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Review

HOW DOES MATURATION VESSEL INFLUENCE WINE QUALITY? A CRITICAL LITERATURE REVIEW

O RECIPIENTE DE MATURAÇÃO E SUA INFLUÊNCIA NA QUALIDADE DO VINHO: REVISÃO BIBLIOGRÁFICA CRÍTICA

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SUMMARY

Wine maturation consists of wine being stored in vessels after alcoholic fermentation and malolactic fermentation and before bottling. This is a key period during the wine's evolution, with changes in the physicochemical and sensory characteristics, especially in the colour, aroma, flavour and mouthfeel. Traditionally, oak barrels have been the main vessel choice for the maturation period. However, due to new technology and increasing consumer interest, winemakers are now using different vessels which vary in material, shape and size to mature their wines. Despite this gain in popularity, there are key questions remaining regarding how exactly variations in maturation vessel physical parameters affect wine quality during maturation. This review summarises how variations to maturation vessel material, size, and shape influence wine quality, specifically regarding oxygen permeation, thermal conductivity, and the release of exogenous compounds. Overall, the vessel material and size have a significant influence over the oxygen transfer rate of the vessel, and the associated changes to colour, aroma and mouthfeel, which occur with oxygen ingress. Maturation vessels may be conceptually viewed on a scale of 'inertness', with more inert vessels, such as stainless-steel tanks, generally having higher thermal conductivity, lower oxygen transfer rate and less release of exogenous compounds, with the opposite being true for the more active vessels such as oak barrels. Finally, this review points out gaps in the literature such as how maturation vessel parameters influence lees-wine interaction. This review aims to lay out paths for future research needed to shed light on how maturation vessel choice affects wine quality.

RESUMO

A maturação do vinho decorre durante o período de conservação após a fermentação alcoólica e a fermentação maloláctica, até ao seu engarrafamento. Trata-se de um período chave para a evolução do vinho, em que se verificam alterações nas suas características físico-químicas e sensoriais, especialmente na cor, aroma, gosto e sensações de boca. Tradicionalmente, as barricas de carvalho têm sido o principal recipiente utilizado durante esta etapa. Contudo, a utilização de recipientes diversos em termos de material, forma e dimensão tem aumentado devido a desenvolvimentos tecnológicos e ao crescente interesse dos consumidores. Apesar da popularidade crescente de alguns recipientes alternativos, o conhecimento sobre como as variações nos parâmetros físicos dos recipientes de maturação influenciam a qualidade do vinho durante a sua maturação é insuficiente. Neste estudo são revistos os recipientes de maturação mais comuns, no que respeita a material de construção, permeação ao oxigénio, condutividade térmica, potencial de cedência de substâncias, e sua influência na qualidade do vinho. O tipo de material e a dimensão do recipiente têm uma influência significativa sobre a taxa de transferência de oxigênio e, consequentemente, em alterações na cor, aroma e sensações de boca, que ocorrem na sua presença. Os recipientes de maturação podem ser classificados de acordo com a sua inerticidade, com recipientes mais inertes, como os depósitos de aço inoxidável, com maior condutividade térmica, menor taxa de transferência de oxigênio e menor libertação de substâncias exógenas, sendo o oposto verdadeiro para os recipientes mais ativos, nomeadamente as barricas de carvalho. Finalmente, esta revisão revela lacunas na literatura sobre como as características dos recipientes de maturação influenciam a interação borras-vinho. Esta revisão visa traçar caminhos para investigação futura, necessária para melhor compreensão de como a escolha do recipiente de maturação influencia a qualidade do vinho.

Keywords: Wine maturation, maturation vessel, oxygen permeation, thermal dynamics, wine quality.
Palavras-chave: Maturação do vinho, recipiente de maturação, permeação de oxigénio, dinâmica térmica, qualidade do vinho.

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INTRODUCTION

Wine ageing can be generally divided into two stages, the first being the ‘maturation phase’, in which bulk wine is stored in large vessels of varying material, shape, and size (Figure 1); the most common and widespread being oak barrels, along with various other materials such as stainless steel, clay, concrete, and plastic (Ribéreau-Gayon *et al.*, 2006; Morata *et al.*, 2019) - Figure 1. In the initial phase, known as maturation, the wine is more exposed to the ingress of oxygen and other exogenous compounds which derive from both the vessel material as well as from the various post-fermentation treatments. Furthermore, several stabilisation processes can be performed during maturation, such cold stabilisation to induce tartrate precipitation and natural settling to increase wine limpidity. The second phase is the ‘bottle ageing phase’, in which the wine is sealed into bottles for ageing, where their accessibility to treatments and exposure to oxygen is significantly reduced (Boulton *et al.*, 1999). Wine is dynamic, both physicochemically and sensorially, and a key aspect of a wine’s sensorial evolution is the maturation process before packaging. Although there are variations which can be made during the ageing process, the most scope for wine evolution and alteration occurs during maturation, mostly due to the nature of the maturation vessels, which create a much more active environment for the wine, leading to large changes in overall wine quality in relatively short periods of time. This review will therefore focus on the maturation phase of the overall ageing process.

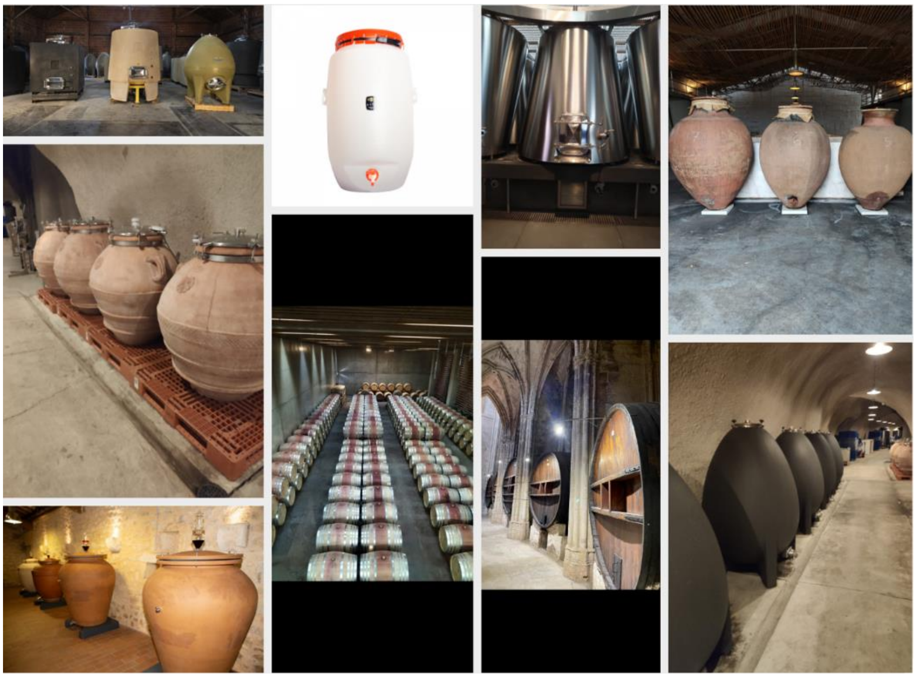


Figure 1. A sample of maturation vessels of varying shapes, sizes and materials.

Over the past 10-20 years, the exploration into alternative vessels for ageing has become increasingly popular globally (Gil i Cortiella *et al.*, 2020, 2021), with the re-utilisation of ancestral ageing vessels, such as clay amphoras or qvevris, becoming ever more fashionable (Rytköken *et al.*, 2019; Harutyunyan and Malfeito-Ferreira, 2022). Although there has been much research into the various factors surrounding maturation in oak barrels (Garde-Cerdán and Ancín-Azpilicueta, 2006; Chira and Teissedre, 2015; del Alamo-Sanza and Nevares, 2018), there is comparatively less studies regarding the ever-more popular other materials used to mature wines such as clay and concrete. Furthermore, there is very little in depth research attempting to unravel and understand how the individual parameters of material, shape and size interact to effect wine quality during the maturation process.

The earliest ageing vessels were made from clay, with Southern Armenian clay vessels being the earliest evidence of their use for both fermentation, maturation, and storage (Areshian *et al.*, 2012). These early clay maturation vessels may be seen as the precursor which spread, along with grape vines, from ancient Mesopotamia into the Mediterranean basin, where many countries have different names for the same kind of clay storage vessel such as the

Portuguese “talhas”, the Roman “dolia” and the Greek “pithoi” (Peña, 2007; Kourakou-Dragona, 2016). In today’s world, oak is by far the dominant material used to age wines, but this has not always been the case. Indeed, in ancient times it was clay which was preferred over wood for the maturation of high-quality wines (Billiard, 1913; Harutyunyan and Malfeito-Ferreira, 2022). The use of oak was popularised during the Roman period and was not initially used for qualitative purposes, but instead as a means of light, portable and durable transport which were much more efficient to transport to the outer reaches of the empire - like England in 250 A.D - than the heavier and more fragile clay vessels (Twede, 2005; Morata *et al.*, 2019). In modern times, with the advent of new technologies being able to create and mould new materials at a mass scale, stainless steel and plastics have also been in use as maturation vessel material (Morata *et al.*, 2019).

KEY CHEMICAL AND SENSORY MODIFICATIONS OCCURING DURING MATURATION

Colour is the first sensorial attribute a wine consumer is exposed to when drinking wine; it thus is an important qualitative factor in red wine. A key phenomenon which occurs during the process of maturation and ageing of red wines, is the evolution and stabilisation of colour. Young red wines derive their red colour from anthocyanin pigments which, having a flavylium form, absorb green light and thus have a red colour (Zhang *et al.*, 2022). With the exception of teinturier varieties, these anthocyanin molecules are extracted from red grape skins during the maceration process. Due to a lack of electrons, the structure of the flavylium anthocyanin molecule is unstable and highly reactive, meaning anthocyanins tend to be found in their glycosylated forms in wine and are susceptible to transformation and degradation (Brouillard *et al.*, 1997; He *et al.*, 2012; Escribano-Bailón *et al.*, 2019). The reactivity of these free anthocyanins leads to a phenomenon known as co-pigmentation, which occurs in young red wines (Boulton, 2001). Co-pigmentation is the first step involving anthocyanins and other compounds present in wines and precedes the eventual formation of stable polymeric pigments formed during wine maturation. The formation of polymeric pigments results in a wine colour change from red purple to brick red (Alcalde-Eon *et al.*, 2006). These polymeric pigments are more chemical stable and are less vulnerable to the bisulfite bleaching which affects anthocyanins in the flavylium form (Peng *et al.*, 2002; du Toit *et al.*, 2006a). These pigments also persist over longer periods of storage without being degraded. In general, the stabilisation and transformation of anthocyanins during wine storage can occur via several different pathways, but often involves the presence of proanthocyanidins (also known as condensed tannins) and trace amounts of oxygen. The major polymeric pigments formed during colour stabilisation of Tannin - Anthocyanin condensation products (T-A) and pyranoanthocyanins (de Freitas and Mateus, 2010; Oliveira *et al.*, 2019) - Figure 2. The condensation of proanthocyanidins and anthocyanins can be either direct or mediated by aldehydes, predominantly acetaldehyde, which makes up over 90% of wine aldehydes (Remy-Tanneau *et al.*, 2003). Essentially, anthocyanins can perform the role of nucleophile or electrophile in these reactions (Salas *et al.*, 2004), forming either a T-A pigment, when it acts as an electrophile, or an A-T pigment (anthocyanin-tannin), when it acts as a nucleophile. Acetaldehyde, the majority of which is produced during alcoholic fermentation as a metabolite of yeast activity, and also partly as a product of ethanol oxidation, and produced during the micro-oxygenation process which often occurs during maturation due to the air permeability of some maturation vessels, can also mediate the formation of T-A pigments (Liu and Pilone, 2000) (Figure 2). T-A pigments can also be formed via the involvement of other compounds found in wine, such as vanillin – an aldehyde derived from oak contact or glyoxylic acid, each forming different polymeric pigments (Spillman *et al.*, 1997; Pissarra *et al.*, 2003; Sousa *et al.*, 2007; Oliveira *et al.*, 2019).

Another anthocyanin derived polymeric pigments in wine are pyranoanthocyanins which are characterised by an addition pyran ring (Fulcrand *et al.*, 1997). These compounds are formed via reactions between anthocyanins and pyruvic acid and acetaldehyde to form Vitisin A and B respectively (Fulcrand *et al.*, 1998; Oliveira *et al.*, 2019). Other mediators include hydroxycinnamic acids, diacetyl, acetoacetic acid and p-vinyl-phenols (Schwarz *et al.*, 2003; He *et al.*, 2006; Gomez-Alonso *et al.*, 2012). The majority of pyranoanthocyanins are mostly formed during fermentation rather than ageing when their precursors are at their highest concentrations, because these precursors are often molecules released during yeast metabolism, which is at its most active during yeast metabolism (Morata *et al.*, 2003), although molecules such as diacetyl can also be high during maturation too. Recent research has discovered more elements involved in the colour evolution process which occurs during maturation and ageing, with vinylpyranoanthocyanins being discovered, which were named A type portisins (Mateus *et al.*, 2003, 2004, 2006). These are formed by the combination of flavanols and A-type vitisins in the presence of acetaldehyde. This adds further layer of complexity, in which anthocyanins that have initially reacted with flavanols, along with the mediation of pyruvic acid or oxaloacetic acid to form A-type vitisins (Araujo *et al.*, 2017), then react further to form portisins (Oliveira *et al.*, 2019) - Figure 3. These portisins are of oenological interest as they exhibit a blueish colour (Mateus *et al.*, 2003). The new discovery of a novel anthocyanin derived polymeric pigment demonstrates the need for further research to identify all the polymeric pigments which are formed and contribute to colour and hue during maturation, and to understand their associated chemical pathways which underpin their formation. This is necessary to understand how winemaking choices such as maturation vessel will impact these colour changes.

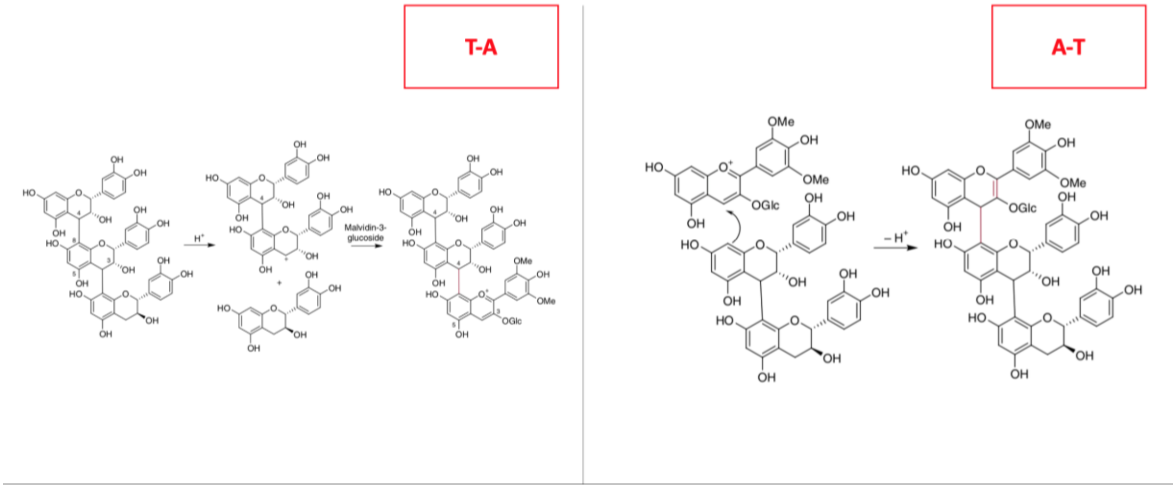
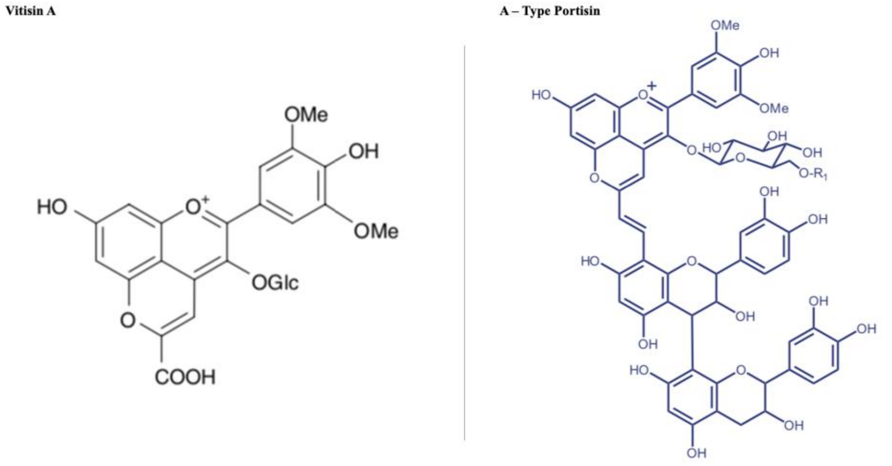


Figure 2. Formation of the Tannin-Anthocyanin (T-A) pigments through a condensation reaction of proanthocyanidins and anthocyanins (left side segment), as well as the formation of Anthocyanin-Tannin (A-T) polymeric pigment, which in this form is colourless (right hand segment). Figure adapted from Waterhouse *et al.* (2016).

There are a large variety of anthocyanin derived products which can occur through different mediation pathways across the whole winemaking process (Figure 4). Although there are still likely further discoveries to made, which will give an even more comprehensive picture of colour stabilisation during maturation and ageing, there are a few decisions regarding maturation vessel choice which will very likely have important effects upon colour stabilisation in red wines. Those mediating compounds which are more associated with alcoholic fermentation, such as pyruvic acid (Figure 4), are unlikely to be largely affected by maturation vessel type, since the quantity of pyruvic acid depends on fermentation dynamics mostly rather than ageing dynamics (Rankine, 1965; Graham, 1979); thus it is important to note that the main influences of maturation vessel will be due to the permeability to oxygen, which will influence the amount of acetaldehyde formed from the oxidation of ethanol, thus providing more substrate mediator for the formation of several polymeric pigments (Figure 4). Mannoproteins, which are released during extended lees contact during maceration, have also been shown to have a colour stabilising effect, with their ability to stabilise monomeric anthocyanin as well as react with A-type vitisins (Escot *et al.*, 2001; Palomero *et al.*, 2007) - Figure 3.

Proanthocyanidins are a key class of the flavonoids family found in grapes and wine. Proanthocyanidins is the umbrella term given to the molecules prodelphinidins and procyanidins, which are oligomeric or polymeric molecules made up from monomeric units of catechin and epicatechin, or gallocatechin and epigallocatechin (Waterhouse *et al.*, 2016). These molecules are found in all grape clusters' fractions, mainly in the seeds, but also in the stems and skins (Brossaud *et al.*, 2001; Jordão and Ricardo-da-Silva, 2019), and their composition and concentration in wine depends on several winemaking factors which affect both their quantity and chemical structure. Their importance in wine is due to their strong sensorial impacts, as they are related to the perception of bitterness and astringency in wine (Ma *et al.*, 2014), their ability to combine with anthocyanins to form stable polymeric wine pigments, and their antioxidant properties. The monomeric units of proanthocyanidins are both astringent and bitter. During maturation and ageing, which can be broadly characterised as acidic and slowly oxidative environment, proanthocyanidins tend to increase in polymerisation degree (DP), which has been shown to increase astringency and decrease bitterness (Peleg *et al.*, 1999; Chira *et al.*, 2009; Sun *et al.*, 2013). However, when the polymerisation degree becomes too high, there is a self-precipitation of proanthocyanidins out of the wine, which will in fact lead to an overall decrease in mean polymerisation degree (mDP) and an associated reduction in astringency (Scollary *et al.*, 2012). Oxygen (which is a key variable in maturation vessels) has been found to have a large impact upon mDP in wines, with proanthocyanidins generally increasing in mDP with higher levels of micro-oxygenation during maturation (del Carmen Llaudy *et al.*, 2006). This tendency towards higher degrees of polymerisation when exposed to oxygen during maturation is often mediated by acetaldehyde (Timberlake and Bridle, 1976). Several studies showed that acetaldehyde reacts with proanthocyanidins to increase DP to the point of precipitation out of the wine, leading to an overall reduction in mDP and causing an overall reduction in astringency and a 'softening' of wine (Atanasova *et al.*, 2002; McCord, 2003; Chira *et al.*, 2012; Parpinello *et al.*, 2012; Anli and Cavuldak, 2013). Maturation variables have been shown to have a large impact on proanthocyanidin evolution in wines, with increasing temperature being correlated with a higher rate of procyanidin degradation (Dallas *et al.*, 1995). The evident influence of oxygen and temperature upon proanthocyanidin evolution indicates that maturation vessel choice will have a large impact of the sensory outcome of a wine based upon its effects on proanthocyanidin evolution. Other wine matrix factors such as sulfur dioxide (SO_2) concentration can influence proanthocyanidin evolution, with wines of higher levels of SO_2 having lower rates of procyanidin evolution (Dallas *et al.*, 1995). This finding is further corroborated by observations from Tao *et al.* (2007), who found that under the same maturation conditions, wines with low SO_2 had significantly lower monomeric anthocyanins and proanthocyanidins than wines matured with higher SO_2, which may be due to SO_2's ability to reduce, and thus reverse, the oxidised polyphenols back to their original state. Regarding pH, Dallas *et al.* (2003) found that very low pH (2.0) had the highest rate of procyanidin degradation, with wines of pH 3.2 exhibiting the highest procyanidin stability during maturation. Indeed, further studies have shown that pH is essential to the proanthocyanidin evolution associated with micro-oxygenation (MOX) during maturation. Kontoudakis *et al.* (2011) found that wines matured at lower pH (3.1) had significantly higher levels of ethyl-linked pigments, polymeric pigments, and PVPP index, with the phenolic evolution and their associated changes to colour and wine mouthfeel induced by MOX being almost non-existent in wines of high pH (3.9).


Vitisin A

A – Type Portisin

F**igure 3.** Chemical structure of the key polymeric pigments, Vitisin A (left) and A-type Portisin (right). Figure adapted from Waterhouse *et al.* (2016).

The maturation process is not only characterised by evolution of compounds already present in the wine, but also by the potential integration of exogenous compounds into the wine. The choice of maturation vessel is very important here, with the most comprehensive research being carried out on oak barrels, in which a whole host of exogenous compounds are released into the wine, which can cause large and often very desirable changes to the sensory properties of a wine. These include hydrolysable tannins and volatile aroma compounds (Kaya *et al.*, 2017; Carpena *et al.*, 2020; Pfahl *et al.*, 2021), the details of which are discussed later in this review. The introduction of exogenous compounds into wines from their maturation vessel is not always a desirable occurrence, with the epoxy resins used to coat some maturation vessels being related to a 'bitter almond flavour', deriving from abnormally elevated concentrations of benzoic aldehyde (Moreno-Arribas and Polo, 2009). Whether a maturation vessel donates exogenous compounds is highly dependent upon its material, with shape and size likely to have second effect upon this variable, something which is discussed in further detail later in the review.

The extended period in which wine is stored in a maturation vessel also allows for the natural sedimentation, in which unstable colloidal matter settles at the bottom, resulting in a more limpid wine. The size and shape of a maturation vessel may impact the speed of this phenomenon, thus needs to be considered.

The following section will outline how these chemical and sensory modifications, which occur during wine maturation, can be influenced by the physical parameters to material, shape and size of a maturation vessel.

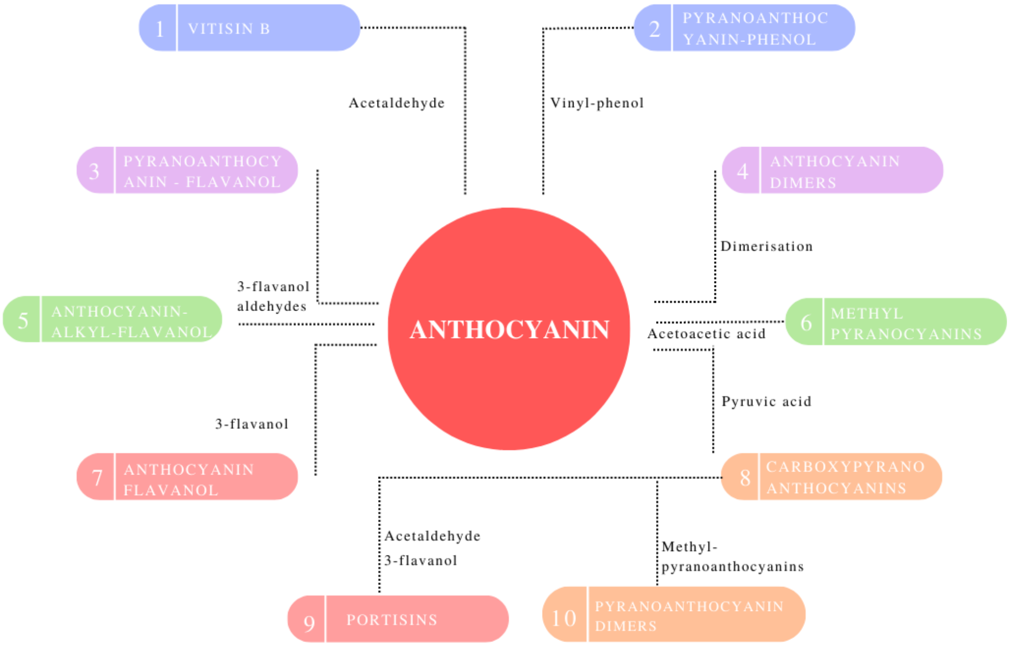


Figure 4. Summary of the main anthocyanin derived products found after red wine fermentation and maturation, along with the associated elements which mediate their production, which are indicated along the dotted lines. Figure adapted from de Freitas and Mateus (2011).

PHYSICAL PARAMETERS INFLUENCING MATURATION DYNAMICS

The type of maturation vessel dictates the environment conditions to which the wine is subjected during the maturation period. Two key parts of this environment, which are under strong influence from maturation vessel, are the wine's exposure to oxygen, as its temperature.

Oxygen is arguably the key parameter when discussing the maturation of wines. On one hand, oxidation is the main way wines lose their palatability over time, becoming gradually more 'oxidised' and thus, faulty, unless indeed this is an intended stylistic characteristic, as with Madeira and Xeres/Sherry styles of wine. As a result, many aspects of winemaking (with the exceptions of previously mentioned oxidative styles) are performed with the intention of minimising the wines' contact with oxygen, such as the addition of SO_2 as an antioxidant. Conversely, oxygen can also be viewed as crucial to a wines development during ageing and is a key determinant of final wine style, with many of the key ageing vessel choices being made due to their differing levels of oxygen permeation levels. The importance of oxygen in wine was first famously identified by Louis Pasteur's quote "C'est l'oxygene qui fait le vin" (Pasteur, 1875). In general terms, oxidation refers to the reaction in which an atom loses an electron. In the context of wine composition, different wine components exhibit varying degrees of susceptibility to oxidation, with phenolic compounds being key substrates involved in important oxidation reactions during maturation and ageing, conferring important sensory changes to the wine (Danilewicz *et al.*, 2008; Oliveira *et al.*, 2011). Other key substrate which are subject to oxidation in wine is ethanol giving rise to acetaldehyde. Acetaldehyde is important sensorially on both a direct and indirectly scale, conferring a 'stewed apple' aroma as well as being a key mediator of many important maturation chemical reactions discussed previously in this review (Waterhouse and Laurie, 2006; du Toit *et al.*, 2006b). Molecular oxygen is consumed in wine in the presence of catalyst transition metals such as Fe(II), forming a hydroperoxyl radical at wine pH, which can then oxidise components with strong hydrogen-donating characteristics such as phenolic compounds (Danilewicz, 2003; Ugliano, 2013). During oxidation, the hydrogen peroxide gives rise to a hydroxyl radical in a reaction known as the Fenton reaction (Waterhouse *et al.*, 2016), which generates 1-hydroxyethyl radical, capable of oxidizing ethanol, producing the major compound associated with an 'oxidised' character' – acetaldehyde (Elias *et al.*, 2009). The slow transference of trace levels of oxygen in what is known as MOX is a key aspect in the maturation process. In modern winemaking, this can occur in two ways, firstly through 'passive MOX', in which oxygen diffuses passively from the atmosphere through a permeable material into the wine, and secondly 'active MOX', in which a diffuser is used to actively transfer oxygen into the wine (Sánchez-Gómez *et al.*, 2020). Trace amounts of oxygen are vital for allowing colour stabilisation in red wine, in which the wine colour changes from purple to orange-red due to monomeric, grape-derived anthocyanins becoming stable polymeric pigments, which are resistant to SO_2 bleaching;, these 'colour stabilisation' reactions involve trace amounts of oxygen and proanthocyanidins (de Freitas and Mateus, 2010; Waterhouse *et al.*, 2016). Oxygen is a major parameter in maturation because it underpins both polymerisation reactions (in which acetaldehyde formed during the Fenton reaction can promote polymerisation), and condensation reactions which can have a beneficial impact on structure (through condensed proanthocyanidins polymerisation). A further benefit of MOX during maturation is elimination of reductive aromas like hydrogen sulfide (Anli and Cavuldak, 2013). Phenolic compounds are affected by oxygen in wine, thus making oxygen during maturation a more influential parameter when discussing the maturation of red wines, as they have naturally higher concentrations of phenolic compounds (Gómez-Plaza and Cano-López, 2011). Although oxygen has been shown to be a powerful tool in improving wine aroma through the partial/complete elimination of reductive and vegetative aromas (González-Sanjosé *et al.*, 2008), improving wine taste and structure through a reduction in astringency (Es-Safi *et al.*, 1999) and stabilising colour (Gómez-Plaza and Cano-López, 2011), it can also have a deleterious effect upon wines during maturation, with excessive amounts of oxygenduring maturation leading to a rapid quality loss in wines (Vidal and Aagard, 2008). Since maturation vessel parameters have a large impact on the rate of oxygen diffusion into the wine, the correct choice of maturation vessel is a key decision when trying to an obtain a wine of desired quality parameters. There are several ways to measure how much a maturation vessel in, firstly is the oxygen transfer rate (OTR) which is purely based on how much oxygen a vessel will allow to diffuse (often directly related to its porosity), and secondly there is the annual total ingress rate (TOIR) which gives a value based upon the amount of oxygen which diffuses through the material, combined with any other paths in which oxygen may pass through the vessel (e.g. bungholes) and therefore is a more holistic and accurate value when trying to compare the variation between maturation vessels regarding oxygen (Nevares and del Alamo-Sanza, 2018).

Temperature is another key factor which influence wine maturation dynamics. Many reactions occur during wine maturation. The Arrhenius equation leads to the conclusion that all chemical reaction speeds increase with increasing temperature (see review by Waterhouse *et al.* (2016) for more detailed explanations of this equation). It thus follows that wine related chemical reactions during storage also increase with temperature, meaning that as a general rule, higher temperature will speed up the maturation process than cooler maturation conditions. Indeed, it has been reported that the degradation of procyanidins during maturation is 5-10 times faster at high temperatures (32 ^{O}C and 42 ^{O}C) (Dallas *et al.*, 1995). The reaction pathways, which are pH dependent, and lead to key maturation related aroma compounds such as hydroxylmethyl furfural (HMF), the hydrolysis of S-methylmethionine to dimethyl sulfide, as well as reactions such as the hydrolysis of proanthocyanidins both exhibit increased reaction rates with increasing temperature (Waterhouse *et al.*, 2016). Therefore, the thermal properties of maturation vessels are a key parameter as they determine the speed of pH dependent reactions. If maturation temperature is not well controlled, and increases to an undesirable level, this can lead to increase production of unwanted compounds in the wine, such as the carcinogen ethyl carbamate, which is formed from non-enzymatic ethanolysis and is a reaction which is highly temperature dependant (Ough *et al.*, 1988), as well as the formation of dimethyl sulfide (DMS), a faulty sulphurous aroma when in high concentration (Waterhouse *et al.*, 2016). In addition, highly fluctuating temperature during maturation is not conducive to effective settling or clarification, with higher temperature increasing the likelihood of protein hazes (Mierczynska-Vasilev and Smith, 2015), and potentially also causing convection currents which hinder the process of natural sedimentation over time, although this remains only a logical conjecture until empirical evidence is provided to support this hypothesis. Taken together, these impacts demonstrate the importance of temperature-controlled maturation, as uncontrolled maturation temperatures can lead to increase faulty/toxic compounds in the wine as well as reducing clarity. However, the diversity of wine in all its forms means that there is a diversity of desirable outcomes, meaning it can sometimes be hard to generalise for ‘desirability’ of some compounds in wine. For instance, the rate of sotolon (3-hydroxy-4,5-dimethyl-2(5H)-furanone) formation is temperature dependent, being an important aroma compound in Portuguese fortified wines such as Madeira or Port (Silva Ferreira *et al.*, 2005; Perestrelo *et al.*, 2019), which would indicate that higher temperatures may be more desirable when attempting to maximise sotolon formation in a wine during maturation. Temperature also has an impact on oxygen uptake, with low temperature increasing oxygen solubility in wine, and high temperature decreasing it (Waterhouse and Laurie, 2006). Since temperature can also affect oxygenation rate, the choice of maturation vessel should be done with an understanding of the possible interactive effects of physical parameters during this process. The thermal properties of a maturation vessel are of most importance to consider as they have a large impact on temperature dependent reactions and overall wine quality. Indeed, several studies have found that storage temperature exerts significant impacts upon colour and phenolic evolution during maturation (Sims and Morris, 1984; Somers and Evans, 1986; Castellari *et al.*, 2001).

MATURATION VESSEL PHYSICAL VARIATION AND ITS EFFECT UPON WINE QUALITY

The following section encompasses the various ways in which a maturation vessel can vary according to physical parameters; these are defined in four ways: material, shape, size and other parameters. This review will then attempt to elucidate how these variations in physical parameters will confer different chemical, spatial and thermal dynamics upon the wine, and in turn effect the previously discussed maturation processes which so greatly impact final wine quality. It is aimed to allow winemakers to make more informed, scientific-based decisions regarding which maturation vessel best fits their desired quality of final wine.

Vessel Material – Wood, Clay, Stainless steel, Concrete, and High-density polyethylene

Wood

Regarding wood, oak barrels are by far the most extensively used, widely investigated and well-known forms of maturation vessel, but in recent years there has been renewed interests in alternative types of wood, which confer different influences upon final wine quality (Zamora, 2019); there has been particular interest in *Castanea sativa Mill.* (Chestnut), *Robinia pseudoacacia* (Acacia), and *Prunus avium* (Cherry) as alternatives to oak (Fernández de Simón *et al.*, 2010; Tavares *et al.*, 2018). Much variation exists within maturation in wood with key parameters such as botanical species, toasting level, cooperage process and age, all having large effects on wine quality (Waterhouse *et al.*, 2016; Pfahl *et al.*, 2021). However, wood as a maturation material can generally be described as a ‘porous solid’ - its permeability to gases but in-permeability to liquid explains why it´s water-tight while also slightly air permeable. It is also a doner of exogenous compounds to the wine which alter its sensory properties (del Alamo-Sanza *et al.*, 2017; Martinéz-Gil *et al.*, 2022).

Wood has an oenologically interesting structural composition, in which ‘heartwood’ planks are used, which have a high concentration of tyloses, which act as plugs inside the xylem, allowing the wood to be watertight. The staves are also obtained in a way that the medullary rays run parallel to the inner side of the barrel, thus preventing wine leaks; however, there is interspecific variation in terms of wood composition, meaning that variation does exist in cooperage techniques depending on wood species (Waterhouse *et al.*, 2016; del Alamo-Sanza *et al.*, 2017).

Wood barrels possess the important property of air permeability, which allows oxygen to diffuse in and create a ‘micro-oxygenation effect’, mediating colour stabilisation through the formation of polymeric pigments, as well as reduce astringency through mediating proanthocyanidin polymerisation reactions with anthocyanins (Zamora, 2003). Oxygen can enter wooden barrels through several paths: directly through the wood and the joints between staves (Vivas and Glories, 1996). The knowledge of oxygen entering the wine through the barrel goes back to over 80 years, with Ribéreau-Gayon (1933), first reporting this occurrence. The oxygen transfer rate is estimated to be about 12 mg/L per year for a 225 L barrel, however this figure can vary according to wood age, botanical species (with French oak barrels being reportable more permeable to oxygen), and wood moisture levels (del Alamo-Sanza *et al.*, 2017). From the literature, the range of OTRs for oak barrels falls within the range of 10 – 28 mg/L per year (Moutounet *et al.*, 1994; Vivas and Glories, 1996; Kelly and Wollan, 2003; del Alamo-Sanza and Nevares, 2014). These OTR values are seen as optimal for wine maturation and has ‘passed the test of time’ regarding its positive effect on wines sensory properties (i.e., reduction in astringency and colour stabilisation through oxygen mediated reactions previously discussed in this review). Regarding oak barrel TOIR values, they are highly variable, ranging from 2 mg/L/year to 42 mg/L/year (Vivas, 1999; del Álamo-Sanza and Nevares, 2014).

One of the main reasons why winemakers employ maturation in wood vessels is because of the aromatic changes resulting from the integration of wood-derived compounds into the wine, which are summarised in Figure 5. These compounds are often derived from the oak wood itself, with lignin, polysaccharides (hemicelluloses and cellulose), lipids and hydrolysable tannins all being oak derived sources which alter the sensory properties of the wine during maturation (Fengel and Wegener, 1989). These can be broadly split into volatile aromatic exogenous compounds, which tend to affect aroma, and non-volatile phenolic exogenous compounds which mainly tend to affect texture and 'mouthfeel'. In terms of aromatic changes deriving from oak lignin, phenolic aldehydes, ketones and volatile phenols, are a key groups of volatile aroma compounds affecting wine sensory properties after ageing. The most impactful of the phenolic aldehydes is vanillin, along with others like aceto-vanillilone, propiovanillone and syringaldehyde – which are of secondary importance in wine (Ohloff, 1978; Boidron *et al.*, 1988; Piggott and Paterson, 1993; Zamora, 2019). These compounds are responsible for the characteristic 'vanilla' aroma found in oak matured wines. The volatile phenols are often associated with spicy and animal aromas, as well as toasted aromas, of which guaiacol, ethyl guaiacol, methyl guaiacol and vinyl guaiacol are associated (Chatonnet, 1991; Romano *et al.*, 2009). However, toasted aromas often also derive from Maillard reaction associated compounds which can occur during oak barrel maturation (Cutzach *et al.*, 1997). It should be noted that volatile phenols which are related to oak barrel ageing are not always desirable, and indeed the hospitable environment which oak wood can provide for spoilage microorganisms such as *Brettanomyces bruxellensis*, which produce the undesirable volatile phenols 4-ethyguaiacol and 4-ethylphenol (Vigentini *et al.*, 2008; Malfeito-Ferreira, 2018), often described as a 'horse sweat' or 'farmyard' type aroma. Regarding the polysaccharide derived aroma compounds, the furan family of compounds, which are produced via a Maillard reaction at the time of toasting the wood staves, produces compounds such as furfural, 5-hydroxymethylfurfural and 5-methyfurfural, contributing to toasted and smoked almond aroma (Fors, 1983; Boidron *et al.*, 1988; Pérez-Coello *et al.*, 1999). Again, not all the polysaccharides derived aroma compounds are positive, with the heat from the toasting process forming acetic acid from polysaccharides, which is associated with a vinegar aroma (Vivas, 2002). Although the increase of around 0.6-1.0 g/L in volatile acidity which this generally causes is below the sensory threshold of acetic acid, this could tip it over the sensory threshold in wines which have already naturally high levels of volatile acidity before entering the barrel for maturation (Guth, 1997; Zamora, 2019). The final class of aroma compounds originate from lipids present in the wood, known as whiskey lactones (β-methyl-γ-octalactones), are found in *trans* and *cis* isomers and are characteristic of coconut and brazil nuts (Chatonnet, 1992; Brown *et al.*, 2006). It should be noted that maturation in wood is associated with all these exogenous compounds, but a great diversity exists in the amount of these compounds transferred into wine, which depend on barrel related factors (botanical and geographical origin, toasting degree) and wine matrix factors (ethanol and pH) (Rodríguez-Rodríguez and Gómez-Plaza, 2012; Dumitriu *et al.*, 2017; Coelho *et al.*, 2019). Regarding botanical origin, *Quercus alba* L., *Quercus robur* L. and *Quercus petraea* (Matts) Liebl.are the most used in wine maturation and their general difference is that *Q. alba* has a higher aromatic impact (due to its high release of β-methyl-γ-octolactone (coconut aroma), vanillin (vanilla aroma), while *Q. robur* has a higher impact upon mouthfeel due to its comparatively high release of ellagitannins (Navarro *et al.*, 2016, 2018). The toasting degree also highly impacts the volatile profile of wines, with very heavy toasting decreasing coconut vanilla aromas (β-methyl-γ-octolactone and vanillin, respectively) but increasing the smoked and toasted aromas (furanic compounds and volatile phenols) (Fernández de Simón *et al.*, 2010; Navarro *et al.*, 2018; Zamora, 2019). Heavier toasting will also impact mouthfeel, due to the high temperatures causing a transformation or degradation of ellagitannins, therefore reducing their extractability and their resultant concentrations in oak matured wines (Peng *et al.*, 1991).

Wood also releases non-volatile phenolic compounds which contribute to changes in wine mouthfeel and texture during maturation, these include coumarins, ellagitannins and phenolic acids (Zhang *et al.*, 2015). Generally, it has been found that the enrichment in ellagitannins can cause subtle but perceptable increases in both astringency and bitterness (Glabasnia and Hofmann, 2006; Michel *et al.*, 2011; Rasines-Perea *et al.*, 2019). This increase in astringency may be counter-balanced by the reducing effects upon astringency and bitterness caused by the micro-oxygenation effect of wood barrel. Coumarins, such as esculetin, scopoletin, fraxiten, umbeliferone and 4-methylumbelliferone derive from cinnamic acids and may sometimes contribute to bitterness in combination, although their concentrations are often below their respective gustatory detection thresholds (Winstel *et al.*, 2020). The phenolic acids' impact upon wine is less sensory but more chemical and nutraceutical, with gallic and ellagic acids both acting as important antioxidants, adding protection against anthocyanins oxidation, as well as acting as co-pigments for anthocyanins and aiding the colour stabilisation process (Mazza and

Bouillard, 1990; Vivas and Glories, 1996; Tengzhen *et al.*, 2019).

Generally, wooden barrels are considered to be relatively ‘thermally inert’, that is they exhibit low thermal conductivity (Pontallier, 1992; Stadler and Fischer, 2020), meaning that they are less responsive to external changes to temperature than other materials and exhibit a greater degree of temperature homogeneity inside the vessel. The thermal conductivity of oak wood is 0.19 mK (Cavus *et al.*, 2019).

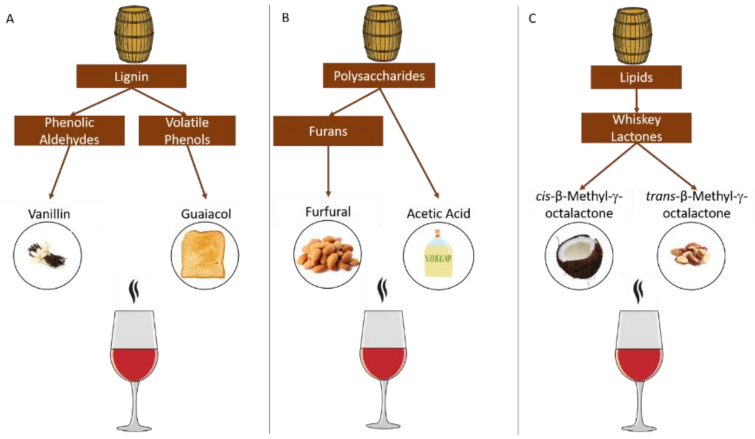


Figure 5. Schematic diagram on some of the key exogenous aroma compounds released from components of oak material. Panel A shows volatile aroma compounds deriving from oak lignin. Panel B shows volatile aroma compounds deriving from oak polysaccharides. Panel C shows volatile aroma compounds deriving from oak lipids. Adapted from Zamora (2019).

Clay

Clay is arguably the original material used to vinify and mature wine (Grace, 1979), and has a recent rise in popularity as winemakers look back towards ancestral techniques to impart novel characteristics on their wine as well as a marketing strategy (Rytkönen *et al.*, 2019; Harutyunyan and Malfeito-Ferreira, 2022; Ubeda *et al.*, 2022).

From a structural point of view, clay has some interesting attributes. Originating from soil, clay is fine-grained and when dried or heated will harden to the mould it was previously shaped to, thus making it a very malleable material in terms of shape and size for making maturation vessels (Grace, 1979). There are two main types of clay used for oenological purposes: (i) Earthenware in which the clay is red or white and fired at relatively low temperatures (1000-1080 °C) – there are the most porous type of clay vessel, so much so that they are often permeable to liquid, meaning that they have to be lined with waterproof coatings like beeswax or pine-pitch (Martins *et al.*, 2018; Nevares and del Alamo-Sanza, 2021); (ii) Claystone, whichis much more fined grained and fired at higher temperature (1148-1316 °C), meaning that although gas exchange can still occur, it is much less porous and require no glazing to make them waterproof (Nevares and del Alamo-Sanza, 2021). Claystone has unique and oenologically interesting permeability properties, as it allows oxygen to diffuse but prevents most of the evaporation which would occur in other types of clay or maturation vessel material (oak barrels for example) (Piergiovanni and Limbo, 2016; Nevares and del Alamo-Sanza, 2021).

Clay is a naturally porous material which allows gaseous exchange through the walls of the vessel into the liquid inside (Baiano *et al.*, 2015). This has two important implications. Firstly, the porous nature of the material may lead to losses in alcohol content as ethanol is able to evaporate and diffuse out of the of the vessel (with the exception of claystone), which was shown to significantly decrease alcohol content in wines matured in amphorae (Baiano *et al.*, 2015); a further loss of alcohol may also be partially ascribed to the oxidation of ethanol to acetaldehyde which occurs as a result of oxygen diffusion through the vessel. Secondly, micro-oxygenation occurs, with all the associated effects previously discussed in this review (colour stabilisation, polyphenolic evolution leading to changes in mouthfeel and astringency).

In a key paper from Nevares and del Alamo-Sanza (2021), the oxygen transmission rate (OTR) of clay amphorae was assessed. It was found that the OTR depended highly upon coatings, with beeswax coating giving a far lower OTR (10-1 109.8535 $cm^3/m^2/day$) than those ‘control’ amphorae which did not have a coating (10-4: 517.35 $cm^3/m^2/day$), as the coatings form a layer of much less porous material which partially inhibits the diffusion of oxygen into the wine during maturation, thus reducing the OTR. As for earth stone, the OTR mainly depends on the temperatures it is exposed to during firing, but rates have been previously quoted to be at a mean of 12.96 mg/L of oxygen per year (Nevares and del Alamo-Sanza, 2018).

Since clay is a natural, heterogenous material, there is a natural variability in oxygen permeability from one vessel to another (Nevares and del Alamo-Sanza, 2021). Furthermore, the various types of clay vessel and their interactions with the difference coatings it's possible to use on earthenware, means that unravelling and specifically defining these interacting effects and natural variability is a key path for future research (Nevares and del Alamo-Sanza, 2021). Although more research is still needed, it can be stated that due to the porous nature of clay vessels, they are suited oxidative maturation of wines (Nevares and del Alamo-Sanza, 2021).

The thermal conductivity of clay vessels also vary from one to another (0.15-1.8 W/(m.K)) (EngineeringToolBox, 2022), but has generally been estimated to be around 1.2 W/(m.K) for ceramic wine containers derived from clay (Nevares and del Alamo-Sanza, 2018). Clay vessels may be described as relatively 'thermally inert' compared to other materials such as steel, which mean they are less reactive to changes in ambient temperature (Morata *et al.*, 2019).

Generally, clay is not known for imparting desirable exogenous compounds into the wine during maturation. However, there are some aspects which could be deleterious if not properly monitored closely. For instance, in some clay vessels (Qvevris), there may be higher release of copper into the wine during maturation, which at its extreme may cause a metal instability (Catarino *et al*., 2008; Gil i Cortiella *et al.*, 2020), but is mostly of relevance regarding the fact that higher degrees of copper can act as catalysts for oxidative reactions during maturation (Danilewicz, 2003; Gil i Cortiella *et al.* 2020). However, the work of Díaz *et al.* (2013) contradicts the notion that copper increases in clay matured wines, as they found that copper levels were lower than those found in conventional wines, perhaps due to higher levels of copper precipitation in these wines or lower endogenous copper levels in the grapes. This reasoning is corroborated by a comprehensive study from Cabrita *et al.* (2018), who investigated the multi-elemental composition of wines aged in Amphorae and found no significant difference in copper levels compared to various multi-elemental studies on conventional wines in the literature. Indeed, as stated by both Diaz *et al.* (2013), Cabrita *et al.* (2018), and Benderschi (2020), coatings such as beeswax or pine-resin provide a protective layer against mineral contamination thus it can be argued that clay vessels which do significantly contribute to the mineral content of the wines reflect a flaw in the vessel's fabrication, rather than an indication of an intrinsic and widespread characteristic of maturation vessels made from clay. This risk of deleterious donation of endogenous compounds is likely to depend on the chemical composition of inorganic compounds which exists in the clay material used to create the maturation vessel, which is highly variable (Soroka, 1979). One important point about clay vessels is that the amount of exogenous compounds which can released into the wine may be further influenced by other factors, such as size, which will influence the surface area (SA) to volume (V) ratio of the wine – maturation vessel wall interface. This SA:V can be highly variable between clay amphorae according to their size (Baiano *et al.*, 2015). However, since there is not research to how changes to surface area to volume ratio may affect the amount of exogenous compound release in clay vessels, this remains only logical conjecture until empirical evidence is presented.

The maturation of wine in clay vessels can lead to a reduction in titratable acidity (Baiano *et al.*, 2015; Benderschi, 2020), as the reaction between clay and acids in the wine causing a cation exchange, with the loss of molecules such as silicon dioxide and iron oxide with the formation of H-Clays (Carroll and Starkey, 1971; Baiano *et al.*, 2015). Wines aged in amphorae have been shown to have decreased flavonoids contents by up to 34% after 12 months (Baiano *et al.*, 2015). Clay amphorae wine maturation, due to its porosity, inevitably also causes a reduction in volatile aroma compounds of up to 15% in glazed amphorae (Baiano *et al.*, 2015) and were sometimes described as having a 'relatively poor' volatile profile compared to wines matured under more reductive conditions, thus this should be bore in mind when choosing a maturation vessel material (Baiano *et al.*, 2015). Gil i Cortiella *et al.* (2020) reported that wines aged in clay vessels have lower levels of several key volatile compounds, such as acyl esters and C6 compounds, as well as generally lower total volatile compounds, thus indicating that wines aged in clay vessels may be less aromatically intense. The findings regarding the loss of volatile compounds in clay was hypothesised to be due to the higher degree of yeast mannoproteins in suspension in clay vessels (due to their oval shape increasing convection currents) which interact with aroma compounds and devolatilize them (Gil i Cortiella *et al.*, 2020), as well as yeast cell walls taking in aroma compounds. In a key study from Díaz *et al.* (2013), it was found that white wines aged in clay Qvevris had higher levels of acetic and lactic acids but a generally lower total acidity, as well as significantly higher antioxidant and total phenolic content. However, the results regarding acetic acid levels may be less to do with the clay material and more to do with the winemaking techniques which traditionally occur with Qvevris vessels, in which oxidative juice handling and long maceration times favour acetic acid production (Jackson, 2008). This extended maceration time may also explain the significantly higher phenolic content, thus demonstrating the importance of separating out the contributing factors, and the need for research to fully elucidate whether the material itself has any effect on total phenolic content.

Stainless steel

Stainless steel tanks have enjoyed a large and steady usage increase in wineries since they were first made available in the 1950s (Cooper, 2004). Today, they are one of the main materials used in winemaking, often for fermentation, but also for maturation purposes. Stainless steel is an alloy which usually has over 11% chromium (Davis, 1994); in the wine industry, the grade of stainless steel tends to be austenitic chromium-nickel stainless steel, which have the desirable properties of being strong, easy to clean and very resistant to corrosion (Zaffora *et al.*, 2021; Matmatch, 2022).

Stainless steel tanks are non-porous materials, meaning that wines are under very reductive conditions when being matured in them, as no oxygen can diffuse through the material (Baiano *et al.*, 2015). However, one reason why they are used is that they can easily be retrofitted with active MOX systems which can precisely control the amount OTRs of the wine during maturation and thus favour the colour and phenolic evolution, characteristic of traditional oak barrel ageing, but in a more purposeful and controlled manner (Anli and Cavuldak, 2013).

A typical stainless-steel tank is likely to have a thermal conductivity of 16.2 W/(m·K) (Matmatch, 2022). This is a very high thermal conductivity compared to clay or wood, denoting that its temperature fluctuates very easily depending on outside temperatures (Boulton, 1979), which can impact convection currents and thus settling efficiency. This high thermal conductivity may seem initially like a disadvantage due to the aforementioned reasons, were it not for the widely used refrigeration and heating belts which are often inbuilt or retrofitted onto stainless steel tanks, taking advantage of the materials' high thermal conductivity which allows easy, efficient and precise temperature control of the vessel (Pontallier, 1992; Morata *et al.*, 2019).

As stainless steel can be described as a highly 'inert' material (Baiano *et al.*, 2015), it is not responsible for any exogenous compounds which positively impact the wines sensory properties. However, there have been reports of higher levels of nickel (Ni) as a result of wine maturation in stainless steel tanks (Teissedre *et al.*, 1998; Catarino *et al.*, 2008), although this is disputed by a study from Galani-Nikolakaki *et al.* (2002), who found that Ni concentrations in wine were not significantly affected by the type of container. This incongruency in the literature may be explained by the quality of tank, with more corroded tanks causing greater risk of metal leeching (Fugelsang and Edwards, 2007; Szentpeteri, 2018). Increased chromium (Cr) concentrations has also been linked to wine production and maturation in stainless steel tanks (Cabrera-Vique *et al.*, 1997; Charnock *et al.*, 2022), however these levels are usually so low they are more significant from a wine authentication standpoint, in which slightly higher trace levels of Cr in a particular wine could associate it to stainless steel production methods. Again, often there is the amendment of adding oak chips to maturing wines in stainless steel tank to impart those exogenous phenolic and aroma compounds, which occur during oak barrel ageing, but nothing relevant (from a wine quality point of view) directly comes from the stainless-steel material during maturation in these kinds of vessels (Jourdes *et al.*, 2011).

Overall, stainless steel may be considered as the most adaptable material mentioned in this review, as it is generally inert but easy to modify and control its physical parameters due to its high thermal conductivity, making it sensitive temperature control systems, as well as being able to use other modifications such active MOX systems or oak chips to exert precise control of temperature, exogenous compounds, and oxygen diffusion rates into the wine during maturation.

Due to the impermeability of stainless steel to gas or liquid, its reductive characteristics may not be desirable as it may preserve reductive off-flavours, such as hydrogen sulfide (H_2S) (Nevares and del Alamo-Sanza, 2021), as well as not facilitating any of the reductions to astringency and improvements to colour stability which the slow diffusion of oxygen causes in other materials which are more permeable to gases (clay, oak and concrete for example). However, this drawback is easily overcome by the use of active MOX systems, which can be used to precisely control the OTR of the wine during maturation (discussed in more detail later in this review).

Concrete

Concrete is an aggregate of fine and coarse rock bound together by cement, which are easy and cheap to construct (Gagg, 2014). Tanks made from concrete are highly insulated giving great thermal inertia, as well as a natural porosity allowing a natural diffusion of oxygen into the wine (Nevares and del Alamo-Sanza, 2018).

Concrete vessels' porosity and thus its OTR vary according to pore size, which depends on manufacturer (Nevares and del Alamo-Sanza, 2018). It has been reported that concrete vessels' OTR can range from 1.22 x10^{-8} and 87.54 cm^3/m^2/day (Maioli *et al.*, 2022) This large range of OTRs may be seen as an advantage, giving winemakers a broad range of options in terms of choosing a maturation vessel to fit their desired OTR. For instance, Nevares and del Alamo-Sanza (2021) recommended choosing a concrete vessel of a relatively low OTR compared to other concrete vessels to get a similar OTR to that of oak barrel. It should also be noted that although porosity can be at a required level in terms of OTR, this is temporally variable, with decreases in OTR observed over time with repeated use, as crystalline and colloidal deposits clog up pores inside the concrete material (Morata *et al.*, 2019), as well as if treated with tartaric acid, or a water-proofing compound leading to reductions in permeability of between 60% and 83% (Prajapati and Arora, 2011; Nevares and del Alamo-Sanza, 2021).

Concrete is well known for its thermal inertia, meaning it is not a good conductor of heat – thus will vary slowly with changing outside temperatures. Although concrete can vary in its thermal conductivity depending on factors such as moisture content, its usual thermal conductivity is approximately 2.25 mK (Yun *et al.*, 2014; Asadi *et al.*, 2018) This thermally stable environment is advantageous for clarification through settling.

As with clay materials, a key difference with using concrete as a maturation vessel material is the lack of beneficial exogenous compounds released into wine, and the general 'volatile inertia' (Nevares and del Alamo-Sanza, 2018). If concrete vessels are not protected by an internal epoxy resin or other such polymer, it is susceptible to partial dissolution of the vessel wall under wine pH values (Gil i Cortiella *et al.*, 2020), which has been shown to cause a release of inorganic compounds into the wine, resulting in wines with higher concentrations of zinc, iron, magnesium, calcium, potassium and manganese (Catarino *et al.*, 2008; Gil i Cortiella *et al.*, 2020). This is an important measure to consider when assessing the risk of a wine to metal or mineral instabilities. Gil i Cortiella *et al.* (2020)highlighted this aspect because they found that wines fermented in concrete vessels had the highest levels of calcium precipitation when compared to stainless steel, polyethylene, or clay – which was hypothesized to be due to the dissolution of calcium into the wine from the concrete vessel walls. Wines matured in concrete produced from less controlled sources were found to have elevated levels of iron to the point of causing ferric hazes (Byrne *et al.*, 1937).

High-density polyethylene (HDPE)

As an alternative to the 'natural vessels' made from concrete, clay or wood, high-density polyethylene (HDPE) or polydimethylsiloxane (PDMS) are the synthetic alternative which may be used as maturation vessels. Polyethylene is a wax made from pure hydrocarbons, which are highly hydrophobic, and is polymerised from units of ethylene (Flecknoe-Brown, 2005).

The OTR of HDPE vessels was characterised by del Alamo-Sanza *et al.* (2015) who considered it to be within the common range of OTRs observed in oak barrels or stainless-steel tanks with an active MOX system, with amount of oxygen diffusion occurring in a 1000 L HDPE and in a stainless steel tank with MOX of the same size (Flecknoe-Brown, 2004). OTR rates in HDPE vessels were found to range from 20.39 mg/L/year to 77.91 mg/L/year (or 0.0388 μg/L/min – 0.0531 μg/L/min). Although the OTR rates are within the range of other common maturation vessel materials, the mechanism in which oxygen enters is governed by different principles. As described by del Alamo-Sanza *et al.* (2015), the entry of oxygen through HDPE tanks is related to the partial pressure gradient outside the maturation vessel, according to the Fick's law, as opposed to the active MOX governed by barometric pressure and Darcy's law in oak barrels (Nevares and del Alamo-Sanza, 2021; Roussey *et al.*, 2021). Research has shown that although the differing physical principles underpinning the oxygen diffusion into the wine compared to other vessel materials, the associated impacts upon wine quality remain similar, with HDPE maturation tanks causing typical outcomes associated with oxygenation, such as stabilisation through anthocyanin polymerisation as well as a 'softening' affect due proanthocyanidin polymerisation, much of these reactions underpinned by acetaldehyde production from ethanol oxidation (del Alamo-Sanza *et al.*, 2015).

Since plastics have very little free electrons, unlike metals which have many, they are very poor heat conductors – with their thermal conductivity of HDPE being generally between 0.450-0.500W/(mK) (Omnexus.specialchem.com, 2022). This general thermal inertia is advantageous for settling purposes, but will be very ineffective when trying to change its temperature using the refrigeration jackets. HDPE is designed to be inert, and thus is not generally associated with exogenous compound donation to the wine during maturation. Different studies have shown that the addition of oak staves or cubes can impart of the exogenous compounds associated with oak barrel ageing often at higher concentrations than with wood barrels. As an example, del Alamo-Sanza *et al.* (2015) reported significantly higher levels of syringic acid, vanillic acid and maltol in HDPE with oak stave matured vessels.

It has been shown that wines matured in HDPE had lower levels of anthocyanins and more polymeric pigments than barrel aged wines, indicating that HDPE matured wines highly promote the oxygen induced reactions previously discussed in this review, which led to the formation of polymeric pigments and thus stabilising colour (del Alamo-Sanza *et al.*, 2015). Total acidity has been shown to drop by 27% during wine ageing in HDPE tanks, compared to 20% in oak barrels, due to a higher level of potassium bitrate crystallisation in the former – which led to a sensorially 'smoother' taste than that of wine aged in oak (Pambianchi, 2021). One potential deleterious impact of HDPE material on wine is that if it's in a light environment, it may allow light through which can be detrimental to the wine (Boulton *et al.*, 1999). In these conditions, photo-chemical reaction can occur leading to the decrease of free SO_2 and of unpleasant compounds, often described as 'boiled' aromas (Lan *et al.*, 2021). Indeed, this is only the case with plastic vessels which are transparent and it should not happen in opaque vessels such as black HDPE tanks. If maturation occurs in light porous HDPE vessels within a winery with high levels of ambient light, important implications for wine quality are expected. This is a relatively under-researched phenomena, with the majority of investigation regarding the effect of light on wine quality being focussed on the bottle ageing, rather than maturation phase of wine making. Bottle ageing where wine is exposed to prolonged period of UV-visible light is associated with several deleterious wine quality changes, including the development off-aromas of 'cooked cabbage', changes in colour due to the photo-degradation of pigments such as riboflavin (Dias *et al.*, 2012; Grant-Preece *et al.*, 2017), and decrease of free SO_2 (Blake *et al.*, 2010; Grant-Preece *et al.*, 2017). Light also accelerates oxygen uptake (Singleton, 1987), which may accelerate the MOX based maturation phenomena, although there is no empirical study which has addressed this possibility. The significant changes to wine quality which UV-visible light exposure can induce during bottle ageing may also occur during maturation in light porous vessels, however until further research is completed to confirm this possibility, it remains only a plausible conjecture.

Comparison of materials

Regarding oxygen diffusion, key aspects were elucidated in a key paper of Vivas and Glories (1993); differences in oxidation processes relating to material porosity were examined. It was found that dissolved oxygen was significantly higher in oak barrels than in vats made from stainless steel, concrete or plastic materials (Vivas and Glories, 1993). This finding contrasts with the findings of del Alamo-Sanza *et al.* (2015), who found that HDPE OTRs were in the upper range of oak barrel OTRs. This divergence in the literature may be explained by other winemaking factors specific of each maturation vessel type, or indeed to recent innovations regarding HDPE tank's permeability to oxygen, with large variations occurring depending on the type and density of HDPE material used and the size of the maturation vessel (Flecknoe-Brown, 2004; 2005). A key feature of HDPE tanks is that their oxygen permeability is fixed over time, whereas other vessels such as oak barrels exhibit reduced oxygen permeability over time as the barrel is moistened (del Alamo-Sanza and Nevares, 2014; Junqua *et al.*, 2021). Oak barrels have bungholes and an 'headspace' above wine, which implies using techniques during maturation, such as 'topping up', as wine evaporates. This may introduce oxygen and lead to high levels of volatile acidity during maturation when compared to HDPE tanks due to acetic acid producing bacteria forming around the bunghole (Pambianchi, 2021). However, further research is needed to empirically prove this theory.

The chemical inertness and low reactivity of stainless steel makes it an ideal vessel or avoiding inorganic compound dissolution into the wine, as is possible in improperly cared for concrete tanks, thus making stainless steel the ideal vessel material for avoiding metal instabilities such as ferric casse (Ribéreau-Gayon *et al.*, 2021).

Phthalates are plastic derived compounds which have negative connotations regarding human toxicity due to their activity as endocrine disrupters (Chatonnet *et al.*, 2014). Several cases have been reported in which phthalates have beendetected in high concentrations in wine (del Carlo *et al.*, 2008), with the contamination sources been ascribed to a wide number of contaminants throughout the winemaking process (Plank and Trela, 2018); however, the major source of these phthalates is the epoxy resins and polyethylene (Giuliani *et al.*, 2020). Since epoxy coatings are commonly used to coat concrete vessels and HDPE tanks contain polyethylene, this may mean that maturation in concrete or HDPE vessels may be at higher risk of contamination with phthalates.

Regarding thermal conductivity variations amongst different maturation vessel materials, this may have important implications regarding (1) settling via sedimentation, as fluctuations in temperature can interfere with convection currents and inhibit settling, and (2) spoilage through the production of acetic acid and ethyl acetate, in which rising winery temperature in spring can increase the evaporation rate of the wine and favour bacterial growth (Ribéreau-Gayon *et al.*, 2021). Given this data, materials which are more thermally inert have a lower risk of developing spoilage bacteria during maturation in warmer months. This result was shown in a study carried out by Chatonnet *et al.* (1993), in which the wine in thermally inert concrete vats had significantly lower levels of acetic acid after 12 months of maturation. However, although temperature likely played a role here, it may also be due to the physical characteristics of the vessel's shape, in which barrel bungholes are a structure point favourable for the growthof acetic acid producing bacteria (Ribéreau-Gayon *et al.*, 2021).. Thus, further research is needed to unravelthe different factors, and their specific impact, upon risk of spoilage. Furthermore, stainless steel, which has a very high thermal conductivity, has been highlighted by Castellari *et al.* (2004) as a material which must be temperature controlled while attempting active MOX treatments to avoid excessive oxygen accumulation.

In one study, the OTR of HDPE tanks was calculated to be 21.71 mg/L/year, placing it within the upper range of what is normal for oak barrels, which is theorised by del Alamo-Sanza *et al.* (2015) to be the reason why wines matured in plastic tanks can have higher levels of polymeric pigments than wines matured in oak barrels, as there was a generally higher level of these MOX related reactions. However, HDPE tanks can vary in their permeability to oxygen and subsequent OTR (Nevares and del Alamo-Sanza, 2018; Sánchez-Gómez *et al.*, 2020), meaning that it cannot be reliably stated that HDPE tanks have a higher OTR than oak barrels.

During sensory trials, it was found that when comparing oak matured wines to wines made in alternative materials such as plastic and stainless steel, the majority (>70%) of consumers without prior sensory training were not able to distinguish between wines matured in different vessels (Wilkinson *et al.*, 2016), but knowledgeable customers were. This has important implications regarding maturation vessel choice, as cheaper material can be used when targeting unknowledgeable consumer bases who drink cheaper wines (Wilkinson *et al.*, 2016).

In an important paper from Ubeda *et al.* (2022), it was found that wines matured in HDPE vessels had a higher variability in terpenes during the first six months of maturation than those matured in clay or stainless-steel vessels, which suggest that HDPE vessel material leads to a higher degree of dispersion of volatile odorant compounds during the initial six-month maturation period.

Vessel Size

Size is an important parameter of maturation vessels which may have large influence on maturation dynamics for wine. One of the reasons is the change of diffusion surface: wine volume ratio (Nevares and del Alamo-Sanza, 2018), which is likely to influence the amount of oxygen entering the wine during maturation. As a general rule, it may be claimed that surface area to volume ratio has a key influence over all important effects that depend on surface area (Singleton, 1974). For instance, wooden barrels of 225 L have an internal diffusion surface of 2.01 m^2 (del Alamo-Sanza *et al.*, 2017), whereas larger containers have a lower diffusion surface area, thus reducing the amount of oxygen dissolved into the wine over time. Indeed, this is also dependent on other factors such as porosity. The size of a maturation vessel will most likely change OTR, with larger vessels having a relatively smaller OTR when compared to smaller vessels of the same material; this will likely slow the oxidative ageing effect on wine’s colour and phenolic composition. However, there is a gap in the literature regarding vessel size’s specific effect on OTR, which presents an exciting opportunity for investigations into this point.

With regard to exogenous compounds, increasing sized vessels have been shown to reduce the number of exogenous compounds released into the wine. Pérez-Prieto *et al.* (2002) found a significant decrease in the exogenous aroma compounds *cis*-β-methyl-γ-lactone and vanillin with increasing barrel volume, with wines matured in 1000 L barrels having a significant reduction in the aforementioned compounds. This finding is in agreement with that of Puech (1987), who observed a decrease of vanillin and syringic acid in wine matured in larger barrels. However, when examining the study of Pérez-Prieto *et al.* (2002) in more detail, it is clear that this effect of volume on exogenous compounds diminishes with time, with used barrels of varying size having no significant differences in these exogenous aroma compounds – indicating that the effect of volume is only oenologically relevant when using new barrels. Furthermore, oak barrels, despite being the traditional material for extracting wood-derived phenolic compounds into the wine during maturation, were found to be significantly less enriched with wood-derived phenolics than stainless steel tanks adapted with an active MOX system and oak staves (Nocera *et al.*, 2020). This is likely due to oak barrel staves’ orientation to the wine (perpendicular to liquid permeation) making their primary and secondary xylem vessels relatively inaccessible compared to added oak staves in stainless steel tanks (Jourdes *et al.*, 2011).

Size also has an important effect upon thermal dynamics of a vessel, with a key study from Boulton (1979) showing that the larger the vessel the more heat is retained, meaning larger fermentation vessels take longer to cool down or heat up. Since the study made by Boulton (1979) focused on how these variations in heath transfer based on size affects fermentation dynamics, further research is needed to elucidate specifically whether these variations affect the dynamics of maturation. This would require a study which evaluated the key changes to wine associated with maturation, such as anthocyanin and proanthocyanidin evolution. A future study could for instance evaluate the mean polyphenolic index in wine after 12 months of maturation in vessels of the same material but varying size.

Vessel Shape

Maturation vessel shape is an under-researched but potentially very important factor affecting a maturations vessel's overall effect upon final wine quality after fermentation. For instance, oval or egg shapes vessels have long been hypothesised to have an impact upon convection currents. Although there is data to support that egg-shaped vessels cause more lees suspension (Guillaument and Caltagirone, 2016), there is not yet the clear scientific evidence to prove or disprove this theory. Since convection currents can potentially inhibit proper settling, this is an important future path for research (Gil i Cortiella *et al.*, 2020). The only study which has investigated this to date is from Gil i Cortiella *et al.* (2020), who's results initially showed no differences in turbidity of wines fermented in vessels of different shape, but contradictorily did find that oval vessels favour protein stabilization, suggesting a higher rate of disturbance in egg-shapes vessels. This is a remarkable topic for further research in order to optimise clarity in maturation vessels.

As with size, the shape of a vessel can impact its diffusion surface: volume ratio (dSA:V). For instance, a spherical geometrical shape has the smallest surface area of all the geometrical shapes, whereas cube shaped vessels had a much higher surface (124%) than a sphere of equal volumes (Boulton *et al.*, 1999). Since maturation can generally be accelerated with the higher dSA:V, shapes of higher surface area will generally cause maturation to be accelerated (Boulton *et al.*, 1999).

One study comparing wine matured for 4.5 months in HDPE vessels of cube and oval shapes, showed that the wine matured in the oval-shaped vessel had significantly higher levels of total esters, ethyl esters, acetate esters, alcohols, acids, terpenoids and norisoprenoids than the wine matured in cubed shaped HDPE vessels (Ubeda *et al.*, 2022). These findings have two relevant implications. Firstly, it would indicate that oval shaped vessels may lead to more aromatically intense wines with higher levels of volatile odorant compounds, and secondly, would indicate in the case of HDPE vessels of differing shape but the same material, vessel shape may therefore have a higher influence over the volatile composition of the matured wine than material type (Ubeda *et al.*, 2022).

Other parameters – Coating, hygiene status, heating, and MOX system

Other factors can also influence maturation dynamics. Issa-Issa *et al.* (2021) compared the effects of ageing vessel on the sensory profile of red wine, and found that coating was a key determinant. Vessels with a non-permeable coating consisting of a food-grade epoxy resin, which stopped any contact between vessel material (in this case clay) and the wine, seem to lead to higher levels of freshness and sourness when compared to those wines aged without this protective coating, which have more intense fruit and sweet flavours. This was theorized to be due to a reduction in MOX ocurrence (Issa-Issa *et al.*, 2021). The coating can have a large impact over both OTR, and hygiene status, with clay and concrete vessels showing largely reduced permeability to oxygen as well as a reduction in exogenous compounds released when epoxy coatings are applied to concrete and clay maturation vessels (Nevares and del Alamo-Sanza, 2021). However, if using epoxy resins to minimise the release of inorganic compounds into the wine in vessels made from clay or concrete, caution must be taken, since some studies have reported the potential of epoxy resins to release harmful bisphenols A (BPAs) into wine (Plank and Trela, 2018).

Hygiene status is a key aspect to consider when choosing maturation vessels. During maturation, spoilage compounds produced from undesirable bacterial or fungal contaminations may cause significant deleterious effects upon final wine quality. Maturation represents a critical period during the winemaking process in terms of spoilage risk. This is due to wines being subject to a highly variable environment in terms of temperature and oxygen – which if managed incorrectly can favour the colonisation of spoilage microorganisms (Malfeito-Ferreira, 2019). Furthermore, the wine vessel material's physical characteristics also varying in their hospitability towards spoilage microorganism growth (Zamora, 2019), for instance oak barrels may be considered as high-risk vessels in terms of sanitary status, due to the potential for spoilage microorganisms to survive in the pores of the wood staves, where cleaning products cannot reach (Zamora, 2019). Indeed, wooden barrels have been described as "practically impossible" to sanitize, with the spoilage yeasts being able to remain in between wood layers and then re-contaminate after the process of sanitation has been carried out (Barata *et al.*, 2013; Morata *et al.*, 2019). Furthermore, wooden barrels have been shown to become more un-hygienic with age, with the increase of *D. bruxellensis* spoilage contaminations increasing with barrel age (Chatonnet *et al.*, 1993). On the other hand, materials which are non-porous and inert offer the best sanitary conditions, such as stainless-steel vessels – in which sanitation is very efficient and allows preventing spoilage (Morata *et al.*, 2019). Size and shape may also influence the hygiene status of a vessel, with vessels of larger size and more accessible shapes being easier to clean than smaller vessels, such as for instance a 225 L barrel, who's shape also means it is hard to access the inside as its only entry point is a small singular bunghole.

Heating systems and active MOX technology now offer winemakers more control then ever during the maturation period, allowing precise control of both the temperature and the amount of oxygen permeation into the wine during maturation (Schmidtke *et al.*, 2011; Mwithiga *et al.*, 2013). These technologies inevitably have variable levels of compatibility depending on vessel material. For instance, heating and refrigeration systems will be most efficient when applied to materials of high thermal conductivity, such as stainless steel (Table I). Secondly, active MOX is often applied to non-permeable tanks due to the ability to precisely control the amount of oxygen entering the wine, as shown by Cano-López *et al.* (2010), who, using stainless steel tanks, could ensure oxygen doses of 3 mL/L/month, without the unpredictability in terms of OTR than materials with variable OTRs bring, such as oak, clay and concrete (Table I). When considering the use of heating and active MOX technologies, materials such stainless steel, which are highly thermally conductive and non-permeable to oxygen, may be considered as highly compatible.

Table I

Oxygen transfer rates (OTRs), thermal conductivity, and types of exogenous compounds released into the wine during maturation across five types of maturation vessel material. N/A - "not available in the scientific body of literature". * - scientific finding which is disputed within the literature

Material	OTR (mg/L/year)	OTR ($cm^3/m^2/day$)	Thermal Conductivity	Exogenous Compounds	References
Oak	10-28	N/A	0.197	Aromatic compounds (phenolic aldehydres, volatile phenols, furans and whiskey lactones) Phenolic compounds (Hydrolysable tannins)	da Zhang et al. (2015); del Alamo-Sanza et al. (2017); Çavus et al. (2019); Zamora (2019); Nevares and del Alamo-Sanza (2021)a
Clay	N/A	5.38 – 12.57	1.2	Inorganic compounds: Cu*	Nevares and del-Alamo Sanza (2018); Gil i Cortiella et al. (2020)
Concrete	N/A	$1.22x10^{-8}$– 87.53	2.25	Inorganic compounds: Zn, Mg, Fe, Mn	Yun et al. (2014); Asadi et al. (2018); Gil i Cortiella et al. (2020); Nevares and del Alamo-Sanza (2021); Maioli et al. (2022);
Stainless Steel	0	0	16.2	None	Matmatch.com (2022)
Plastic (HDPE)	20.39– 77.91	N/A	0.45-0.5	N/A	del Alamo-Sanza et al. (2015); Omnexus.specialchem.com (2022)

CONCLUDING REMARKS

A key criticism of the current state of the art regarding maturation vessel material OTR research, is that the research remains highly imbalanced depending on material. For instance, oak barrels have research which both defined the OTRs and TOIRs – reflecting that a holistic picture of both the materials intrinsic OTR exist, but also how much oxygen enters the wine from the vessel as a whole entity, meaning oxygen permeation at key entry points such as the bungholes has been measured. The same is not observed for other materials such as concrete maturation vessels or clay amphorae, in which it is only the material's intrinsic OTR which has been measured, rather than the TOIR as well which would provide a more "real" result on the total amount of oxygen entering the wine during the maturation period. This a key gap of knowledge, and future research should be aimed at addressing this discontinuity in the literature, in order to be able to compare the oxygen transfer between vessels in a more holistic and precise way.

Although there is considerable research regarding how material, shape and size affect wine quality, these factors are often looked at in isolation, rather than considering the combination of material shape and size together, and the interacting effects which may occur between vessel parameters. Further research could be undertaken to understand how shape, size and material interact to change wine quality during maturation. Furthermore, there is a wealth of evidence to show how UV-visible light can be deleterious to wine quality during bottle ageing, but a paucity of how light can affect the maturation process. Considering that some vessels, such as HDPE, may be lighter porous than others, this is an exciting path for further research.

Lees are the residues which settle after fermentation, their composition is of microbial origin, the majority of which being spent yeast from the alcoholic fermentation and eventually dead lactic bacteria from the end of malolactic fermentation. The contact with the wine and its lees' during maturation is a key phenomenon during maturation, which can have larger compositional and sensory impacts upon final wine quality, this process is known as "sur lie" (Mazauric and Salmon, 2005; Stefenon *et al.*, 2014; Alexandre, 2022). Since the shape and size of a maturation vessel will logically influence the surface area of the contact zone between settled lees and wine – the choice of maturation vessel may have a large influence upon the action of lees on final wine quality. The question of shape, and how it affects the amount of lees in suspension is also a future path to explored, since oval-shape vessels are thought to keep colloidal matter in suspension for longer due to their effect on convection currents inside the vessel, an investigation into how these shapes impact time of lees in suspension is an interesting path for future research.

Maturation vessels may be conceptually considered on a spectrum of 'inertness', with more inert vessels, such as stainless-steel tanks, generally having lower thermal conductivity, lower OTR and less release of exogenous compounds, with the opposite being true for the more active vessels such as oak barrels. By varying the type of vessel material, shape and size, it is possible to exert a large degree of control over both the quantity and speed of maturation related changes to wine quality, such as aromatic evolution via the introduction of exogenous compounds, changes to mouthfeel, and the stabilisation of colour. No vessel can be considered more advantageous than another, since the intended profile of the final wine will determine the vessel parameters that are most congruent with the chosen style. Together, these findings suggest that vessel choice is one the most important options a winemaker must make after primary fermentations have occurred. However, exciting new paths for future research exist to address the need to assess the overall oxygen TOIRs of materials other than oak, as well as the possible impact upon lees suspension and interaction with wine which maturation vessel type may have.

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REFERENCES

Alcalde-Eon C., Escribano-Bailón M.T., Santos-Buelga C., Rivas-Gonzalo J.C., 2006. Changes in the detailed pigment composition of red wine during maturity and ageing: A comprehensive study. *Anal. Chim. Acta,* **563**, 238-254.

Alexandre H., 2022. Aging on lees and their alternatives: Impact on wine. *In: Managing wine quality*. 213-224. Reynolds A.G. (ed.), Elsevier, Cambridge.

Anli R.E., Cavuldak Ö.A., 2013. A review of microoxygenation application in wine. *J. Inst. Brew*., **118**, 268-385.

Araújo P., Fernandes A., De Freitas V., Oliveira J., 2017. A new chemical pathway yielding A-type vitisins in red wines. *Int. J. Mol. Sci*., **18**, 762.

Areshian G.E., Gasparyan B., Avetisyan P.S., Pinhasi R., Wilkinson K., Smith A., 2012. The chalcolithic of the Near East and south-eastern Europe: discoveries and new perspectives from the cave complex Areni-1, Armenia. *Antiquity*, **86**, 115–130.

Asadi I., Shafigh P., Hassan Z.F.B.A., Mahyuddin N.B., 2018. Thermal conductivity of concrete–A review. *J. Build. Eng*., **20**, 81–93.

Atanasova V., Fulcrand H., Cheynier V., Moutounet M., 2002. Effect of oxygenation on polyphenol changes occurring in the course of wine-making. *Anal. Chim. Acta*, **458**, 15–27.

Baiano A., Mentana A., Quinto M., Centonze D., Longobardi F., Ventrella A., 2015. The effect of in-amphorae aging on oenological parameters, phenolic profile and volatile composition of Minutolo white wine. *Food Res. Int*., **74**, 294–305.

Barata A., Laureano P., D'Antuono I., Martorell P., Stender H., Malfeito-Ferreira M., 2013. Enumeration and identification of 4-ethylphenol producing yeasts recovered from the wood of wine ageing barriques after different sanitation treatments. *J. Food Res*., **2**, 140.

Benderschi O., 2020. *Study on Georgian winemaking. Focus on Qvevri wines*. 66 p. Msc. Thesis, Instituto Superior de Agronomia, Universidade de Lisboa.

Billiard R., 1913. La vigne dans l'antiquité. *Rev. des Études Anciennes*, **16**, 375-376.

Blake A., Kotseridis Y., Brindle I. D., Inglis D., Pickering, G. J., 2010. Effect of light and temperature on 3-alkyl-2-methoxypyrazine concentration and other impact odourants of Riesling and Cabernet Franc wine during bottle ageing. *Food Chem*., **119**, 935–944.

Boidron J.N., Chatonnet P., Pons M., 1988. Influence du bois sur certaines substances odorantes des vins. *Oeno One*, **22**, 275–94.

Boulton R., 1979. The heat transfer characteristics of wine fermenters. *Am. J. Enol. Vitic*., **30**, 152–6.

Boulton R., 2001. The copigmentation of anthocyanins and its role in the color of red wine: A critical review. *Am. J. Enol. Vitic*., **52**, 67–87.

Boulton R.B., Singleton V.L., Bisson L.F., Kunkee R.E., 1999. The maturation and aging of wines. *In: Principles and practices of winemaking*. 382–426. Springer, Boston.

Brossaud F., Cheynier V., Noble A.C., 2001. Bitterness and astringency of grape and wine polyphenols. *Aust. J. Grape Wine Res*., **7**, 33–39.

Brouillard R., George F., Fougerousse A., 1997. Polyphenols produced during red wine ageing. *Biofactors*, **6**, 403–10.

Brown R.C., Sefton M.A., Taylor D.K, Elsey G.M., 2006. An odour detection threshold determination of all four possible stereoisomers of oak lactone in a white and a red wine. *Aust. J. Grape Wine Res*., **12**, 115–8.

Byrne J., Saywell L.G., Cruess W.V., 1937. The iron content of grapes and wine. *Ind. & Eng. Chem. Anal. Ed*., **9**, 83-4.

Cabrera-Vique C., Teissedre P.L., Cabanis M.T., 1997. Determination and levels of chromium in French wine and grapes by graphite furnace atomic absorption spectrometry. *J. Agric. Food Chem.*, **45**, 1808–1811.

Cabrita M.J., Martins N., Barrulas P., Garcia R., Dias CB., Pérez-Álvarez E.P., 2018. Multi-element composition of red, white and palhete amphora wines from Alentejo by ICPMS. *Food Control*, **92**, 80–85.

Cano-López M., López-Roca J.M., Pardo-Mínguez F., Gómez-Plaza E., 2010. Oak barrel maturation vs. micro-oxygenation: effect on the formation of anthocyanin-derived pigments and wine color. *Food Chem.*, **119**, 191-195.

Carpena M., Pereira A.G., Prieto M.A., Simal-Gandara J., 2020. Wine aging technology: Fundamental role of wood barrels. *Foods*, **9**, 1160.

Carroll D., Starkey H.C., 1971. Reactivity of clay minerals with acids and alkalies. *Clay Miner.*, **19**, 321–33.

Castellari M., Piermattei B., Arfelli G., Amati A., 2001. Influence of aging conditions on the quality of red Sangiovese wine. *J. Agric. Food Chem.*, **49**, 3672–6.

Castellari M., Simonato B., Tornielli G.B., Spinelli P., Ferrarini R., 2004. Effects of different enological treatments on dissolved oxygen in wines. *Ital. J. Food Sci.*, **16**, 387-396.

Catarino S., Curvelo-Garcia A.S., Bruno de Sousa R., 2008. Revisão: Elementos contaminantes nos vinhos. *Ciência Téc. Vitiv.*, **23** (1), 3-19.

Çavuş V., Şahin S., Esteves B., Ayata U., 2019. Determination of thermal conductivity properties in some wood species obtained from Turkey. *Bioresources*, **14**, 6709–6715.

Charnock H.M., Cairns G., Pickering G.J., Kemp B.S., 2022. Production method and wine style influence metal profiles in sparkling wines. *Am. J. Enol. Vit.*, **73**, 170-182.

Chatonnet P., 1991. Incidence du bois de chêne sur la composition chimique et les qualités organoleptiques des vins. 224 p. PhD thesis, Univ Bordeaux II.

Chatonnet P., 1992. Les composés aromatiques du bois de chêne cédés aux vins. Influence des opérations de chauffe en tonnellerie. *In*: *Le bois et la qualité des vins des eaux-de-vie*. 81-91. Vigne et Vin Publ. Intern., Bordeaux.

Chatonnet P., Boidron J., Dubourdieu D., 1993. Influence des conditions d'élevage et de sulfitage des vins rouges en barriques sur le teneur en acide acétique et en ethyl-phenols. *J. Int. Sci. Vigne Vin*, **27**, 277–298.

Chatonnet, P., Boutou, S., Plana, A., 2014. Contamination of wines and spirits by phthalates: types of contaminants present, contamination sources and means of prevention. *Food Addit. Contam.*, **31**, 1605-1615.

Chira K., Teissedre P.-L., 2015. Chemical and sensory evaluation of wine matured in oak barrel: Effect of oak species involved and toasting process. *Eur. Food Res. Technol.*, **240**, 533–47.

Chira K., Schmauch G., Saucier C., Fabre S., Teissedre, P. L., 2009. Grape variety effect on proanthocyanidin composition and sensory perception of skin and seed tannin extracts from Bordeaux wine grapes (Cabernet Sauvignon and Merlot) for two consecutive vintages (2006 and 2007). *J. Agric. Food Chem.*, **57**, 545-553.

Chira K., Jourdes M., Teissedre P.-L., 2012. Cabernet sauvignon red wine astringency quality control by tannin characterization and polymerization during storage. *Eur. Food Res. Technol.*, **234**, 253–261.

Coelho E., Teixeira J.A., Domingues L., Tavares T., Oliveira J.M., 2019. Factors affecting extraction of adsorbed wine volatile compounds and wood extractives from used oak wood. *Food Chem.*, **295**, 156–64.

Cooper D., 2004. A history of steel tank structural design. *Wine Bus Mon*. Available at: https://www.winebusiness.com/wbm/?go=getArticleSignIn&dataId=32887 (accessed 13/06/2022).

Cutzach I., Chatonnet P., Henry R., Dubourdieu D., 1997. Identification of volatile compounds with a "toasty" aroma in heated oak used in barrel making. *J. Agric. Food Chem.*, **45**, 2217-24.

Dallas C., Ricardo-da-Silva J.M., Laureano O., 1995. Degradation of oligomeric procyanidins and anthocyanins in a Tinta Roriz red wine during maturation. *Vitis*, **34**, 51–6.

Dallas C., Hipólito-Reis P., Ricardo-da-Silva J.M., Laureano, O., 2003. Influence of acetaldehyde, pH, and temperature on transformation of procyanidins in model wine solutions. *Am. J. Enol Vitic.*, **54**, 119-124.

Danilewicz J.C., 2003. Review of reaction mechanisms of oxygen and proposed intermediate reduction products in wine: central role of iron and copper. *Am. J. Enol. Vitic.*, **54**, 73-85.

Danilewicz J.C., Seccombe J.T., Whelan J., 2008. Mechanism of interaction of polyphenols, oxygen, and sulfur dioxide in model wine and wine. *Am. J. Enol. Vitic.*, **59**, 128–36.

Davis J.R., 1994. ASM specialty handbook. Stainless steels. 521 p., ASM International.

de Freitas V.A.P., Mateus N., 2010. Updating wine pigments. In: *Recent advances in polyphenol research*. 59-89. Wiley-Blackwell, Hoboken.

de Freitas V., Mateus N., 2011. Formation of pyranoanthocyanins in red wines: A new and diverse class of anthocyanin derivatives. *Anal. Bioanal. Chem.*, **401**, 1467–1477.

del Alamo-Sanza M., Nevares I., 2014. Recent advances in the evaluation of the oxygen transfer rate in oak barrels. *J. Agric. Food Chem.*, **62**, 8892–8899.

del Alamo-Sanza M., Nevares I., 2018. Oak wine barrel as an active vessel: A critical review of past and current knowledge. *Crit. Rev. Food Sci.*, **58**, 2711–2726.

del Alamo-Sanza M., Laurie V.F, Nevares I., 2015. Wine evolution and spatial distribution of oxygen during storage in high-density polyethylene tanks. *J. Sci. Food Agric.*, **95**, 1313–1320.

del Alamo-Sanza M., Cárcel L.M., Nevares I., 2017. Characterization of the oxygen transmission rate of oak wood species used in cooperage. *J. Agric. Food Chem.*, **65**, 648–55.

del Carlo M., Pepe A., Sacchetti G., Compagnone D., Mastrocola D., Cichelli A., 2008. Determination of phthalate esters in wine using solid-phase extraction and gas chromatography–mass spectrometry. *Food Chem.*, **111**, 771–777.

del Carmen Llaudy M., Canals R., González-Manzano S., Canals J.M., Santos-Buelga C., Zamora F., 2006. Influence of micro-oxygenation treatment before oak aging on phenolic compounds composition, astringency, and color of red wine. *J. Agric. Food Chem.*, **54**, 4246–4252.

Dias D.A., Smith T.A., Ghiggino K.P., Scollary G.R., 2012. The role of light, temperature and wine bottle colour on pigment enhancement in white wine. *Food Chem.*, **135**, 2934-2941.

Díaz C., Laurie V.F., Molina A.M., Bücking M., Fischer R., 2013. Characterization of selected organic and mineral components of qvevri wines. *Am. J. Enol. Vitic*., **64**, 532–537.

du Toit W.J., Lisjak K., Marais J., du Toit M., 2006a.The effect of micro-oxygenation on the phenolic composition, quality and aerobic wine-spoilage microorganisms of different South African red wines. *S. Afr. J. Enol. Vitic*., **27**, 57–67.

du Toit W.J., Marais J., Pretorius I.S., du Toit M., 2006b. Oxygen in must and wine: A review. *S. Afr. J. Enol. Vitic*., **27**, 76–94.

Dumitriu G.D., de Lerma N.L., Zamfir C.I., Cotea V.V., Peinado RA., 2017. Volatile and phenolic composition of red wines subjected to aging in oak cask of different toast degree during two periods of time. *LWT*, **86**, 643–651.

Elias R.J., Andersen M.L., Skibsted L.H., Waterhouse A.L., 2009. Identification of free radical intermediates in oxidized wine using electron paramagnetic resonance spin trapping. *J. Agric. Food Chem*., **57**, 4359–4365.

Engineeringtoolbox. https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html (accessed 08/08/2022)

Es-Safi N.E., Fulcrand H., Cheynier V., Moutounet M., 1999. Studies on the acetaldehyde-induced condensation of (−)-epicatechin and malvidin 3-O-glucoside in a model solution system. *J. Agric. Food Chem*., **47**, 2096–2102.

Escot S., Feuillat M., Dulau L., Charpentier C., 2001. Release of polysaccharides by yeasts and the influence of released polysaccharides on colour stability and wine astringency. *Aust. J. Grape Wine R*., **7**, 153–159.

Escribano-Bailón M.T., Julián C., Rivas-Gonzalo., Garcia-Estévez I., 2019. Wine colour and stability. In: *Red Wine Technology*. 195-203. Morata A. (ed.), Elsevier, London.

Fengel D., Wegener G., 1989. Wood. Chemistry, ultrastructure, reactions, 612 p. Walter de Gruyter, Berlin.

Fernández de Simón B., Muiño I., Cadahia E., 2010. Characterization of volatile constituents in commercial oak wood chips. *J. Agric. Food Chem*., **58**, 9587-9596.

Fors S., 1983. Sensory properties of volatile Maillard reaction products and related compounds. In: *The Maillard reaction in foods and nutrition*.185-286. ACS Symposium Series, vol. 215, American Chemical Society, Washington.

Fugelsang K.C., Edwards C.G., 2007. Wine microbiology: practical applications and procedures. 393 p. Springer, New York.

Fulcrand H., Cheynier V., Oszmianski J., Moutounet M., 1997. An oxidized tartaric acid residue as a new bridge potentially competing with acetaldehyde in flavan-3-ol condensation. *Phytochemistry*, **46**, 223–227.

Fulcrand H., Benabdeljalil C., Rigaud J., Cheynier V., Moutounet, M., 1998. A new class of wine pigments generated by reaction between pyruvic acid and grape anthocyanins. *Phytochemistry*, **47**, 1401-1407.

Flecknoe-Brown A., 2004. Controlled permeability' moulded wine tanks-new developments in polymer catalyst technology. *Aust. NZ. Grapegrower & Winemaker*, **480**, 59-61.

Flecknoe-Brown A., 2005. Oxygen-permeable polyethylene vessels: A new approach to wine maturation. *Aust. NZ. Grapegrower & Winemaker*, **494**, 53.

Gagg C.R., 2014. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail Anal*., **40**, 114–40.

Galani-Nikolakaki S., Kallithrakas-Kontos N., Katsanos A.A., 2002. Trace element analysis of Cretan wines and wine products. *Sci. Total Environ*., **285**, 155–163.

Garde-Cerdán T., Ancín-Azpilicueta C., 2006. Review of quality factors on wine ageing in oak barrels. *Trends Food Sci. Tech*., **17**, 438-447.

Gil i Cortiella M., Úbeda C., Covarrubias J.I., Peña-Neira Á., 2020. Chemical, physical, and sensory attributes of Sauvignon blanc wine fermented in different kinds of vessels. *Innov. Food Sci. Emerg. Technol*., **66**, 102521.

Gil i Cortiella M., Ubeda C., Covarrubias J.I., Laurie V.F., Peña-Neira Á., 2021. Chemical and physical implications of the use of alternative vessels to oak barrels during the production of white wines. *Molecules*, **26**, 554.

Giuliani A., Zuccarini M., Cichelli A., Khan H., Reale M., 2020. Critical review on the presence of phthalates in food and evidence of their biological impact. *Int. J. Environ. Res. Public Health*, **17**, 5655.

Glabasnia A., Hofmann T., 2006. Sensory-directed identification of taste-active ellagitannins in American (*Quercus alba* L.) and European oak wood (*Quercus robur* L.) and quantitative analysis in bourbon whiskey and oak-matured red wines. *J. Agric. Food Chem*., **54**, 3380–3390.

Gómez-Alonso S., Blanco-Vega D., Gómez M.V., Hermosín-Gutiérrez I., 2012. Synthesis, isolation, structure elucidation, and color properties of 10-acetyl-pyranoanthocyanins. *J. Agric. Food Chem*., **60**, 12210–12223.

Gómez-Plaza E., Cano-López M.A., 2011. A review on micro-oxygenation of red wines: Claims, benefits and the underlying chemistry. *Food Chem*., **125**, 1131–1140.

González-Sanjosé M.L, Ortega-Heras M., Pérez-Magariño S., 2008. Microoxygenation treatment and sensory properties of young red wines. *Food Sci. Technol. Int*., **14**, 123–130.

Grace V., 1979. Amphoras and the ancient wine trade. 32 p. The American school of classical studies at Athens, Princeton.

Graham R.A., 1979. Influence of yeast strain and pH on pyruvic acid production during alcoholic fermentation. *Am. J. Enol. Vitic*., **30**, 318–320.

Grant-Preece P., Barril C., Schmidtke L.M., Scollary G.R., Clark A.C., 2017. Light-induced changes in bottled white wine and underlying photochemical mechanisms. *Crit. Rev. Food Sci. Nutr*., **57**, 743-754.

Guillaument R., Caltagirone J.P., 2016. Cahier technique. Comment définir la cuve la mieux adaptée à ses besoins pour optimiser sa production et obtenir l'équilibre souhaité? Une solution rapide: la simulation numérique de la circulation du vin dans des cuves de différentes géométries. *Rev. Française d'Oenol*., **279**, 13–16.

Guth H., 1997. Quantitation and sensory studies of character impact odorants of different white wine varieties. *J. Agric. Food Chem*., **45**, 3027–3032.

Harutyunyan M., Malfeito-Ferreira M., 2022. Historical and heritage sustainability for the revival of ancient wine-making techniques and wine styles. *Beverages*, **8**, 10.

He J., Santos-Buelga C., Mateus N., de Freitas V., 2006. Isolation and quantification of oligomeric pyranoanthocyanin-flavanol pigments from red wines by combination of column chromatographic techniques. *J. Chromatogr. A*, **1134**, 215–225.

He F., Liang N-N., Mu L., Pan Q.H., Wang J., Reeves M.J., 2012. Anthocyanins and their variation in red wines II. Anthocyanin derived pigments and their color evolution. *Molecules*, **17**, 1483–1519.

Issa-Issa H., Lipan L., Cano-Lamadrid M., Nemś A., Corell M., Calatayud-García P., 2021. Effect of aging vessel (clay-tinaja versus oak barrel) on the volatile composition, descriptive sensory profile, and consumer acceptance of red wine. *Beverages*, **7**, 35.

Jackson R.S., 2008. Wine science: principles and applications. 717 p. Academic Press, Canada.

Jordão A.M., Ricardo-da-Silva J., 2019. Evolution of proanthocyanidins during grape maturation, winemaking, and aging process of red wines. *In: Red Wine Technology*. 177-189. Morata A. (ed.), Academic Press, London.

Jourdes M., Michel J., Saucier C., Quideau S., Teissedre P.-L., 2011. Identification, amounts, and kinetics of extraction of C-glucosidic ellagitannins during wine aging in oak barrels or in stainless steel tanks with oak chips. *Anal. Bioanal. Chem*. **401**, 1531–1539.

Junqua R., Zeng L., Pons A., 2021. Oxygen gas transfer through oak barrels: a macroscopic approach. *OENO One*, **55**, 53-65.

Kaya A., Bruno de Sousa R., Curvelo-Garcia A.S., Ricardo-da-Silva J., Catarino S., 2017. Effect of wood aging on mineral composition and wine ^{87}Sr/^{86}Sr isotopic ratio. *J. Agric. Food Chem*., **65**, 4766-4776.

Kelly M., Wollan D., 2003. Micro-oxygenation of wine in barrels. *Aust. NZ. Grapegrower & Winemaker*, 29–32.

Kontoudakis N., González E., Gil M., Esteruelas M., Fort F., Canals J.M., Zamora F., 2011. Influence of wine pH on changes in color and polyphenol composition induced by micro-oxygenation. *J. Agric. Food Chem*., **59**, 1974-1984.

Kourakou-Dragona S., 2016. Vine and wine in the ancient Greek world. Foinikas Publications, Athens.

Lan H., Li S., Yang J., Li J., Yuan C., Guo A., 2021. Effects of light exposure on chemical and sensory properties of storing Meili Rosé wine in colored bottles. *Food Chem*., **345**, 128854.

Liu S.Q., Pilone G.J., 2000. An overview of formation and roles of acetaldehyde in winemaking with emphasis on microbiological implications. *Int. J. Food Sci. Tech*., **35**, 49-61.

Ma W., Guo A., Zhang Y., Wang H., Liu Y., Li H., 2014. A review on astringency and bitterness perception of tannins in wine. *Trends Food Sci. Tech*., **40**, 6–19.

Maioli F., Picchi M., Guerrini L., Parenti A., Domizio P., Andrenelli L., 2022. Monitoring of Sangiovese red wine chemical and sensory parameters along one-year aging in different tank materials and glass bottle. *ACS Food Sci. Technol*., **2**(2), 221–239.

Malfeito-Ferreira M., 2018. Two decades of “horse sweat” taint and Brettanomyces yeasts in wine: Where do we stand now? *Beverages*, **4**, 32.

Malfeito-Ferreira M., 2019. Spoilage yeasts in red wines. *In: Red wine technology*. 219–233. Morata A. (ed.), Elsevier, London.

Martínez-Gil A., Del Alamo-Sanza M., Nevares I., 2022. Evolution of red wine in oak barrels with different oxygen transmission rates. Phenolic compounds and colour. *LWT*, **158**, 113133.

Martins N., Garcia R., Mendes D., Freitas A.M.C., da Silva M.G., Cabrita M.J., 2018. An ancient winemaking technology: Exploring the volatile composition of amphora wines. *LWT*, **96**, 288–95.

Mateus N., Silva A.M.S., Rivas-Gonzalo J.C., Santos-Buelga C., de Freitas V., 2003. A new class of blue anthocyanin-derived pigments isolated from red wines. *J. Agric. Food. Chem*., **51**, 1919–23.

Mateus N., Oliveira J., Santos-Buelga C., Silva A.M.S., de Freitas V., 2004. NMR structure characterization of a new vinylpyranoanthocyanin–catechin pigment (a portisin). *Tetrahedron Lett*., **45**, 3455–7.

Mateus N., Oliveira J., Pissarra J., González-Paramás A.M., Rivas-Gonzalo J.C., Santos-Buelga C., 2006. A new vinylpyranoanthocyanin pigment occurring in aged red wine. *Food Chem*., **97**, 689–95.

Matmatch, 2022. https://matmatch.com/learn/material/aisi-304-stainless-steel. (accessed 13/06/2022)

Mazauric J.P., Salmon J.M., 2005. Interactions between yeast lees and wine polyphenols during simulation of wine aging: I. Analysis of remnant polyphenolic compounds in the resulting wines. *J. Agric. Food Chem*., **53**, 5647–53.

Mazza G., Brouillard R., 1990. The mechanism of co-pigmentation of anthocyanins in aqueous solutions. *Phytochemistry*, **29**, 1097–102.

McCord J., 2003. Application of toasted oak and micro-oxygenation to ageing of Cabernet Sauvignon wines. *Aust. NZ. Grapegrower & Winemaker*, **7**, 43–51.

Michel J., Jourdes M., Silva M.A., Giordanengo T., Mourey N., Teissedre P-L., 2011. Impact of concentration of ellagitannins in oak wood on their levels and organoleptic influence in red wine. *J. Agric. Food Chem.*, **59**, 5677–83.

Mierczynska-Vasilev A., Smith P.A., 2015. Current state of knowledge and challenges in wine clarification. *Aust. J. Grape Wine Res*., **21**, 615–26.

Morata A., Gómez-Cordovés M.C., Colomo B., Suárez J.A., 2003. Pyruvic acid and acetaldehyde production by different strains of Saccharomyces cerevisiae: relationship with vitisin A and B formation in red wines. *J. Agric. Food Chem*., **51**, 7402–7409.

Morata A., González C., Tesfaye W., Loira I., Suárez-Lepe J A., 2019. Maceration and fermentation: New technologies to increase extraction. *In: Red Wine Technology*. 35-49. Morata A. (ed.), Academic Press, London.

Moreno-Arribas M.V., Polo M.C., 2009. Wine Chemistry and Biochemistry. 735 p. Springer, New York.

Moutounet M., Mazauric J.P., Saint-Pierre B., Micaleff J.P., Sarris J., 1994. Causes et conséquences de microdèformations des barriques au cours de l’élevage des vins. *Revue d’ Oenologes*, **74**, 34-39.

Mwithiga G., Magama P., Hlophe M., 2013. Humidity Control System for Wine Maturation Structures. In: Advanced Materials Research. *Trans. Tech. Publ*., **824,** 301–310.

Navarro M., Kontoudakis N., Gómez-Alonso S., García-Romero E., Canals J.M., Hermosín-Gutíerrez I., 2016. Influence of the botanical origin and toasting level on the ellagitannin content of wines aged in new and used oak barrels. *Food Res. Int*., **87**, 197–203.

Navarro M., Kontoudakis N., Gómez-Alonso S., García-Romero E., Canals J.M., Hermosín-Gutíerrez I., 2018. Influence of the volatile substances released by oak barrels into a Cabernet Sauvignon red wine and a discolored Macabeo white wine on sensory appreciation by a trained panel. *Eur. Food Res. Technol*., **244**, 245–258.

Nevares I., del Alamo-Sanza M., 2018. New materials for the aging of wines and beverages: Evaluation and comparison. 375–407. *In: Food packaging and preservation*. Elsevier, New York.

Nevares I., del Alamo-Sanza M., 2021. Characterization of the oxygen transmission rate of new-ancient natural materials for wine maturation containers. *Foods,* **10**:140.

Nocera A., Ricardo-da-Silva J.M., Canas S., 2020. Antioxidant activity and phenolic composition of wine spirit resulting from an alternative ageing technology using micro-oxygenation: A preliminary study. *Oeno One*, **54**, 485-496.

Ohloff G., 1978. Recent developments in the field of naturally-occurring aroma components. *Progress Chem. Org. Nat. Prod*., **35**, 431–527.

Oliveira C.M., Ferreira A.C.S., De Freitas V., Silva A.M.S., 2011. Oxidation mechanisms occurring in wines. *Food Res. Int*., **44**, 1115–1126.

Oliveira J., de Freitas V., Mateus N., 2019. Polymeric pigments in red ines. In: *Red wine technology*. 207-217. Morata A. (ed.), Academic Press, London.

Omnexus. https://omnexus.specialchem.com/polymer-properties/properties/thermal-insulation#:~:text=Plastics%20are%20poor%20heat%20conductors,for%20conduction%20mechanisms%20like%20metals. (accessed 15/07/2022)

Ough C.S., Crowell E.A., Gutlove B.R., 1988. Carbamyl compound reactions with ethanol. *Am. J. Enol. Vitic*., **39**, 239–42.

Palomero F., Morata A., Benito S., González M.C., Suárez-Lepe J.A., 2007. Conventional and enzyme-assisted autolysis during ageing over lees in red wines: Influence on the release of polysaccharides from yeast cell walls and on wine monomeric anthocyanin content. *Food Chem*., **105**, 838–46.

Pambianchi D., 2021. A comparative study on the evolution of wine aged for 12 months in a flextank vs. a two-year-old oak barrel. https://flextank.com/2021/05/11/flextank-vs-a-two-year-old-oak-barrel-a-study/. (accessed 15/07/2022)

Parpinello G.P., Plumejeau F., Maury C., Versari A., 2012. Effect of micro-oxygenation on sensory characteristics and consumer preference of Cabernet Sauvignon wine. *J. Sci. Food Agric*., **92**, 1238–44.

Pasteur M.L., 1875. Etudes sur le vin. Librairie F. Savy, Paris, France.

Peleg H., Gacon K., Schlich P., Noble A.C., 1999. Bitterness and astringency of flavan-3-ol monomers, dimers and trimers. *J. Sci. Food Agric*., **79**, 1123–1128.

Peña J.T., 2007. Roman pottery in the archaeological record. Cambridge University Press, Cambridge.

Peng S., Scalbert A., Monties B., 1991. Insoluble ellagitannins in *Castanea sativa* and *Quercus petraea* woods. *Phytochemistry*, **30**, 775–8.

Peng Z., Iland P.G., Oberholster A., Sefton M.A., Waters E.J., 2002. Analysis of pigmented polymers in red wine by reverse phase HPLC. *Aust. J. Grape Wine Res*., **8**, 70–75.

Perestrelo R., Silva C., Câmara J.S., 2019. Madeira wine volatile profile. A platform to establish madeira wine aroma descriptors. *Molecules*, **24**, 3028.

Pérez-Coello M.S., Sanz J., Cabezudo M.D., 1999. Determination of volatile compounds in hydroalcoholic extracts of French and American oak wood. *Am. J. Enol. Vitic*., **50**, 162–165.

Pérez-Prieto L.J., López-Roca J.M., Martínez-Cutillas A., Pardo Mínguez F., Gómez-Plaza E., 2002. Maturing wines in oak barrels. Effects of origin, volume, and age of the barrel on the wine volatile composition. *J. Agric. Food Chem*., **50**, 3272–6.

Pfahl L., Catarino S., Fontes N., Graça A., Ricardo-da-Silva J., 2021. Effect of barrel-to-barrel variation on color and phenolic composition of a red wine. *Foods*, **10**, 1669.

Piergiovanni L., Limbo S., 2016. Introduction to food packaging materials. In: *Food Packaging Materials*. 1-3. Springer, Cham.

Piggott J.R., Paterson A., 1993. Understanding natural flavors. 318 p. Springer Science & Business Media, New York.

Pissarra J., Mateus N., Rivas-Gonzalo J., Santos Buelga C., de Freitas V., 2003. Reaction between malvidin 3-glucoside and (+)-catechin in model solutions containing different aldehydes. *J. Food Sci*., **68**, 476–81.

Plank C.M., Trela B.C., 2018. A review of plastics use in winemaking: Haccp considerations. *Am. J. Enol. Vitic*., **69**, 307–320.

Pontallier P., 1992. The intervention of oak wood in the making of great red wines. *J. Wine Res*., **3**, 241–247.

Prajapati H.T., Arora N.K., 2011. A study on oxygen permeability of concrete containing different water proofing admixtures and cementrations materials. *Int. J. Adv. Eng. Res. Stud*., **1**, 55-58.

Puech J.-L., 1987. Extraction of phenolic compounds from oak wood in model solutions and evolution of aromatic aldehydes in wines aged in oak barrels. *Am. J. Enol Vitic*., **38**, 236-238.

Rankine B.C., 1965. Factors influencing the pyruvic acid content of wines. *J. Sci. Food Agric*., **16**, 394–398.

Rasines-Perea Z., Jacquet R., Jourdes M., Quideau S., Teissedre P.-L., 2019. Ellagitannins and flavano-ellagitannins: Red wines tendency in different areas, barrel origin and ageing time in barrel and bottle. *Biomolecules*, **9**, 316.

Remy-Tanneau S., Le Guernevé C., Meudec E., Cheynier V., 2003. Characterization of a colorless anthocyanin− flavan-3-ol dimer containing both carbon− carbon and ether interflavanoid linkages by NMR and mass spectrometry. *J. Agric. Food Chem*., **51**, 3592–3597.

Ribéreau-Gayon J., 1933. Contribution à l’étude des oxydations et réductions dans les vins. 205-210. Delmas.

Ribéreau-Gayon P., Dubourdieu D., Donèche B., Lonvaud A., 2006. Handbook of enology, volume 1: The microbiology of wine and vinifications. John Wiley & Sons, Chichester.

Ribéreau-Gayon P., Glories Y., Maujean A., Dubourdieu D., 2021. Handbook of enology, volume 2: The chemistry of wine stabilization and treatments. John Wiley & Sons, Chichester.

Rodríguez-Rodríguez P., Gómez-Plaza E., 2012. Dependence of oak-related volatile compounds on the physicochemical characteristics of barrel-aged wines. *Food Technol. Biotech*., **50**, 59.

Romano A., Perello M.C., Lonvaud-Funel A., Sicard G., de Revel G., 2009. Sensory and analytical re-evaluation of “Brett character. *Food Chem*., **114**, 15–19.

Roussey C., Colin J., Du Cros R.T., Casalinho J., Perré P., 2021. In-situ monitoring of wine volume, barrel mass, ullage pressure and dissolved oxygen for a better understanding of wine-barrel-cellar interactions. *J. Food Eng*., **291**, 110233.

Rytkönen P., Vigerland L., Borg E.A., 2019. Georgia tells its story: Wine marketing through storytelling. *AAWE*, **240**, 15.

Salas E., Atanasova V., Poncet-Legrand C., Meudec E., Mazauric J.P., Cheynier V., 2004. Demonstration of the occurrence of flavanol–anthocyanin adducts in wine and in model solutions. *Anal. Chim. Acta*., **513**, 325–332.

Sánchez-Gómez R., del Alamo-Sanza M., Martínez-Gil A.M., Nevares I., 2020. Red wine aging by different micro-oxygenation systems and oak wood—effects on anthocyanins, copigmentation and color evolution. *Processes*, **8**, 1250.

Schmidtke L.M., Clark A.C., Scollary G.R., 2011. Micro-oxygenation of red wine: Techniques, applications, and outcomes. *Crit. Rev. Food Sci.*, **51**, 115–131.

Schwarz M., Wabnitz T.C., Winterhalter P., 2003. Pathway leading to the formation of anthocyanin− vinylphenol adducts and related pigments in red wines. *J. Agric. Food Chem.*, **51**, 3682–3687.

Scollary G.R., Pásti G., Kállay M., Blackman J., Clark A.C., 2012. Astringency response of red wines: Potential role of molecular assembly. *Trends Food Sci. Tech.*, **27**, 25-36.

Silva Ferreira A.C., Ávila I.M.L.B, Guedes de Pinho P., 2005. Sensorial impact of sotolon as the "perceived age" of tawny port wines. *In: Natural Flavors and Fragrances ACS Symposium Series*. 141-159. Frey C. and Rouseff R. (ed.) American Chemical Society, Washington.

Sims C.A., Morris J.R., 1984. Effects of pH, sulfur dioxide, storage time, and temperature on the color and stability of red muscadine grape wine. *Am. J. Enol. Vitic*., **35**, 35–39.

Singleton V.L., 1974. Some aspects of the wooden container as a factor in wine maturation. *In: The chemistry of winemaking*, **137**, 254-277. Webb A.D. (Ed.), Amer. Chem. Soc., Boston.

Singleton V.L., 1987. Oxygen with phenols and related reactions in musts, wines, and model systems: observations and practical implications. *Am. J. Enol. Vit.*, **38**, 69-77.

Somers T.C., Evans M.E., 1986. Evolution of red wines I. Ambient influences on colour composition during early maturation. *Vitis*, **25**, 31–39.

Soroka I., 1979. Portland cement paste and concrete. 338 p. Macmillan International Higher Education, London.

Sousa C., Mateus N., Silva A.M.S., González-Paramás A.M., Santos-Buelga C., de Freitas V., 2007. Structural and chromatic characterization of a new Malvidin 3-glucoside–vanillyl–catechin pigment. *Food Chem.*, **102**, 1344–1351.

Spillman P.J., Pollnitz A.P., Liacopoulos D., Skouroumounis G.K., Sefton MA., 1997. Accumulation of vanillin during barrel-aging of white, red, and model wines. *J. Agric. Food Chem.*, **45**, 2584–2589.

Stadler E., Fischer U., 2020. Sanitization of oak barrels for wine—A review. *J. Agric. Food Chem.*, **68**, 5283–5295.

Stefenon C.A., Bonesi C.D.M., Marzarotto V., Barnabé D., Spinelli F.R., Webber V., 2014. Phenolic composition and antioxidant activity in sparkling wines: Modulation by the ageing on lees. *Food Chem.*, **145**, 292–999.

Sun B., de Sá M., Leandro C., Caldeira I., Duarte F.L., Spranger I., 2013. Reactivity of polymeric proanthocyanidins toward salivary proteins and their contribution to young red wine astringency. *J. Agric. Food Chem.*, **61**, 939–946.

Szentpeteri C., 2018. Winery equipment: Steel yourself for double duty tanks: Analysing the best stainless steel grades for your wine tank. *Aust. NZ. Grape and Wine, 656.*

Tao J., Dykes S.I., Kilmartin P.A., 2007. Effect of SO_2 concentration on polyphenol development during red wine micro-oxygenation. *J. Agric. Food Chem.*, **55**, 6104-6109.

Tavares M., Jordão A.M., Ricardo-da-Silva J.M., 2018. Impact of cherry, acacia and oak chips on red wine phenolic parameters and sensory profile. *Oeno One*, **51**, 329-342.

Teissedre P.-L., Cabrera Vique C., Cabanis M.T., 1998. Determination of nickel in French wines and grapes. *Am. J. Enol. Vitic.*, **49**, 205–210.

Tengzhen M., Chen K., Yan H., Shunyu H., Yang B., 2019. Red winemaking in cold regions with short maturity periods. *In: Red Wine Technology*. 357- 370. Morata A. (ed.), Academic Press, London.

Timberlake C.F., Bridle P., 1976. Interactions between anthocyanins, phenolic compounds, and acetaldehyde and their significance in red wines. *Am. J. Enol. Vitic*. **27**, 97–105.

Twede D., 2005. The cask age: The technology and history of wooden barrels. *Packag. Technol. Sci.*, **18**, 253–264.

Ubeda C., Peña-Neira Á., Gil i Cortiella M., 2022. Combined effects of the vessel type and bottle closure during Chilean Sauvignon Blanc wine storage over its volatile profile. *Food Res. Int.*, **156**, 111178.

Ugliano M., 2013. Oxygen contribution to wine aroma evolution during bottle aging. *J. Agric. Food Chem.*, **61**, 6125–6136.

Vidal S., Aagaard O., 2008. Oxygen management during vinification and storage of Shiraz wine. *Aust. NZ Wine Ind. J.*, **23**, 56–63.

Vigentini I., Romano A., Compagno C., Merico A., Molinari F., Tirelli A., 2008. Physiological and oenological traits of different Dekkera/Brettanomyces bruxellensis strains under wine-model conditions. *FEMS Yeast Res.*, **8**, 1087–1096.

Vivas N., 1999. Modelisation et calcul du bilan des apports d'oxygene au cours de l'elevage des vines rouges. IV-elevage des vins rouges en conditions d'oxygations m enagees controlees. *Progrès Agric. Vitic*., **116**, 305–311.

Vivas N., 2002. Manuel de tonnellerie: À l'usage des utilisateurs de futaille. 207 p. Éditions Féret, Bordeaux.

Vivas N., Glories Y., 1993. Les phénomènes d'oxydoréduction liés à l'élevage en barrique des vins rouges: aspects technologiques. *Rev. Fr. Oenol.*, **33**, 33-38.

Vivas N., Glories Y., 1996. Role of oak wood ellagitannins in the oxidation process of red wines during aging. *Am. J. Enol. Vitic*., **47**, 103–107.

Waterhouse A.L., Laurie V.F., 2006. Oxidation of wine phenolics: A critical evaluation and hypotheses. *Am. J. Enol. Vitic.*, **57**, 306–313.

Waterhouse A.L., Sacks G.L., Jeffery D.W., 2016. Understanding wine chemistry. 443 p. John Wiley & Sons, Chichester.

Wilkinson K., Li S., Crump A., 2016. Wine maturation: Oak alternatives: a balance between science and finance. *Wine Vitic. J.*, **31**, 31–35.

Winstel D., Gautier E., Marchal A., 2020. Role of oak coumarins in the taste of wines and spirits: Identification, quantitation, and sensory contribution through perceptive interactions. *J. Agric. Food Chem.*, **68**, 7434–7443.

Yun T.S., Jeong Y.J., Youm K.-S., 2014. Effect of surrogate aggregates on the thermal conductivity of concrete at ambient and elevated temperatures. *Sci. World J.*, **13**, 939632.

Zaffora A., i Franco F., Santamaria M., 2021. Corrosion of stainless steel in food and pharmaceutical industry. *Curr. Opin. Electrochem.*, **29**, 100760.

Zamora F., 2003. Elaboración y crianza del vino tinto: Aspectos científicos y prácticos. 225 p. Ediciones Mundi-Prensa, Madrid.

Zamora., 2019. Barrel aging; Types of wood. *In: Red wine technology*. 125-143. Morata A. (ed). Academic Press, London.

Zhang B., Cai J., Duan C-Q., Reeves M.J., He F., 2015. A review of polyphenolics in oak woods. *Int. J. Mol. Sci.*, **16**, 6978–7014.

Zhang X., Jeffery D.W., Li D., Lan Y., Zhao X., Duan C., 2022. Red wine coloration: A review of pigmented molecules, reactions, and applications. *Compr. Rev. Food Sci. F.*, **21**, 3834-3866.