

Review

Red Wine Aging in Oak Barrels: The Influence of Toasting Levels on Aromatic Profile, Phenolic Composition, and Sensory Properties

Tanja Marković ^{1,2} 

¹ Teaching Institute of Public Health of Osijek-Baranja County, Franje Krežme 1, 31000 Osijek, Croatia; tanja.markovic.zzjz@gmail.com

² Faculty of Food Technology Osijek, Josip Juraj Strossmayer University of Osijek, Franje Kuhača 18, 31000 Osijek, Croatia

Abstract

The aging of wine in oak barrels is a crucial stage in winemaking, greatly influencing its chemical composition, sensory characteristics, and overall quality. Since the Roman Empire, oak barrels have replaced clay amphorae due to their practical and sensory advantages. During barrel aging, interactions between wine, wood, and oxygen improve structure, reduce astringency, develop aromas, and stabilize color. Oak barrels undergo a toasting process that enhances their chemical reactivity and influence on wine. The degree of toasting, which ranges from light to heavy, determines the type and concentration of extractable compounds and shapes the aroma and phenolic profile. Light toasting preserves tannin structure and fruity notes, while heavy toasting releases vanillin, lactones, and caramelized products that contribute to smoky aromas. Factors such as oak species, wood age, processing method, and toasting level all contribute to the final wine profile. This review summarizes the latest findings on the influence of toasting intensity on the chemical composition of red wines, with a focus on aromatic and phenolic compounds and their sensory effects. Extraction mechanisms and their role in defining wine characteristics are also discussed, providing guidance for winemakers to optimize barrel toasting strategies and achieve desired wine styles and qualities.

Keywords: oak barrels; toasting; wine aging; aromatic profile; phenolic compound; sensory properties



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1. Introduction

Grapevines and wine have been an integral part of human civilization since ancient times, in terms of both winegrowing traditions and the development of winemaking technologies. Although clay pots and amphorae were used to store wine in the past, the introduction of wooden barrels marked a turning point, as they proved to be more functional and chemically active in their interaction with wine [1,2]. Oak barrels are particularly valued for the aging of wine and spirits due to their positive effects on the product, such as improving color stability, increasing natural clarity, and enriching the wine with more complex aromas and flavors [1].

Aging wine in oak barrels, also known as traditional or natural aging, is a proven method in the production of premium wines. During this process, slow oxidation by the wood and the extraction of compounds such as tannins, lactones, and phenols improve the color, aroma, and taste of the wine, allowing it to reach its full maturity [3]. The crucial stage

in barrel production is toasting, which involves exposing the inner surface of the barrel to heat. It is this process that plays a key role in shaping the chemical and sensory profile of the wine [4]. Toasting causes the thermal degradation of oak polymers (lignin, cellulose, hemicellulose), producing volatile and non-volatile compounds, the most important of which are furfural, vanillin, guaiacol, and lactones. These compounds are extracted into the wine during aging and are responsible for the development of smoky, woody, or vanilla aromas in the wine. In addition, the interaction between wine and wood extracts promotes oxidation reactions, color stabilization through the binding of anthocyanins and tannins, and other chemical transformations that further shape and enrich the sensory profile [5]. The degree of toasting—defined by the intensity and duration of heat exposure to the inner surface of oak barrels and classified as light, medium, or heavy—influences the type and quantity of these compounds, thus shaping the aroma and phenolic profile of the final product [6].

Barrel toasting can be considered a key enological parameter that fundamentally determines the chemical profile and sensory quality of wine during aging. This process modifies the structure of the wood and generates a range of volatile and non-volatile compounds that are transferred to the wine and directly influence its color, aroma, taste, and texture. Understanding the mechanisms and effects of barrel toasting is therefore crucial for controlling wine style, quality, and aging potential [7]. Red wines are rich in polyphenols, bioactive compounds that are transferred from the grapes to the wine [8]. An important part of the red wine production process, which is responsible for the transfer of polyphenols from the grapes to the wine, is maceration. Maceration is a technological process in which the solid components of the grapes (skins, seeds, stems) remain in contact with the must, usually during and after alcoholic fermentation. During this period, phenolic compounds are extracted, primarily anthocyanins, which are responsible for the color of red wines, and tannins, which influence the astringency, structure, and aging potential of the wine [9]. In this context, the aging of red wines in oak barrels is an important phase in which further changes in the phenolic profile take place. These include the transfer of specific compounds from the wood to the wine and reactions that stabilize the color and soften the tannins [10].

The increased interest in the chemical and physical changes that take place during aging led to more intensive research in this area. For the wine industry, this knowledge enables the targeted production of wines with the desired sensory characteristics. At the same time, the study of chemical and physical processes within barrels opens up new opportunities for innovation in oenology and sustainable wine production for the scientific community [11]. The topic of toasting remains relevant, as the different stages of this process allow for precise shaping of the sensory profile of the wine, which is crucial for competitiveness in the market. In addition, more and more research is focusing on innovative approaches such as the use of wood chips, staves, or their combination with micro-oxygenation, which attempt to reproduce the effects of classic aging at a lower cost and with better process control [5,12,13].

Recent studies [14–16] confirmed that toasting barrels has a significant impact on the release of volatile and non-volatile compounds that characterize the chemical composition and sensory profile of wine. However, most available publications focus on individual compound groups or comparisons of different wood species, while the comprehensive analysis of the effects of toasting degree remains limited.

Therefore, the aim of this review is to summarize the existing knowledge on the influence of oak barrel toasting on phenolic compounds (anthocyanins, tannins, pigment stabilization), volatile components (lactones, volatile phenols, lignin degradation products, caramelization derivatives), basic chemical parameters, and sensory characteristics of wine.

Particular attention is paid to comparing the results of different studies identifying known discrepancies and the factors that cause them in order to identify research gaps and provide guidelines for future research.

2. Materials and Methods

In order to identify the latest findings and trends in this field, relevant literature was researched primarily using Google Scholar, supplemented by targeted searches in Web of Science and Scopus. The search strategy was based on combinations of English keywords such as “wine aging,” “oak barrel,” “barrel toasting,” “phenolic profile,” “volatile compounds,” “aroma,” “sensory properties,” “micro-oxygenation,” and “micro-oxidation” applied to article titles and abstracts. The search focused on publications from the last ten years (2015–2025). In addition, selected key studies published before 2015 that are frequently cited in the context of the historical development of barrel use and the understanding of fundamental chemical mechanisms were also included to ensure the completeness of the review.

The publications listed in Tables S1 and S2 were selected according to the following criteria: (i) original, peer-reviewed research articles; (ii) published between 2015 and 2025; (iii) written in English; and (iv) focusing on the influence of oak barrel toasting on the phenolic composition, volatile compounds, or sensory properties of red wines. Review articles, conference abstracts, and studies that did not directly address these aspects were excluded.

3. Oak Wood Compounds: From Toasting Chemistry to Wine Aroma Profiles

Wooden barrels are not only practical vessels but also a source of complex aromas and flavors that contribute to the development of wine and spirits. They remain an indispensable tool in the aging process of some of the world’s finest wines [17]. The oak species most commonly used for barrel production are *Quercus alba*, *Quercus robur*, and *Quercus petraea*. The extraction of volatile and non-volatile compounds from the wood depends on several factors: the botanical species and geographical origin of the wood [18–20], the ratio between the surface area of the barrel and its volume, the duration of contact between the wine and the barrel [21,22], the aging process, the method of barrel toasting [16,18], and the composition of the wine during barrel aging [23]. However, the methods used to process the wood, including drying, the type of cut of the logs, and, in particular, toasting [24], have the greatest influence on the final profile of the wine. After cutting and drying, which enable the wood to be processed properly and unwanted extracts to be removed, the toasting phase (bousinage) follows [25,26]. During this process, the inner surface of the barrel is exposed to an open flame, with the temperature on the inside of the staves reaching between 200 °C and 250 °C [26].

Thermal treatment breaks down lignin, cellulose, and hemicellulose—structural polymers that make up about 90% of wood—producing various aromatic and chemical compounds that are transferred to the wine [27]. Toasting is usually carried out using wood as a heat source, less commonly with gas flames, hot air convection, or infrared radiators [28]. In winemaking, three basic degrees of toasting are generally distinguished, light, medium, and heavy, each resulting in a specific chemical profile of the wood [29,30]. The duration and intensity of toasting influence the thermal degradation of the wood components and the formation of new compounds, which in turn affect the aroma and taste of the wine [30]. The most important compounds that are formed or more easily released during toasting include oak lactones, vanillin, eugenol, furfural, and various phenolic derivatives, which impart aromas such as vanilla, coconut, spices, smoke, and caramel [11]. The remaining 10% of the wood composition consists of extractive substances, among which ellagitannins

are particularly significant [31]. Not only do they contribute to the antioxidant properties of wine and react with flavan-3-ols and anthocyanins to create new pigments, but they also strongly influence the sensory characteristics of wine—flavor, texture, astringency, and the perception of fullness, smoothness, and roundness [32]. Therefore, the toasting method, together with the type of oak and the duration of contact between the wine and the wood, is considered a decisive factor in shaping the final sensory profile of the wine. The main groups of compounds and the most important changes that occur in them during the heat treatment of the wood are presented below.

3.1. Lactones

Oak lactones consist of two isomeric γ -lactones: the cis isomer and the trans isomer. The cis isomer has a significantly lower odor threshold and is four to five times more intense than the trans isomer. These compounds are found in all oak species used for barrel production; however, compared to other species, cis-lactones occur in significantly higher concentrations in American white oak (*Quercus alba*), which is the most important difference to French oak (*Quercus petraea* and *Quercus robur*) [31,33]. One of the most important oak lactones is β -methyl- γ -octalactone, also known as whisky lactone. The cis isomer of this compound imparts intense aromas of coconut, wood, and nuts, while the trans isomer has a lower aroma intensity [34]. The concentration of these compounds depends on several factors, including the oak species, its geographical origin, and the drying and toasting processes used during barrel production. Toasting has a particularly strong influence: moderate toasting can significantly increase the lactone content, while very high temperatures or excessive toasting can reduce the concentration through evaporation. In addition, the amount of lactone extracted into the wine depends on the aging time, the barrel volume, and whether the barrel has been used before [35]. These lactones are formed by the dehydration of certain fatty acid derivatives present in wood and impart aromas of wood, coconut, and Brazil nut to wine, while also enhancing the vanilla notes in wine [6,30,33].

Although the role of oak lactones in wine aroma formation is well documented, recent studies by Feng et al. [36,37] show that their concentration and sensory contribution are influenced by numerous factors. The authors showed that the geographical origin of *Quercus alba* oak has a significant influence on the concentrations of cis- and trans-lactones in Tempranillo wines. Wines aged in oak barrels from different regions showed significant differences in the concentrations of these compounds, with these differences roughly corresponding to those that occur during longer wine aging. This suggests that the origin of the wood can have as important an influence on the aroma profile of the wine as the duration of aging itself. It should be noted that the concentration of cis-lactone increases in the early stages of storage, while it may decrease with prolonged contact between wine and wood due to evaporation or conversion to other compounds. On the other hand, Ross-Magahy et al. [14] showed that the toasting method can have an equally strong or even stronger influence than the origin of the wood. Higher concentrations of cis-lactone were found in lightly toasted staves during the early stages of storage. However, during longer aging in medium- and heavily toasted barrels, the lactones had a more pronounced sensory contribution, suggesting that initial losses at higher temperatures can be offset by slower extraction and accumulation in the wine. Most studies on lactones focus on individual grape varieties or specific aging conditions, so comprehensive analyses of their effects remain limited. Future research should examine the interactions between oak species, wood origin, toast intensity, and aging duration in more detail in order to better assess the contribution of cis- and trans-lactones to the aroma profile of wine.

3.2. Ellagitannins

Ellagitannins are non-volatile phenolic compounds found in the heartwood of oak trees, where they can account for a significant proportion of the total phenolic content. They belong to the class of hydrolyzable tannins and, due to their ability to bind to proteins, contribute to the texture perception of wine, particularly the sensations of astringency and bitterness [38–40]. The most common ellagitannins are castalagin and vescalagin, C-glycoside ellagitannins that account for 40–60% of the total ellagitannin content in oak wood [41]. After transfer to wine, these compounds undergo condensation, hydrolysis, and oxidation, producing other derivatives such as ethyl esters and flavano-ellagitannins [10,42]. The amount of C-glycosidic ellagitannins in oaks used for wine production depends on the oak species (e.g., *Quercus robur*, *Quercus petraea* and *Quercus alba*), the age of the trees, their geographical origin, forestry practices, the part of the trees used, and the techniques used to produce the staves, in particular, the duration and methods of drying and toasting. It is important to note that the two European oak species most commonly used for the production of oak barrels, *Quercus robur* and *Quercus petraea*, have a higher ellagitannin content than *Quercus alba* [42]. The ellagitannin content can serve as a distinguishing feature between French and Eastern European oaks (*Quercus robur* and *Quercus petraea*) and Portuguese and Spanish oaks (*Quercus pyrenaica*) [37].

González-Centeno et al. [10] were among the first to investigate the relationship between ellagitannins, volatile compounds, and sensory perception during barrel aging. In Cabernet Sauvignon wines from France, Italy, and the US that had been aged in barrels with different toasting levels, they reported an 84–96% increase in ellagitannin concentrations within 12 months, accompanied by an increase in volatile compounds derived from the wood and a significant decrease in fruity aromas. The kinetics and intensity of the changes varied depending on the combination of the wine matrix and the toasting. Sensory analysis confirmed a strong correlation between the perception of wood aromas and compounds such as trans-whisky lactone, guaiacol, and vanillin, while bitterness and pungency correlated significantly with ellagitannins. It was confirmed that the toasting process does not act in isolation, but interacts with the grape variety and its chemical background, laying the foundation for subsequent studies that analyzed the structural changes and the influence of oak species in more detail.

More recent studies showed that the behavior of ellagitannins during aging is more complex than previously thought. In terms of comparing oak species, Jordi et al. [43] showed that *Quercus alba* has significantly lower ellagitannin levels than European species, while *Quercus pyrenaica* is similar to *Quercus petraea* in terms of content. Such differences confirm that the choice of oak species and its geographical origin can be just as important for the ellagitannin profile of wine as the technological processing of the must. Furthermore, Tarko et al. [44] emphasized that thermal treatment affects not only the total amount but also the conversion of the structural forms of ellagitannins, which directly influences the perception of bitterness, pungency, and color stability.

While most previous research focused on wine, studies with distillates provide additional valuable insights, as the matrix is simpler and allows for more accurate tracking of kinetics. For example, Gadrat et al. [41] found in the cognac maturation model that the concentrations of the eight major C-glycoside ellagitannins increase during the first months of aging and then gradually decrease. It was also found that stronger toasting promotes higher extraction of ellagitannins, while high toasting levels led to a significant reduction in total amounts, except in the case of certain derivatives such as β -1-O-ethylvescalagin, which proved to be more resistant to thermal decomposition. Although these results were obtained with distillate, they provide important clues for understanding the kinetics and transformation of ellagitannin and can serve as a reference model for interpreting similar

processes in wine. These results underscore that it is not just a quantitative reduction in ellagitannin as a result of toasting but structural changes that determine its sensory contribution in the long term.

Although recent research [43,45] has significantly improved our understanding of ellagitannins, the question remains how they convert into different derivatives during storage and how these forms influence interactions with anthocyanins and condensed tannins. Future research should combine accurate quantification and tracking of individual structural forms with parallel sensory testing to more reliably clarify their role in color stability and the perception of bitterness and astringency.

3.3. Furanic Compounds

Furanic compounds are heterocyclic molecules including furan, furfural, and its derivatives (5-methylfurfural, 5-hydroxymethylfurfural), as well as furanones. Some of these compounds occur naturally, but most are formed during the thermal decomposition of polysaccharides such as hemicellulose and cellulose in oak barrels during toasting [46]. Furfural and 5-methylfurfural, both derivatives of furan, impart aromas reminiscent of almonds and toasted almonds. Although they are not considered essential aroma compounds in red wine due to their high perception threshold, they can enhance the perception of other compounds from oak, such as lactones. Furfural is the most common compound in this group and is easily reduced to furfuryl alcohol, which smells like mustard and has a high perception threshold. Its concentration is generally higher in wines that are aged longer in oak barrels, as longer aging allows more time for reduction [47]. While the concentration of most volatile compounds from oak increases over time during barrel aging, furfural and 5-methylfurfural tend to accumulate in the early stages of aging but are then reduced to corresponding alcohols (furfuryl alcohol, tetrahydrofurfuryl alcohol) [48].

Studies conducted in recent years have confirmed that the formation of furanic compounds can be explained not solely by the intensity of toasting but also by the structural properties of the wood, which determine its Oxygen Transmission Rate (OTR). Ross-Magahy et al. [14] showed that in wines made from Tempranillo grapes from *Quercus petraea*, the highest concentrations of furfural and 5-methylfurfural occur with medium and medium-long toasting, while lightly toasted barrels show significantly lower levels. Although these compounds rarely occur above their threshold levels, sensory analysis showed that they contribute to the perception of caramel and almond notes, especially in combination with other volatile wood markers. On the other hand, Sánchez-Gómez et al. [49] showed that the anatomical properties of the wood, measured by OTR, also alter the volatile composition after toasting: wood with low OTR contained more furanic compounds (furfural, 5-methylfurfural, 5-hydroxymethylfurfural), while wood with high OTR had a higher proportion of trans- β -methyl- γ -octalactone and 4-ethylguaiacol. Together, these results show that the content of furanic compounds in wine is determined not only by the thermal treatment of the wood but also by the physiological properties of the wood itself. Ross-Magahy et al. [14] highlight the influence of toasting degree and storage duration on the concentrations of furfural and 5-methylfurfural. Sánchez-Gómez et al. [49] show that anatomical differences in wood, reflected in the OTR, can lead to different volatile profiles even in the early stages of aging. This confirms that the behavior of furanic compounds is the result of several factors and that they must be considered in the broader context of interactions between wood structure and technological processing of the must.

3.4. Phenolic Aldehydes

In addition to volatile phenols and phenyl ketones, the thermal decomposition of lignin produces phenolic aldehydes, which give the wine smoky, woody, vanilla, and spicy aromas [31]. During toasting at temperatures between 120 and 165 °C, the thermal decomposition of lignin leads to an increase in phenolic aldehydes, especially cinnamaldehyde, coniferaldehyde, and sinapaldehyde. However, at temperatures above 165 °C, more intense thermolysis leads to the breakdown of cinnamaldehyde into benzaldehydes (vanillin and syringaldehyde) and hydroxybenzoic acids (vanillic acid and syringic acid), which are then further broken down into volatile phenols [50]. Subsequent dehydration converts some of these compounds into lactones [44]. The most important aldehydes are syringaldehyde and vanillin, which can be extracted from untoasted wood, although they occur in significantly higher concentrations in heavily toasted wood. Vanillin is the main carrier of vanilla aroma in wines aged in oak barrels. Medium-toasted barrels generally provide the most balanced vanillin content, while heavily toasted barrels often result in lower vanillin concentrations [51]. In addition to these general formation mechanisms, recent studies increasingly emphasize the variability of phenolic aldehydes depending on the aging conditions.

For example, Pichler et al. [16] showed that even within different variants of medium toasting levels, the concentrations of vanillin and syringaldehyde can vary considerably, highlighting the sensitivity of these compounds to the nuances of heat treatment. Ross-Magahy et al. [14] confirmed that medium and medium-long toasts result in higher vanillin levels compared to light toasts, but that concentrations decrease after 18 months, suggesting degradation or conversion during longer aging. Gombau et al. [52] further emphasized the importance of wood thickness and surface area. Longer contact time increased the proportion of phenolic aldehydes in the wine, and their concentrations increased over time. These results show that the behavior of aldehydes is influenced not only by the intensity of extraction but also by complex interactions between the degree of toasting, the duration of storage, and the properties of the wood.

Future research should focus on the relationship between the concentration of phenolic aldehydes and their actual sensory effect. It is particularly important to clarify the extent to which vanillin and syringaldehyde contribute independently to wine aroma, and the extent to which their perception depends on synergistic interactions with other compounds derived from oak.

3.5. Volatile Phenols

Volatile phenols originate from naturally occurring components in grapes and wine, primarily hydroxycinnamic acids such as p-coumaric and ferulic acids. These phenolic acids can occur in wine as esters of tartaric acid, but also in free form or bound to anthocyanins and ethanol [53]. This diverse group of compounds includes eugenol, trans-isoeugenol, guaiacol, methylguaiacol, ethylguaiacol, vinylguaiacol, ethylphenol, and vinylphenol, which are among the most important representatives [43]. Certain yeast species of the genera *Brettanomyces* and *Dekkera*, which frequently colonize wooden barrels, are capable of decarboxylating cinnamic acids, leading to the formation of these volatile phenols in wine. Their presence is therefore often associated with wines that have been aged in barrels, especially those that have previously been used for storing wine [54]. Eugenol and related compounds contribute to the aroma of cloves, while guaiacol and its derivatives add smoky and toasted notes to the aroma profile. Ethylphenol and vinylphenol are known to produce a highly undesirable odor often described as “horse sweat” [43]. These compounds can serve as indicators of wine spoilage and barrel contamination. Their formation can be mitigated by adding sulfites to inhibit the growth of *Brettanomyces* or by filtering mature wine to remove undesirable compounds [11].

Although the presence of volatile phenols in wine is well known, recent studies show how much their concentration and sensory contribution depend on the degree of toasting and the length of storage. Ross-Magahy et al. [14] showed that light toasting leads to higher eugenol and guaiacol levels after 12 months, while medium toasting makes a greater sensory contribution after 18 months thanks to the accumulation and slow degradation of these compounds. Chen et al. [55] came to a similar conclusion when they studied Cabernet Sauvignon with increased ethanol content and showed that the extraction of volatile phenols depends not only on the degree of toasting, but also on the composition of the wine matrix itself, in particular the ethanol content. Therefore, the results obtained with wines of different alcohol contents cannot simply be generalized. Pichler et al. [16] also showed that eugenol is only present in wines aged in toasted barrels and that its concentration increases over the course of 12 months, with differences within the medium toasting levels (medium, medium+, medium-long). These results confirm that even relatively subtle changes in the toasting mode can have a measurable effect, although the sensory relevance of these differences remains questionable. Gombau et al. [52] confirmed, using alternative oak wood forms, that the thickness and heat profile of the material have a significant influence on the formation of eugenol and other volatile phenols, suggesting that, in addition to toasting, the geometry of the wood is also an important factor. Finally, Qian et al. [56] studied Cabernet Sauvignon from two clones aged for 12 months in barrels of different origins and showed that the development of volatile phenols is primarily influenced by the aging time, while the grape variety and the origin of the barrel have additional but smaller and intertwined effects, further complicating the interpretation.

Overall, the studies show seemingly contradictory but ultimately complementary patterns: shorter aging in lightly toasted barrels results in higher levels of volatile phenols, while longer aging in more heavily toasted barrels can lead to a more pronounced sensory effect. To clarify this dynamic, future studies would need to precisely quantify the kinetics of eugenol and guaiacol formation and degradation in relation to toasting parameters, wood geometry, and wine composition (alcohol, pH, phenolic profile). An integrated approach combining chemical and sensory data could ultimately enable a more reliable model for understanding the role of volatile phenols in the complex aroma profile of wine.

To summarize the preceding sections, a diagram of the main groups of compounds formed during oak toasting and their aromatic contribution to wine is presented (Figure 1).

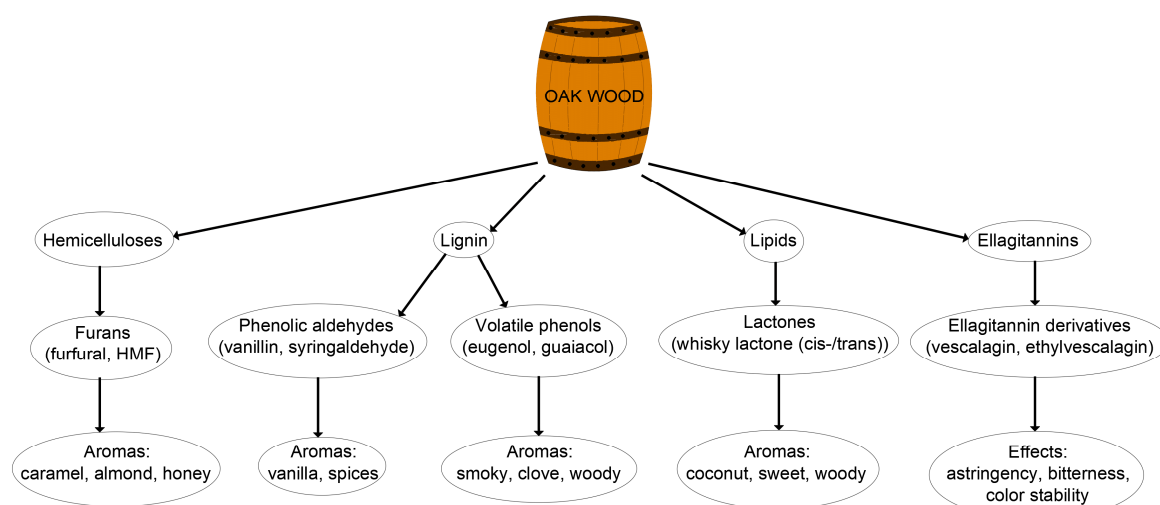


Figure 1. Main groups of oak wood compounds formed during toasting and their aromatic contributions to wine.

4. Discussion: Influence of Toasting on Wine

While the previous chapter focused on the chemical transformations that take place during oak aging and the compounds that are formed, this chapter deals with their effects on wine. During barrel aging, these volatile and non-volatile compounds diffuse into the wine matrix and are involved in a series of oxidation, condensation, and polymerization reactions that affect the phenolic composition, aroma profile, and basic physicochemical parameters of the wine. This chapter examines how different toasting levels, wood species and origins, and the duration of wine contact with wood affect the extraction and transformation of compounds, focusing on the comparative results of various studies, the contradictions observed, and the methodological challenges.

4.1. Influence of Toasting on the Basic Chemical Parameters of Wine

Fundamental parameters of wine, such as pH, total acidity (TA), and oxygen (DO, OTR), are important indicators of the chemical stability and aging potential of wine [57]. While most current studies on oak barrel aging focus on changes in phenolic and volatile compounds (González-Centeno et al. [10]; Lu et al. [23]; Ross-Magahy et al. [14]), the role of fundamental parameters is often only mentioned in passing.

The results of various studies consistently confirm that pH and TA remain within the typical ranges for red wines during aging, with a slight increase in pH and a decrease in acidity, but without significant differences between barrel types, toasting levels, or granulation (Chen et al. [55]; Pichler et al. [16]; Pfahl et al. [58]). In contrast, oxygen proved to be a crucial yet insufficiently studied parameter: most studies are based on qualitative interpretations of the “micro-oxidative” effect of yeast, without quantitative measurement of DO or OTR (Ross-Magahy et al. [14]; Casassa et al. [32]). Only recent studies have introduced oxygen as an explicit variable, either through the use of controlled micro-oxygenation (Cebrián-Tarancón et al. [59]) or through the concept of “tailor-made oxygen barrels” classified according to OTR (Prat-García et al. [60]). It was confirmed that, although pH and TA are relatively inert indicators, it is precisely the control of oxygen supply that is a decisive oenological tool for shaping the basic parameters and, indirectly, phenolic stability during aging.

Recent studies on the development of fundamental parameters during barrel aging confirm that pH and TA are stable indicators, while the greatest differences arise from oxygen supply and how it can be controlled. Among the studies conducted over the past decade, Chen et al. [55] stand out because they focused on wines with a very high ethanol content (>16% vol.), which are expected to have a higher oxidation potential. They analyzed Cabernet Sauvignon in barrels of different grain sizes and toasting levels, but the results showed that the pH and titratable acidity remained within typical limits, with no clear dependence on barrel type. The organic acids changed over the course of 12 months (decrease in malic acid, increase in lactic acid), but this was due to the natural development of the wine and not to the effect of the oak wood. This work confirms that the basic parameters develop relatively independently of the grain size and degree of toasting.

A few years earlier, Pichler et al. [16] monitored Merlot in barrels with different “medium” toasting variations and compared it with a stainless steel container. Although the focus was on phenols and aromas, systematic measurement of pH and TA over a period of 12 months showed a typical pattern: a slight increase in pH and a decrease in TA, regardless of the type of barrel. The stainless steel container provided slightly more stable acidity values, while the wooden barrels showed slight fluctuations, which were probably related to micro-oxygenation. It was confirmed that the basic parameters are not a reliable indicator of differences between aging methods, but rather reflect differences between inert and porous containers.

The variability between barrels themselves is pointed out by Pfahl et al. [58], who showed that pH and TA exhibit only minimal variations between samples of the same declaration, while the main differences concern phenolic compounds and color. Similarly, Ross-Magahy et al. [14] and Lu et al. [23] confirmed the stability of the basic parameters during storage for 9 to 18 months, with no significant differences between treatments (toasting level, granulation, oak type). González-Centeno et al. [10] additionally showed that pH and TA remain stable regardless of the wine's country of origin, toasting method, or wood type, despite significant differences in phenolic and aromatic profiles. Casassa et al. [32] report a typical increase in pH and a decrease in TA over a period of 15 months, with no differences between toasting techniques, confirming that mechanical variations in barrel production do not affect the basic parameters, but rather the phenolic and aromatic profile. In contrast to all these studies, Cebrián-Tarancón et al. [59] explicitly included micro-oxygenation as a variable. In combination with toasted wine lees, they showed that controlled oxygenation can accelerate phenolic polymerization and color stabilization, with a minimal but measurable increase in pH. This study confirms that oxygen, rather than wood itself, is a key factor in modulating the fundamental parameters.

The most important contribution to this topic comes from Prat-García et al. [60] with their concept of customized oxygen barrels. They systematically compared barrels with different OTR (LOTR vs. HOTR) and measured the dissolved oxygen in the wine. They showed that HOTR barrels allow more than twice as much oxygen to pass through as LOTR barrels, resulting in faster oxidation of phenols and more dynamic color development. However, the pH and TA remain stable. It was clearly confirmed that micro-oxygenation in the barrel can be passively controlled by selecting barrels according to OTR—opening up a new dimension in the control of the aging process.

Summary and Critical Evaluation

Although numerous studies clearly confirm the importance of oak type, toasting level, and aging time for the development of the sensory profile of wine, there are significant methodological limitations that make it difficult to draw clear conclusions. Most of the available studies are based on a limited number of grape varieties, mostly international red varieties such as Cabernet Sauvignon, Merlot, and Tempranillo, which limits the possibility of generalizing the results to other varieties and style categories of wine. Additional complexity arises from inconsistent sensory analyses—differences in the composition of test groups, evaluation methodology, and aging duration often make it impossible to directly compare the results of different studies. Most studies are conducted under strictly controlled experimental conditions that do not fully reflect the complexity of commercial production and multi-year storage, further limiting the external validity of the results. Although the relationship between chemical composition and sensory properties is well documented, there are relatively few studies that use integrated analytical and sensory approaches (e.g., a combination of GC-MS, HPLC, and advanced sensory analyses) to map these relationships in detail. These methodological differences and gaps point to the need for systematic and standardized investigations that would allow for a more reliable assessment of the influence of individual oenological parameters on the sensory properties of wine.

4.2. Phenolic Compounds and Phenolic Profile of Wine

Phenolic compounds play a crucial role in the color, taste, acidity, and antioxidant properties of wine. These compounds represent a large and diverse group of secondary plant metabolites characterized by one or more phenolic groups, and contribute significantly to the sensory and chemical profile of wine. They originate primarily from the grapes,

although some important compounds (e.g., ellagitannins) are extracted from the wood during the aging of wine in barrels. Phenolic compounds are generally classified into two main groups: flavonoids (e.g., anthocyanins, flavanols, flavonols) and non-flavonoids (e.g., phenolic acids, stilbenes).

4.2.1. Flavonoids

Flavonoids consist of 15 carbon atoms (C6–C3–C6) arranged in two aromatic rings connected by a three-carbon bridge that forms a heterocyclic C ring. This carbon skeleton and the various radicals attached to it are responsible for the chemical diversity of this group. Their antioxidant effect is primarily based on their ability to bind free radicals and chelate metal ions (Cu and Zn), thereby preventing reactions catalyzed by free radicals [61,62]. Flavonoids are more numerous and richer in phenols than non-flavonoids and include several subgroups relevant to wine, such as flavonols, anthocyanins, and flavan-3-ols.

Flavonols—These are found in the skins of berries and are transferred to the must and wine during maceration. They are primarily synthesized in the grape in response to light exposure and accumulate in the skin as protection against ultraviolet (UV) radiation. They are derived from six main aglycones—kaempferol, quercetin, myricetin, isorhamnetin, laricetin, and syringetin—which differ in their substitution groups on the B ring. In grapes, they accumulate exclusively as 3-O-substituted compounds, such as 3-O-glucoside, 3-O-glucuronide, 3-O-galactoside, and even 3-O-acetylglucoside [63,64]. During winemaking, flavonols are extracted from the skin in a similar way to anthocyanins, but somewhat more sporadically due to the less polar properties of their structure. Their presence in wine depends primarily on the duration of contact with the skin, with significant amounts being released after a few days of maceration [32]. Although they are present in smaller quantities compared to other flavonoids such as anthocyanins and proanthocyanidins, their key role in red wines is related to copigmentation, a process that stabilizes the color of the wine. The quantitative and qualitative composition of flavonols in wine depends on numerous factors related to the grapes (variety, sun exposure, ripeness), as well as winemaking practices, aging, and storage conditions [63].

Anthocyanins—These are primary compounds responsible for the red color of wine. In the *Vitis vinifera* grape, anthocyanins typically occur as 3-O-glycosides of five anthocyanidins: delphinidin, cyanidin, petunidin, peonidin, and malvidin [50]. Anthocyanins occur in wine in three forms: as a light red flavillium cation, as a colorless carbinol pseudobase, and as a violet quinoid form. The concentration of each form depends on the pH of the solution [65]. At low pH (below 4), all anthocyanins are present as flavillium cations (red). As the pH value increases, the color intensity changes, transitioning from colorless to violet or blue in neutral to alkaline solutions [62]. The bright red color of wine and its preservation over time require mechanisms to stabilize the pigment, primarily copigmentation, which can account for 30–50% of the color in young red wines [65,66]. During aging, the proportion of simple, monomeric anthocyanins decreases, while more complex polymeric pigments—stable color compounds formed by condensation reactions between anthocyanins and tannins—are formed. This transformation is followed by the oxidation and degradation of anthocyanins, as well as the formation of new pigments and possible interactions or coprecipitation with tannins and other components of wine, which further contribute to the reduction in the concentration of monomeric anthocyanins [67]. Condensation reactions mediated by acetaldehyde, which lead to polymers with ethyl bonds, play a key role in the condensation of anthocyanins and tannins under oxidative conditions and contribute to increased color intensity and stability. These ethyl bridges are not stable over time and gradually convert to vinyl-linked polymers and vinylpyrananthocyanins. Among these, vitisins are particularly important due to their contribution to

long-term color stability. They occur naturally in wine as products of the reaction between anthocyanins and acetaldehyde or other metabolites of yeasts [68]. During the aging of red wines, a number of anthocyanin derivatives can be identified, including flavanol and anthocyanin adducts, flavanol-ethyl-anthocyanin complexes, carboxypyrananthocyanidins such as vitisin A, and pyrananthocyanidins with substituents. Polymeric pigments also play an important role. These derivatives contribute to the sensory properties, color, and antioxidant properties of wine and are crucial for the quality of wine during aging [60].

Flavan-3-ols—These are synthesized in the skin and seeds of grapes in the early stages of development after flowering, with concentrations of monomers and polymers remaining stable after ripening begins. In grapes and wine, they occur as monomers or polymers known as proanthocyanidins or condensed tannins, respectively. Four main components are typically found in *Vitis vinifera* berries: catechin, epicatechin, epigallocatechin, and epicatechin gallate [69]. Flavan-3-ols are monomeric flavonoids consisting of a benzopyran unit with an aromatic ring attached to the C2 carbon of the pyran ring. These monomeric structures can combine to form dimers, oligomers (3–10 flavan-3-ol units), and polymers (more than 10 units). All of these complex structures are collectively referred to as condensed tannins. When they consist of (+)-catechin and (–)-epicatechin and their gallate esters, they are referred to as proanthocyanidins [38].

4.2.2. Non-Flavonoids

Phenolic acids—These compounds are found in the skin, pulp, and seeds of grapes and can be divided into two main groups: hydroxybenzoic acids and hydroxycinnamic acids. Hydroxybenzoic acids (HBA) are characterized by a basic structure consisting of an aromatic ring with six carbon atoms and a monovalent side chain (C6–C1). This group includes gallic acid, p-hydroxybenzoic acid, protocatechuic acid, vanillic acid, and syringic acid. Gallic acid, which is mainly found in seeds, is considered the most important phenolic acid because it is the precursor of all hydrolyzable tannins. In addition to its key role in the biosynthesis of tannins, gallic acid contributes to the structure, stability, and antioxidant properties of wine [38]. Hydroxycinnamic acids (HCA), on the other hand, are characterized by an aromatic ring with a side chain of three carbon atoms (C6–C3). The most common representatives of this group are caffeic acid, ferulic acid, p-coumaric acid, and sinapic acid [70]. Hydroxycinnamic acids are among the dominant phenolic compounds in wine, especially when esterified with tartaric acid in the form of cinnamic acid esters, which play a key role in the formation of volatile phenols. Under certain conditions, especially in the presence of yeasts of the genus *Brettanomyces/Dekkera*, p-coumaric acid and ferulic acid can act as precursors of volatile phenols. These microorganisms are capable of enzymatically converting such compounds into volatile phenols such as 4-ethylphenol, 4-ethylguaiacol, and 4-ethylcatechol, which are responsible for specific off-flavors in wine, often described as “horse sweat,” “stable smell,” “leather,” or “lacquer.” Elevated concentrations of these compounds can significantly alter the sensory properties of wine [71]. In addition, phenolic acids, especially hydroxybenzoic acids, can act as co-pigments in wine. They contribute to the formation of more stable pigments and help stabilize color in young red wines through co-pigmentation with anthocyanins. Furthermore, their presence is associated with sensory perceptions such as astringency and bitterness, which additionally influence the overall aroma and flavor profile of the wine [38]. Phenolic acids are an important subgroup of non-flavonoid compounds in grapes and wines that have gained attention in recent decades due to their potential health benefits, including antioxidant, antibacterial, antiviral, anticarcinogenic, anti-inflammatory, and vasodilatory effects [72,73].

Stilbenes—Stilbenes are phenolic compounds consisting of two phenyl rings connected by an ethylene bridge, creating a C6–C2–C6 structure. The presence of a double bond allows

for the existence of trans and cis configurations. Aromatic rings are usually substituted by various functional groups, including hydroxyl, methyl, methoxy, prenyl, and geranyl groups [61,74]. The concentration of stilbenes in grapes and wine depends on the grape variety, growing conditions, climate, harvest, and viticultural practices such as pruning and irrigation. In addition, factors such as ripeness, maceration, and yeast activity during winemaking also influence the final stilbene content in wine [61,75]. Stilbenes are classified as phytoalexins because they play a role in the plant's defense mechanisms against pathogens. Their synthesis is often triggered in response to infestation by phytopathogens or environmental stressors such as UV radiation, ozone, heavy metal ions, mechanical damage, or cold [61]. The best-known bioactive stilbene is resveratrol. Its biosynthesis occurs via the phenylalanine pathway, and it is produced by plants in response to stress conditions such as injury, UV radiation, or fungal infections. Resveratrol occurs in two isomeric forms: cis- and trans-resveratrol. The cis isomer is more prevalent before fermentation of the must, while the finished wine product typically contains a higher proportion of the trans isomer [76]. Trans-resveratrol is the dominant form in grapes and may undergo methylation and polymerization during fermentation, resulting in compounds such as piceid, pterostilbene, and viniferin, as well as glycosylation [77]. Stilbenes exhibit a wide range of beneficial biological activities, including antibacterial, antifungal, cardioprotective, neuroprotective, and anticarcinogenic effects. Due to their antioxidant, anti-inflammatory, and chemopreventive potential, stilbenes are being intensively studied in relation to the prevention and treatment of diseases such as cancer and obesity [61,78,79].

A schematic representation of the classification of phenolic compounds in wine is shown in Figure 2.

Phenolic Compounds in Wine

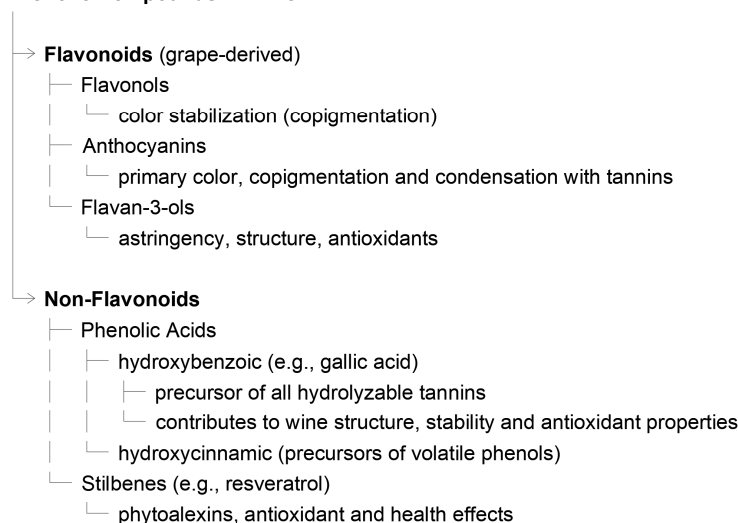


Figure 2. Classification of phenolic compounds in wine.

Polyphenols are secondary metabolites of the grapevine, whose synthesis and accumulation depend on the grape variety, climatic and topographical conditions, and viticultural practices. During winemaking, they are extracted from the skins and seeds during maceration, and the formation of the must marks the beginning of a series of chemical changes and interactions with other molecules. For red grape varieties, pre-fermentation maceration is often used, during which the solid components of the grapes remain in contact with the must before fermentation. Cold maceration (4–8 °C) promotes anthocyanin stability and more selective extraction. Despite the high phenolic content in the skin, less than 50% ends up in the wine due to the limited permeability of the cell walls. Therefore, modern techniques increasingly aim to increase phenolic extraction in order to achieve a better sensory

profile. The extracted phenols undergo further biochemical transformations during the aging of the wine in oak barrels. There, they react with wood components, with the degree of toasting of the barrels having a strong influence on the oxidation and polymerization of the phenols and on the formation of compounds that are important for the color, texture, and aroma intensity of the wine.

The analyzed studies confirm the key role of phenolic compounds—especially tannins and anthocyanins—in the formation of wine's color, structure, and aging potential. Most studies [55,80–82] report a decrease in free anthocyanins and a parallel increase in more stable complex pigments during aging, which is an expected trend and is usually accompanied by condensation with tannins. This leads to color stabilization and a reduction in astringency, which is considered a desirable outcome in wine aging. However, the intensity and direction of the changes vary depending on the grape variety and origin, degree of toasting, and specific technological conditions (e.g., ethanol content, microoxygenation). While the general pattern of anthocyanin reduction and increase in more stable pigments is repeated, individual studies emphasize the role of specific conditions.

For example, Chen et al. [55] showed that under conditions with high ethanol content (>16% vol.), grapes with medium berry size and barrels that underwent more intense toasting better preserved the phenolic balance, stabilized the color, and reduced the loss of red hues. These results confirm the important role of toasting in maintaining phenolic balance and wine quality, even under difficult conditions with high alcohol content. Pichler et al. [80] described a similar process, but with a focus on the dynamics of individual phenolic groups. Their study confirmed a decrease in monomeric anthocyanins and an increase in polymeric color, but they emphasize that toasting was not statistically significant in all parameters. While Pichler et al. highlight the role of additional factors such as harvest and microoxygenation, Del Fresno et al. [82] place greater emphasis on the degree of toasting itself as a trigger for phenolic transformation. Their results showed that stronger toasting accelerates the breakdown of anthocyanins and the formation of more complex pigments, thereby improving the color of the wine despite an overall lower total phenolic content. This difference shows that there are different interpretations of the significance of individual factors in the literature, highlighting the need for further comparative studies under strictly controlled conditions.

Studies showed that not only the grape variety and degree of toasting, but also various technological and production-related factors associated with winemaking influence the phenolic composition of wine. Pfahl et al. [58] found that the differences between barrels can be greater than the differences between barrel manufacturers, with the parameters related to anthocyanins showing the greatest sensitivity. On the other hand, Casassa et al. [32] analyzed barrels made using different wood joining techniques and concluded that such processes have less influence on phenols than decisive factors such as age and degree of toasting. Taken together, these results confirm that toasting remains the most important parameter for the formation of the phenolic profile of wine, but also that the natural variability between barrels can significantly complicate the interpretation of the results. Since oak, despite its tradition, exhibits considerable variability and dependence on technological processing, some research also focuses on alternative wood and biomass sources. Interestingly, such materials (Martínez-Gil et al. [31] with *Quercus pyrenaica*; Jordão et al. [15] with South American species; Guerrero-Chanivet et al. [27] with chestnut and oak; Olate-Olave et al. [83] and Cebrián-Tarancón et al. [59] with vine wood) show potential diversity in their phenolic profile. While chestnut produced a more phenolic wine, mulberry wood exhibited milder sensory characteristics. Alternative materials such as grapevine residues showed selective effects: format and dosage are crucial for the preservation of phenols, and micro-oxygenation can act as a catalyst for conversion. However, these

approaches often show contradictory results, and there is a lack of systematic comparison with classic oak wood under controlled conditions.

Methodologically, most research relies on spectrophotometric methods, such as ultraviolet–visible (UV–VIS) spectroscopy, which is used to determine total phenolic content and basic color parameters, and the Folin–Ciocalteu assay, a colorimetric method for estimating total phenolics based on their reducing capacity. These techniques provide valuable but limited information about total phenolic content. A smaller number of studies use more advanced chromatographic techniques, such as High-Performance Liquid Chromatography with Diode Array Detection (HPLC-DAD) and Liquid Chromatography–Mass Spectrometry (LC-MS), which enable sensitive detection, separation, and quantification of individual phenolic compounds, thus revealing the effects of different degrees of roasting with greater accuracy. However, phenolic changes are rarely systematically linked to sensory results, which makes comprehensive interpretation difficult.

Summary and Critical Evaluation

Previous studies clearly confirm that the degree of toasting and the type of oak have a strong influence on the phenolic profile of wine, especially on ellagitannins, flavan-3-ols, and anthocyanins. The changes observed include a reduction in ellagitannin concentration with increasing toasting intensity, as well as changes in the condensation reactions of tannins and anthocyanins, which determine the color and taste of wine during aging. However, there are significant discrepancies between individual studies, which can be attributed to differences in grape varieties, aging time, technological processes, and experimental designs. Most of the available studies are based on a limited number of varieties (mostly Cabernet Sauvignon, Merlot, Tempranillo) and a relatively short observation period, which makes it difficult to generalize the results. Innovative approaches, such as the use of alternative phenolic sources (other woods, grapevines), open up new perspectives, but there is currently a lack of long-term and sensory-validated confirmation.

Future research should therefore focus on standardizing experimental conditions (toasting level), combining classical and advanced analytical techniques, and systematically integrating chemical and sensory data to elucidate the mechanisms of phenolic transformation under the influence of toasting.

Table S1 provides a structured overview of key studies examining the influence of oak origin and toasting level on the phenolic composition and color of red wines. It summarizes the author and year, type of wood/barrel, toasting level, wine type and aging duration, monitored phenolic parameters, and highlights the main findings as well as methodological specificities.

4.3. Volatile Compounds and the Aroma Profile of Wine

The aroma of wine is a complex mixture of chemical compounds that arise during different stages of winemaking and represent one of the most important factors influencing the quality of wine and consumer perception [84]. Although grapes and wine contain hundreds of chemical components, only a small fraction of these have a significant impact on sensory perception. The perception of aroma results from the interaction between chemical compounds and sensory receptors [85]. The most important volatile compounds that contribute to the aroma of wine include acids, higher alcohols, esters, terpenes, pyrazines, phenols, aldehydes, and certain thiols. Depending on their origin, wine aromas are divided into three categories: primary (from the grape), secondary (developed during fermentation), and tertiary (developed during aging) [86]. Although yeasts and bacteria release volatile aroma compounds from the grapes during fermentation, a significant portion of the aroma potential remains untapped, and the decisive changes take place during the

aging and storage of the wine [87]. Tertiary aromas are produced by two main processes: (i) oxidation of primary and secondary compounds under the influence of Dissolved Oxygen (DO) and (ii) extraction of compounds from wooden barrels, mostly oak, resulting in typical aromatic wood notes [88]. Barrel aging is often referred to as oxidative aging, as small amounts of oxygen penetrate through the porous structure of the wood or are added in a controlled manner through micro-oxygenation. During this process, volatile and non-volatile compounds are transferred from the wood to the wine, creating a unique aroma profile.

In addition to oxidation and the transfer of compounds, the condensation of tannins and flavonols, pigment polymerization, and the formation of new compounds through the charring of the inside of the barrel are also significant. Toasting leads to the breakdown of hemicellulose, lignin, and ellagitannins, producing furans, vanillin, and lactones, while simultaneously reducing norisoprenoids and other sensitive compounds [11,89]. The final aroma depends on numerous factors: the botanical species and origin of the oak wood [18–20], the barrel size and surface area ratio [90], the duration of contact between the wine and the wood [21,91], the drying and toasting method [16,18], and the chemical composition of the wine itself [23].

Among the earlier studies from the last decade, that of González-Centeno et al. [10] stands out as it has provided an important framework for understanding volatile compounds. The authors tracked the development of ellagitannins and volatile wood markers in Cabernet Sauvignon wines during a one-year aging process in new French barrels with different toasting methods in three wine regions (France, Italy, USA). They showed that even when using identical barrels (same origin, aging, and cooperation process), different wine matrices and different toasting levels lead to different extraction kinetics. Wood volatile markers (whisky lactones, guaiacol, vanillin) increase systematically over a 12-month period, but more rapidly in wines with higher alcohol content, while fruit esters decrease, with toasting together with hydration altering the ratio of cis to trans whisky lactones. Time was identified early on as a key factor in the interaction between toasting and matrix as a framework that determines the extent and direction of changes.

A few years later, Dumitriu et al. [48] extended this framework to the early stages of aging. In an experiment with Fetească neagră wine aged for only 1.5 and 3 months, they showed that even in this short period of time, the volatile profiles differed significantly depending on the degree of toasting. Wines from medium-toasted barrels had the highest concentrations of volatile wood compounds, while lightly toasted barrels had higher phenolic content. Using chemometrics (Principal Component Analysis (PCA), a multivariate statistical technique used to visualize patterns and groupings in complex datasets, and cluster analysis, a method that groups samples based on similarity), the aroma of the wine was clearly differentiated according to toasting and aging, and sensory evaluation confirmed that medium toasting after 3 months provides the best balance between fruity and woody notes. While González-Centeno [10] emphasized the importance of the interaction between matrix and barrel, Dumitriu et al. [48] showed that early decisions about toasting determine the course of volatile compound development; however, due to the short duration, the stability of these differences in the long term remains an open question.

In the same period, Del Fresno et al. [82] offered valuable insights for winemakers. They examined Tempranillo that had been aged in French barrels of the same declared origin and toasting, but from different manufacturers, and demonstrated that the volatile compounds still differed significantly. More heavily toasted barrels released higher amounts of volatile phenols (eugenol, guaiacol), whereas the levels of phenolic aldehydes and furans (vanillin, syringaldehyde, furfural) were lower. No clear pattern was observed for lactones. Although the basic color parameters did not vary, the aroma profile of the wine was

sensitive to seemingly minimal differences in toasting. The authors emphasized that commercial specifications such as “medium toasting” do not guarantee an identical aroma, which is an important criticism of the lack of standardization in barrel production.

Pichler et al. [16] also addressed the same topic of subtle differences after tracking Merlot from two vintages in different barrels with “medium” toast variants (medium, medium+, medium long, premium medium) and in stainless steel tanks over a period of 12 months. Their results confirmed that even small differences in the duration and temperature of toasting influenced the aroma profile: wooden barrels consistently enriched the wine with smoky, spicy, and woody notes, while stainless steel preserved the fruity and floral aromas. The sensory evaluation rated the wines from the premium medium barrels highest, which maintained a balance between primary and woody aromas. Compared to Del Fresno [82], this work further highlights that winemakers choose not only the toasting degree but also among a wide range of nuances within the same designation.

Another line of research expands the focus to additional wood parameters. Sánchez-Gómez et al. [49] investigated the volatile components of oak wood (*Quercus petraea*), classified according to OTR. They showed that wood with different OTR values, despite similar anatomical characteristics, produces different volatile profiles after toasting: Low Oxygen Transmission Rate (LOTR) logs were rich in furandanal and phenolic aldehydes, while High Oxygen Transmission Rate (HOTR) logs contained more lactones and ethylguaiacol. These differences were transferred to the wines at the sensory level: LOTR wines had smoky notes, while HOTR wines had coconut and wood aromas. This work is particularly important as it extends the discussion of toasting beyond time and temperature, incorporating microstructural wood properties that influence oxygen transport and, consequently, the extraction of volatile compounds.

While earlier studies mainly emphasized variability within European oak, Lu et al. [23] introduced a broader geographical context. By comparing American, French, and Slovakian oak, they showed that species has a much greater influence than geographical location itself. American oak produced wines with the highest levels of whisky lactone, eugenol, and cis-isoeugenol, with pronounced toasted and spicy notes; Slovakian oak was characterized by a high content of trans-whisky lactone, while French oak left a milder aromatic impression. It was also found that medium toasting released more vanillin, guaiacol, and syringol than light toasting, resulting in a more pronounced aroma profile. The dynamics of transfer showed that the most important compounds are likely to be released in the first few months, after which the rate slows down—a result consistent with González-Centeno [10], but this time confirmed by comparing different oak species. The study confirms the relationship between oak species and toasted notes with aromatic descriptors (toasted versus smoky notes), but due to the short aging period, the question of their long-term stability remains open.

On this basis, Casassa et al. [32] investigated the influence of different techniques of bending and toasting oak in French barrels on Cabernet Sauvignon. The results showed that after 15 months in the barrel and a further 3 months in the bottle, only a few compounds (4-vinylguaiacol, eugenol, cis-lactone) were sensory relevant (OAV > 1). Eugenol was particularly pronounced in wines from water-bent barrels, while cis-whisky lactone remained the most relevant compound across all treatments. The limited aromatic contribution is attributed to the short toasting time (20 min), confirming that the intensity and duration of toasting are decisive factors for the release of volatile compounds and outweigh technical variations in barrel production.

The latest contribution to this series comes from Ross-Magahy et al. [14], who focus on the interaction between toast level (light, medium, medium-long) and wood granulation (standard, extra-fine) in oak barrels (*Quercus petraea*) with two aging periods (12 and

18 months). Their results show that the degree of toasting had a stronger influence than the grain size: during the shorter aging period, light toasting in combination with standard grain size had the strongest effect, while during the longer aging period, medium toasting with fine grain size resulted in the highest concentrations of volatile compounds. The work emphasizes that the aroma profile of wine is not static but changes dynamically between 12 and 18 months, confirming that the thermal degradation of lignin and hemicellulose controls the development of volatile compounds.

Most studies relied on Gas Chromatography–Mass Spectrometry (GC–MS), a technique that enables the separation, identification, and quantification of volatile compounds with high sensitivity, while Stir Bar Sorptive Extraction–Gas Chromatography–Mass Spectrometry (SBSE–GC–MS) was typically applied to concentrate and analyze trace volatile compounds during the early aging phase. In addition, PCA and other chemometric methods were frequently used to distinguish samples based on toasting level or aging time, while sensory evaluation serves as an important confirmation of the chemical results. Particularly noteworthy are studies in which chemical and sensory data are interpreted together (González-Centeno [10], Pichler [16], Casassa [32], Lu [23]), as they enable a more robust link between individual compounds and perception descriptors: eugenol as the source of spicy notes, cis-whisky lactone as a stable carrier of coconut-wood aromas, and guaiacol and syringol as markers of smoky aromas. However, systematic investigations on the kinetics of individual volatile compounds in relation to perception thresholds and potential interactions—such as masking or synergy—in different wine matrices remain scarce. To provide a clearer overview of the volatile compound groups discussed in this section and their relationship to oak toasting, Table 1 summarizes the key compound classes, toasting-related behaviour, and associated aroma descriptors.

Table 1. Key volatile compound groups affected by oak toasting and their aromatic contributions.

Compound Group	Individual Compounds	Source	Effect of Toasting	Aromatic Notes
Lactones	cis-/trans-whisky lactone	oak	medium–heavy toasting increases intensity; cis/trans ratio depends on hydration and oak species	coconut, fresh wood
Phenols and phenolic derivatives	guaiacol, eugenol, syringol, cis-isoeugenol, ethylguaiacol, 4-vinylguaiacol	oak	linear increase with toasting level; eugenol often peaks at medium toasting	smoky, spicy, toasty notes
Phenolic aldehydes	vanillin, syringaldehyde	oak	medium toasting yields the highest vanillin; heavy toasting may cause degradation	vanilla, sweet
Furans	furfural, 5-methylfurfural, furandiones	oak	sharp increase under heavy toasting; LOTR oak → higher furandione levels	caramel, almond, roasted
Esters	ethyl ester fractions (e.g., ethyl hexanoate, ethyl octanoate)	fermentation	faster decline in heavily toasted barrels (oxidation, adsorption onto oak)	fruity, fermentation-derived notes

Summary and Critical Evaluation

Previous studies consistently confirm that the degree of toasting, the type of oak and the properties of the wood (e.g., granulation, oxygen permeability) play a decisive role in shaping the aroma profile of wine. Moderate to heavy toasting usually leads to increased concentrations of important volatile wood markers such as whisky lactone, eugenol, vanillin, and furfural, which contribute to notes of coconut, spice, smoke, and caramel. The early stages of aging (3–6 months) are considered crucial for the kinetics of volatile compound release, while stabilization or transformation is observed later, depending on the oak species and the duration of toasting. However, differences in the intensity and dynamics of extraction are evident between individual studies, which can be attributed to differences in toasting methods, the origin of the wood, the technical specifications of the barrels, and the composition of the wine matrix. An additional complexity arises from the different classifications of toasting levels between manufacturers, which makes a direct comparison of results difficult.

Although the chemical profile of volatile compounds is well described, there are relatively few studies that systematically link these data to sensory results and perception thresholds, especially for longer storage periods. Future research should therefore include standardized definitions of toasting, the application of advanced analytical methods, the tracking of the kinetics of individual compounds in relation to perception thresholds, and the integration of chemical and sensory analyses under real oenological conditions.

Table S2 provides a structured overview of key studies investigating the influence of oak wood origin and toasting level on the volatile composition of red wines. It summarizes the author and year, type of wood/barrel, toasting level, wine type and aging duration; monitors the volatile parameters, and highlights the main findings as well as methodological specificities.

5. Sensory Properties of Wine

Among the numerous components that contribute to the enjoyment of wine, aroma and taste play a central role. The sensory perception of wine results from complex interactions between its chemical constituents and human taste and olfactory systems. Volatile compounds are primarily responsible for aroma, while non-volatile compounds shape taste and sensations such as sweetness, acidity, bitterness, and saltiness. The balance of these compounds is crucial to understanding how wine interacts with the senses and how its characteristics influence the overall sensory experience [92].

Numerous studies showed that the market value of aged wines and their color are closely related to the concentration of phenolic compounds [93], which, if derived from oak barrels, are crucial for the sensory properties of wine, including color, taste, bitterness, and astringency [94]. Among the most important are furans, which are produced when wood is toasted and impart smoky and nutty notes, and vanillin, which is responsible for the aroma of vanilla and coffee. Flavanols, such as condensed tannins, play an important role in the perception of astringency and texture, as their polymerization during aging affects interactions with salivary proteins. In addition, β -methyl- γ -octalactone, commonly known as “whisky lactone” or oak lactone, is a key volatile compound derived from oak wood that contributes coconut and woody notes to wine, while volatile phenols such as eugenol and guaiacol enhance spicy and smoky notes [10,95,96]. To gain insight into the sensory characteristics most frequently valued by researchers, an analysis of the studies reviewed was conducted. The results clearly show that astringency, woody, and spicy notes are among the most frequently mentioned sensory categories associated with barrel-aged wines. Fruity and smoky aromas are also frequently reported, while sweetness and overall

wine quality are less often assessed. This distribution reflects the importance of phenolic compounds from wood and their influence on the organoleptic perception of wine.

Studies confirmed that different types of oak (American, French, Slovakian) and degrees of toasting have a significant influence on the sensory properties of wine. For example, research by Chira et al. [29] showed that French oak, especially when subjected to medium or heavy toasting, develops pronounced notes of spices, vanilla, and smoke, while American oak enhances coconut and sweet wood notes. Dumitriu et al. [48] and Lu et al. [23] showed that longer storage in medium or heavy toasted barrels leads to reduced astringency and improved sensory balance. Furthermore, González-Centeno et al. [10] emphasize that the content of ellagitannins—which are responsible for bitterness and texture—varies considerably depending on the degree of toasting and the type of wood, which affects the aromatic and flavor complexity. A comparison between wines aged in stainless steel tanks and those aged in oak barrels clearly shows that barrels improve the aroma and texture of wine, especially when medium or heavily toasted barrels are used. The most balanced aroma profile was achieved in premium medium-toasted barrels, which produced wines with the highest sensory quality [16].

This is confirmed by a recent study by Pichler et al. [16] on Merlot wines, which compared the aroma profiles of wines aged for 12 months in different types of barrels and stainless steel tanks. The results show that the wine samples aged in French premium barrels with medium toasting exhibit the greatest intensity of fruit and floral aromas, with an optimal balance between volatile phenols, esters, and alcohol. This variant also showed lower astringency, a fuller body, and a softer mouthfeel, resulting in the highest overall sensory ratings among all samples. The PCA in their study further confirms these results. The samples from premium barrels were placed in the diagram area with positive sensory characteristics such as fruitiness, sweetness, and spicy and floral notes, while the samples from stainless steel tanks or heavily toasted barrels exhibited more pronounced oxidative notes, a higher concentration of carbonyl compounds, and increased volatile acidity, which negatively affected the sensory profile.

These differences are also evident in the PCA diagram (Figure 3), which illustrates the different sensory profiles of wines aged under different conditions [16]. PCA confirms that premium medium-toasted barrels not only enhance the wine's aromatic profile but also contribute to a more balanced flavor and texture, resulting in a smoother and more harmonious sensory perception.

These results underscore the importance of careful selection of barrels and toasting levels as key oenological tools for shaping wine quality. In addition to the type of barrels and the degree of toasting, the aging process itself also plays a crucial role in the development of positive sensory characteristics. Over time, astringency decreases and color stabilizes, further enhancing the overall organoleptic experience.

Oenological techniques such as controlled oxidation (e.g., micro-oxygenation) support the favorable chemical transformations of phenolic compounds during aging, while the addition of sulfur dioxide (SO₂) protects the wine from undesirable oxidation processes and microbiological spoilage [92,93]. However, excessive concentrations of certain phenolic compounds, especially tannins and individual volatile acids, can lead to pronounced bitterness and pungency, which negatively affect the sensory balance. Therefore, achieving a harmonious phenolic profile, in which tannins and anthocyanins are present in optimal proportions, is crucial for color stability and achieving high sensory quality in wine [93].

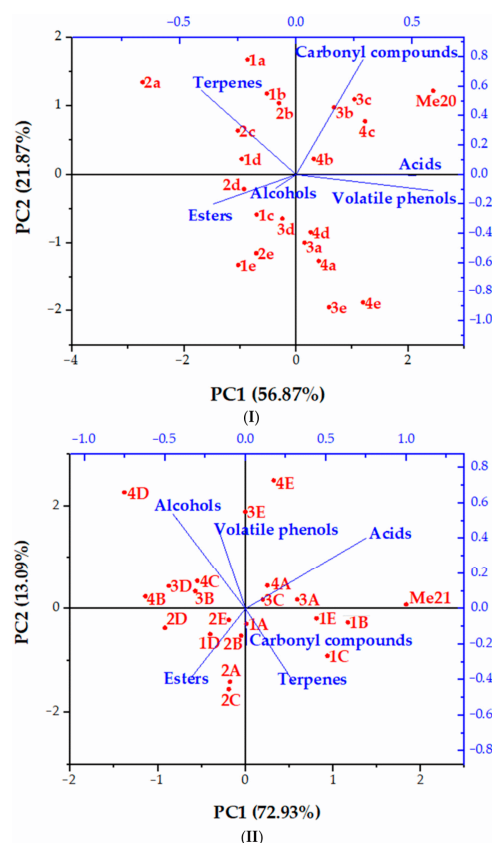


Figure 3. Principal component analysis (PCA) biplots showing the distribution of Merlot red wine samples from vintages 2020 (I) and 2021 (II) based on their sensory attributes and main aroma compound groups, after 12 months of storage in different vessels. Red labels represent wine samples, and blue vectors indicate aroma compound groups (carbonyl compounds, acids, volatile phenols, esters, alcohols and terpenes) [16]. Reproduced from [16] under the terms of the Creative Commons Attribution License (CC BY 4.0). Note: Detailed abbreviations are provided in [16].

Summary and Critical Evaluation

Although most studies consistently confirm the importance of the influence of wood type and toasting degree on the sensory properties of wine, there are differences between the individual studies in the interpretation of the significance of individual factors. For example, while Chira et al. [29] and González-Centeno et al. [10] clearly highlight the differences between French and American oak in terms of aroma profile, the results of Lu et al. [23] and Pichler et al. [16] show that the interaction between toasting level and grape variety can be just as important and sometimes even decisive for the formation of the sensory profile. In addition, there are methodological differences between the studies—the sensory panels used, the terminology, and the analytical approaches often differ, making it difficult to directly compare the results and draw general conclusions. There is also a noticeable lack of systematic monitoring of changes in sensory properties over a longer storage period and a lack of standardized protocols. All of this points to the need for additional, carefully designed comparative studies that would allow for a clearer definition of the relationships between chemical composition, technological factors, and sensory perception of wine.

6. Conclusions

Toasting of oak barrels represents a key oenological practice that influences the chemical composition and sensory properties of wine. As highlighted in the introduction, this practice played a dual technological and organoleptic role for centuries: it replaced am-

phorae and at the same time contributed to the development of a more complex wine profile. An evaluation of the available literature showed that the degree of toasting has a significant influence on the extraction and transformation of phenolic and volatile compounds. Light toasting emphasizes the tannin structure and fruity aromas, while heavier toasting leads to the formation of compounds such as vanillin, lactones, furans, and phenols, which impart more complex spicy, coconut, and smoky notes to the wine.

While the effects on the phenolic and aromatic profile are well documented, changes in the basic physicochemical parameters during barrel aging have been less systematically studied and are generally of lesser importance. Studies that integrate chemical and sensory data are particularly valuable, as they provide a deeper understanding of the relationships between individual compounds and sensory descriptors. However, methodological differences between studies—including grape varieties, aging durations, and analytical approaches—make direct comparisons difficult and highlight the need for further standardized research.

Future studies should combine advanced analytical techniques with sensory methods to elucidate the mechanisms of extraction and conversion of compounds at different toasting levels and their role in shaping the final wine profile. Beyond scientific insight, such an approach would provide winemakers with valuable guidelines for optimizing wood selection and toasting levels according to the desired wine style.

Although recent studies already cover different oak species and geographic origins under controlled toasting conditions, a greater degree of methodological harmonization and comparative analysis is needed to define their effects more precisely. Multivariate statistical analyses and integrated approaches can offer additional value by enabling a more detailed connection between chemical indicators and sensory perception, which is crucial for reliable modeling of the influence of various factors. In the context of sustainable production, the use of alternative wood species and biomass, as well as the analysis of their behavior at different toasting levels compared to traditional oak, is an interesting approach for future research. Such approaches could contribute to the development of innovative oenological tools while preserving the characteristic sensory identity of wine.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/beverages11060165/s1>, Table S1: Overview of selected studies on the impact of oak barrel origin and toasting level on phenolic composition and color of red wines; Table S2: Overview of selected studies on the impact of oak barrel origin and toasting level on volatile composition of red wines.

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