows the total concentration of ellagitannins and the total content of low molecular weight phenolic compounds in green, dried, and toasted wood of *Quercus* specimens but of different species than the traditional ones (*Quercus*: *pyrenaica*, *faginea*, *frainetto*, *oocarpa*, and *humboldtti*) and woods other than oak (*castanea sativa*, *robina pseudoacacia*, *prunus avium*, *prunus cereaus fraxinus americana*, and *fraxinus excelsior*). In general, the ranges found for total ellagitannins and low molecular weight phenolic compounds in the same species are broad due to factors such as the type of treatment and the intensity and variability within the species, and are shown in Table 1.

As can be seen in Table 1, the species *Robinia pseudoacacia* (acacia), *fraxinus americana* (ash), and *fraxinus excelsior* (ash) do not contain ellagitannins in their composition. With regard to cherry, no studies have been found on the species *Prunus cereaus*. The ellagitannins in *Prunus avium* were not detected in the studies by Sanz et al. [43,44], with only very small quantities of castalagina (0.04 mg/g) and vescalagina (4.19 µg/g) being detected in the work of Alañon et al. [31], insignificant quantities with respect to the habitual contents that exist in the woods used in cooperage. As regards woods other than oak, the eight ellagitannins have only been found in the species *Castanea sativa* Mill (chestnut). The ranges of ellagitannins in dried chestnut are between 4.74 and 76.3 mg/g and in toasted vary from 0.66 to 10.51 mg/g (Table 1). As with oak [17,32,135], toasting decreases the concentration of these ellagitannins. In general, the total concentration in ellagitannins is similar to that found in traditional oaks. In addition to ellagitannins, other hydrolysable tannins not present in oak have been found in chestnut. In addition, cherry and acacia have condensed tannins, never found in oak, in their composition. All this means that there is an important qualitative difference between these different woods and *Quercus* with respect to the composition of the traditional oak used in wine ageing. The main phenolic components analyzed specially in the green and seasoned wood of these new species of *Quercus* were ellagitannins (Table 1), with similar results to those found in other oaks traditionally used in oenology. Drying and toasting degrade these compounds as well as traditional *Quercus* woods. The eight ellagitannins identified in the traditional oaks were found in all the new species of *Quercus*, except in the case of the *Q. oocarpa*, which did not present dimer ellagitannins (A, B, C, and D Roburins) in its composition. *Q. pyrenaica*, *Q. faginea*, and *Q. oocarpa* had a similar range of total ellagitannin concentration among them; moreover, ellagitannins of these species were between *Q. robur* and *Q. alba*, and more similar to *Q. petraea*. However, *Q. humboldtii* showed a lower concentration than the other new species and more similar to *Q. alba*. On the other hand, *Q. frainetto* is distinguished especially from the other species by its higher content of pentosylated dimers, and a monomer concentration that is similar to the rest of *Quercus*, which makes it the species with the highest content in ellagitannins (108 mg/g). Unlike ellagitannins, low molecular weight compounds during drying and toasting increase their concentration in both *Quercus* and other woods, just like traditional oaks. *Castanea sativa* Mill. wood has the highest low molecular weight phenolic

(LMWP) content (Table 1). In general, the total LMWP contents found in the acacia (*Robinia pseudoacacia* L.), cherry (*Prunus*), and ash (*Fraxinus*) woods are lower than in the others, especially after drying. Ellagic and gallic acids are the main LMWPs in *Q. pyrenaica*, *Q. faginea*, *Q. humboldtii*, and *Castanea sativa* as in traditional oaks. Only in the toasted wood of *Q. humboldtii* does this not occur, as the majority were coniferaldehyde and sinapaldehyde. This behaviour has also been observed in traditional woods, especially in the species *Q. alba* and/or *Q. robur* [7,17,47,48], although the most common profile is that mentioned above. In *Q. oocarpa* and *Q. frainetto*, only the ellagic and gallic acids were studied [36], probably because they are the majority in this species. Furthermore, there is more ellagic acid than gallic acid in *Q. pyrenaica*, *Q. faginea*, *Q. humbolditti*, and *Q. oocarpa*, as usually occurs in traditional oaks; however, in *Q. frainetto* and *Castanea sativa*, this relationship was reversed. Compared to traditional oak, the most different woods were acacia, cherry, and ash, as in none of the three were these acids the majority. With the exception of the dry wood of *P. cereaus*, the majority component of which was ellagic acid, gallic acid was not detected [40]. Similarly, neither gallic acid nor ellagic acid were detected in the wood of the considered *Fraxinus* species [43].

Table 2 represents the concentration of some of the most representative volatile compounds of traditional oak for their aromatic contribution to wine during the ageing process analyzed by gas chromatography (GC) in green wood and dried and toasted specimens of the genus *Quercus*, but of different species to the traditional ones (*Quercus*: *pyrenaica*, *faginea*, and *humboldtti*) and woods other than oak (*castanea sativa*, *robina pseudoacacia*, *prunus*, and *fraxinus excelsior* and *american*). This table does not list *Q. oocarpa* and *Q. frainetto*, as no work has been found with the concentrations of these volatile compounds. Only Vivas [21] shows the presence of vanillin and eugenol β-Methyl-γ-octalactone in these species as well as *Q. alba*, *Q. petraea*, and *Q. robur* and oxo-3-retro-α-ionol in addition to *Q. alba*. Regarding cherry, in Table 2 the species is not indicated since it was not identified in the studies found. In addition, as these compounds are formed during drying and especially during toasting, only one work in green wood has been found that studied the species *Q. pyrenaica*. The concentration of the volatile species represented in Table 2 shows that the majority of the green and dried wood of *Q. pyrenaica* is cis-β-Methyl-γ-octalactone, 59 and 68 μg/g, respectively; in the dry wood of *Q. faginea* it is furfural with 17.6 μg/g, and in *Q. humbolditti* it is eugenol with 2.65 μg/g. However, the majority in non-*Quercus* woods after drying is vanillin. As for the wood after toasting, which is usually used in the processes of ageing wines, in almost all species the content of furfural is higher than that of the other five aromas as generally occurs in traditional oaks [17,51,55,60], with the exception of *Q. faginea*, *Fraxinus american*, and *Fraxinus excelsior*, with vanillin content being the highest. The guaiacol levels in medium-toasted ash woods were much higher than those detected in the other toasted woods, even those normally found in traditional oak, so a more pronounced smoke character can be expected when using toasted ash wood in ageing wines. In some studies, the concentrations of eugenol found in *Q. pyrenaica* were very high, especially when they were subjected to light toasting, much more so than in those normally found in traditional oaks, so that when using these woods we would have more spicy wines, especially with notes of clove. In general, Table 2 shows that woods not belonging to the genus *Quercus* do not have either β-Methyl-γ-octalactone or cis-β-Methyl-γ-octalactone in their composition. Only the study by Caldeira et al. [53] found small amounts of these isomers in chestnut (0.23 and 0.34 μg/g in the isomer trans and cis, respectively), but using 55% ethanol to extract them. The two isomers of β-Methyl-γ-octalactone have a high sensory impact on the wines after wood maturation [136], giving the wines coconut, toasted, and wood notes; moreover, theses isomers allow French and American oaks to be differentiated [59,137,138]. *Q. humboldtii* also presented very low concentrations of these two isomers. Regarding the species *Q. faginea*, the concentration of these two isomers in its wood has only been found in the work of Cadahía et al. [51], in which they also study the traditional oak species, observing that the concentrations in this species are within the usual values found in the traditional species (*Q. robur*, *Q. petraea*, and *Q. alba*). The wood of *Q. pyrenaica* has been more widely studied, so we find wider ranges of concentrations, depending on the origin, drying, and toasting. In general, we could say that some woods have higher concentrations than those found in traditional woods, especially the cis isomer.

Many options for woods to be used in cooperage are available and suitable and there may be more. However, with the exception of the species *Q. pyrenaica*, there have not been many studies carried out on the aforementioned woods and the corresponding treatments in cooperage. Therefore, it is considered of great interest to know more about the aromatic composition of these woods, thus offering more information to coopers and oenologists about the wood they can use for their wines, thus providing that distinctive sought-after seal.

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