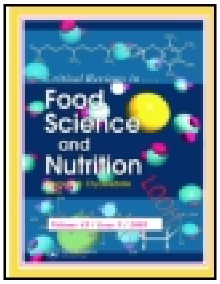

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Advances in Wine Ageing Technologies for Enhancing Wine Quality and Accelerating Wine Ageing Process

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Advances in Wine Ageing Technologies for Enhancing Wine Quality and Accelerating Wine Ageing Process

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Abstract

Wine ageing is an important process to produce high-quality wines. Traditionally, wines are aged in oak barrel ageing systems. However, due to the disadvantages of the traditional ageing technology such as lengthy time needed, high cost, etc., innovative ageing technologies have been developed. These technologies involve ageing wines using wood fragments, application of micro-oxygenation, ageing on lees or application of some physical methods. Moreover, wine bottling can be regarded as the second phase of wine ageing and is essential for most wines. Each technology can benefit the ageing process from different aspects. Traditional oak barrel ageing technology is the oldest and widely accepted technology. The application of wood fragments and physical methods are promising in accelerating ageing process artificially while application of micro-oxygenation and lees are reliable to improve wine quality. This paper reviews recent developments of the wine ageing technologies. The impacts of operational parameters of each technology on wine quality during ageing are analyzed, and comparisons among these ageing technologies are made. In addition, several strategies to produce high-quality wines in a short ageing period are also proposed.

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Keywords: bottling; electric fields; gamma radiation; high pressure; lees; micro-oxygenation; nanogold photocatalysis; oak barrel; ultrasonic waves; wine ageing; wood fragments.

1. Introduction

Wine plays an important role in our daily life. There are many different types of wine or wine styles that are produced in the world. These include still table wines, sparkling wines and fortified wines (Jackson, 1994). Generally speaking, winemaking process consists of growing and harvesting grapes, fermentation, ageing and bottling. However, this process varies slightly in some regions. Occasionally, the ageing process can be divided into two phases. The first one is called maturation, which refers to changes in wines after fermentation and before bottling, and the second phase of ageing is bottling (Jackson, 1994). During wine ageing, groups of subtle reaction occur, which tend to improve the taste and flavour of wine over time. Traditional ageing technology is based on the storage of wine in oak barrels due to the positive effects on sensory characteristics (Perez-Prieto *et al*., 2003) and the enrichment of wood-related aromatic compounds in wine (Ortega-Heras *et al*., 2004; Matějíček *et al*., 2005).

The composition of wine is complex and changes continuously during ageing. Phenolic compounds are very important to define the quality of wine. They not only contribute to wine's organolectic characteristics such as appearance, odour and mouth-feel sensations (Boulton, 2001; Robichaud & Noble, 1990), but may also act as antioxidants, with mechanisms involving both metal chelation and free-radical scavenging (Li *et al*., 2009). Among them, anthocyanins, non-anthocyanic phenols (including flavan-3-ols, flavonols and hydroxycinnamic acids), together with the polymeric pigments resulting from the reactions between anthocyanins and other phenols, are the main compounds with the greatest sensory influence on wine. Anthocyanins and polymeric pigments are responsible for the colour of red wine while non-anthocyanic phenols, especially flavan-3-ols and flavonols, give wines their astringency, structure and bitterness (Boulton, 2001). The antioxidant properties are mainly due to flavonols and stilbenes (Augustin *et al*., 2005; Eiro & Heinonen, 2002). On the other hand, volatile compounds related to aroma also have a significant impact on the quality of wine. Monoterpenes are responsible for the primary wine aroma (Pisarnitskii, 2001). During alcoholic fermentation, a large group of aromatic compounds are formed, including higher alcohols, aldehydes, esters, acids, ketones and others (Hashizume & Samuta, 1997; Martin *et al*., 1992). Ageing can modify these compounds and give wines their distinct fragrances. Woods also transfer a series of aromatic substances to wines when they are aged in oak barrels. The volatile compounds extracted from wood are mainly furfural compounds, guaiacol, oak or whisky lactone, eugenol, vanillin, syringaldehyde and volatile phenols. Moreover, there are many other nutrient substances contributing to wine's flavour and quality, such as polysaccharides, free amino acids and peptides (Zeng *et al*., 2008; Alcaide-Hidalgo *et al*., 2008).

It is well-known that due to the pungent smell, harsh taste and some possible harmful side-effects, most of fresh wines need to be aged for a period before selling and drinking. Although the oak barrel ageing technology has been extensively applied for centuries, several disadvantages of this traditional technology exist. Firstly, ageing process in barrel normally takes from 3-5 months to 3-5 years or even longer, which is time-consuming. Secondly, barrels are pricy, take up a lot of space in the winery and they cannot be used for a long time. Thirdly, as barrels become older, they may be contaminated by undesirable microorganisms such as the yeast genera *Brettanomyces* and *Dekkera*. These yeasts can produce significant concentrations of ethylphenols, which have unpleasant horsy and medicinal aromas (Suárez *et al*., 2007). In addition, during barrel ageing, there is a great wine loss due to evaporation that causes financial losses to winemakers (Adana *et al*., 2005). Considering these negative effects of barrel on ageing, scientists have put great efforts into developing new ageing techniques and improving present techniques. One of these involves putting small pieces of wood, usually known as oak chips, into wines in order to produce a woody aroma and taste on wine (Morales *et al*., 2004). To simulate the mild oxygenation of wine during barrel ageing, micro-oxygenation can be employed to introduce small, measured amounts of oxygen into wines (Guerrero *et al.*, 2010). In some wines, the presence of lees during ageing can improve their organoleptic characteristics (Barrio-Galán *et al*., 2011). Furthermore, several studies are focused on the application of woods of different types, geographical origins and prior treatments during ageing (Gambuti *et al*., 2010; Kozlovic *et al*., 2010) to improve the traditional barrel ageing system. Besides the above technologies mentioned, some physical methods have also been developed to accelerate the ageing process, which involve ultrasonic waves (Chang & Chen, 2002), gamma rays (Chang, 2003), electric fields (Zeng *et al*., 2008), nanogold photocatalysis (Lin *et al*., 2008) and high pressure (Li *et al*., 2005a; 2005b). These technologies are promising to artificially accelerate the ageing process and enhance the sensory quality of wine.

Therefore, the objective of this paper is to review the recent development of technologies for accelerating wine ageing process and enhancing wine quality. The impacts of operational parameters of each technology on wine quality during ageing are analyzed. Furthermore, comparisons of current ageing technologies are carried out to identify advantages and

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disadvantages of each one. Lastly, several strategies are proposed to produce high-quality wines in a short ageing period, which may be an important research area in the future and benefit the modern winemaking industry.

2. Development of Wine Ageing in Barrel System

Wine ageing in barrel is one of the most common methods in winemaking process and oak wood has been used to construct wine barrels for over 2000 years (Jackson, 1994). The main oak species used are *Quercus alba* from North America and *Q. robur* (also known as *Q. pedunculata*) and *Q. sessilis* (also known as *Q. petraea* or *Q. sessiliflora*) from France. Oak barrels can benefit wines in two different aspects. On one hand, astringency-related phenolic compounds and oak-responsible aromatic compounds are transferred to wine during ageing. On the other hand, atmospheric oxygen permeation through the barrel wall allows certain compounds to be oxidized gently, which results in a reduction of astringency and changes in colour (Bozalongo *et al*., 2007).

There are numerous studies about wine ageing in oak barrel and several conclusions could be obtained. Firstly, oak species and their geographical origins play an important role on defining oak compositional differences and oxygen diffusion rates. For instance, the concentration of *cis*-lactone, which is one of the most sensorially important compounds, is higher in American oak than in French oak (Sauvageot & Feuillat, 1999). Moreover, wines aged in American oak barrels have a higher *cis*/*trans*-lactone ratio than those aged in French oak barrels (Gómez-Plaza *et al*., 2004; Garde-Cerdán & Ancín-Azpilicueta, 2006). On the other hand, the natural rate of permeation of oxygen into oak barrels is lower for American oaks than for French oaks, probably due to the higher porosity of French woods (Nevares & Álamo, 2008).

Secondly, wood seasoning and toasting in cooperage is required to produce high-quality barrels suitable for wine ageing. Seasoning not only decreases the high percentage of humidity in wood to make it in balance with the ambient humidity, but also promotes the wood maturation by reducing bitterness and astringency, and increasing aromatic properties (Simón *et al*., 2010). Toasting is applied for wood bending during barrel assembly and encourages the pyrolysis of lignin, tannins and hemicelluloe. There are three different toasting intensities, light, medium and heavy. Light toasting produces few pyrolytic by-products that results in less aromatic compounds but more tannins. Medium toasting produces many phenolic and furanilic aldehydes, which provides woods a vanillin and roasted character. Heavy toasting destroys or limits the synthesis of phenolic and furanilic aldehydes, and simultaneously generates volatile phenols, which donate a smoky and spicy character (Jackson, 1994). Winemakers can decide the toasting intensity of barrels according to their requirement.

Furthermore, barrel age is another crucial factor, which should be considered for choosing the barrel. Several oak-related volatile compounds extracted from oak become gradually exhausted with barrel reuse. Thus, the initial extraction rate of these compounds in new barrels is higher than that in used barrels and more compounds related to toasting can be extracted from new barrels (Gómez-Plaza *et al*., 2004). However, when wines reach deeper layer of wood, oak-related compounds commence to accumulate in wines aged in used barrels due to the transformation of oak wood compounds from woods to wines over time. Therefore, for long-term ageing (12–15 months), the concentrations of most of the oak-related volatile compounds in wines aged in American oak barrels (*Quercus alba*), such as furanic aldehydes and oak lactones, can be similar in new barrels and once-used barrels (Cerdán & Ancín-Azpilicueta, 2006). Although the extraction rate of oak-related compounds in new barrels is higher than that in used barrels, the preservation effect of individual anthocyanins against oxidation enhances when wines are aged in used barrels (Gambuti *et al*., 2010). This is probably because used barrels release lower contents of reactive compounds, such as ellagitannins, low molecular weight phenolic compounds and hydrolysable tannins, than new ones (Barrera-Garcia *et al*., 2007; Gambuti *et al*., 2010). In this way, the reactions between individual anthocyanins and wood released components are weakened in used barrels. Moreover, the lower permeability of used barrel to oxygen also contributes to the preservation effect of individual anthocyanins (Ribèreau-Gayon *et al*., 2006). Another thing about barrel age which should be taken into account is that as barrels get older, they might become populated with the contaminant yeasts like *Brettanomyces* and *Dekkera*, which has already been found 8-mm deep within the wood of barrel staves (Suarez *et al*., 2007). Generally speaking, considering the cost of barrels and the negative effect of old barrels, the frequency of reuse of oak barrels should depend on economics and intensity of barrel character desired.

Besides the characteristics of barrel, the extractive capacity of wine is closely correlated with the wine composition. Sulfur dioxide can act as a solvent of phenols and encourage the extractions of these compounds while classic oenological parameters, such as titrable acidity, pH and ethanol, can directly affect the ethanolysis of wood components. However, the crystals of potassium hydrogen tartrate, which is formed from potassium and tartaric acids, can impede the contact of wines and woods. In some cases, they may even obstruct the wood pores and slow down the diffusion rate of wood components to wine (Ortega-Heras *et al.*, 2007). Therefore, it is necessary to take into account both characteristics of barrels and wine composition to decide the length of ageing time in barrels.

Due to the high cost of purchasing and maintaining oak barrels and the limited supply of current oak resources, new materials as alternatives to American and French oaks have been considered to construct barrels for ageing. Among them, acacia, cherry, chestnut, mulberry and Spanish oak show interesting potentials for replacing the American and French oaks (Table 1). Although these woods could be regarded suitable for barrel production, detailed influences of these woods on the quality of wine need to be elucidated.

In the barrel ageing system, the problem of how to reduce the ageing time without any quality reduction always bothers the oenologists. During ageing, a small amount of oxygen can reach the inner barrel through the semi-permeable walls and many chemical reactions tend to occur near the interface of inner barrel wall. Therefore, a concentration gradient of the products builds near the barrel wall and the accumulation of these products may form a reduction barrier, which prevents fresh wines from reaching the neighborhood of barrel wall. Consequently, the ageing reactions are slowed. Recently, a non-deleterious barrel ageing system was developed to breach the reaction barrier and accelerate ageing (Eustis, 2010). In this semi-permeable wine ageing container, either an internal device or an external device can be fitted, such as an internal circulating pump and an external pump, so that a liquid motion is induced mechanically and fresh wine is brought to the neighborhood of barrel wall to accelerate ageing. Furthermore, Eustis (2010) claimed that with the help of the mechanical motion of liquid, the oxygen transfer from barrel surface to the inner barrel can increase.

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3. Alternative Wine Ageing Systems

As mentioned before, the use of barrel for wine ageing has several disadvantages. Thus, alternative ageing technologies such as ageing using wood fragments, micro-oxygenation treatment and ageing on lees have been employed.

3.1 Wine ageing using wood fragments

One of the alternative ageing systems involves wood fragments addition, such as oak chips and oak staves into wines.

Up to now, the addition of wood chips to wines has been applied in the last decades to provide them an oak flavour in Australia, the USA, South Africa and South America. Since October 2006, the European Union also approved the use of pieces of oak wood during winemaking, but wines treated in this way should be labeled (Bautista-Ortín *et al*., 2008).

In order to understand the advantages of the ageing system in the presence of wood fragments, wines aged in this alternative system should be compared to the traditional barrel-aged ones. Morales *et al.* (2004) found that when the addition of oak chip was at a dose of 2% w/v, the wine vinegar aged using toasted oak chips for 15 days extracted vanillin 20-fold more than that aged in oak barrels for 180 days, and oak chips gave the wine vinegar valuable peculiar characteristics. The evolution of phenolic compounds of low molecular weight in a red wine, including benzoic and cinnamic acids and aldegydes, was analyzed by Sanza *et al*. (2004). During the ageing period of 12 months, the wines aged in barrels showed a slower evolution than those aged with oak chips. Both the extraction rate of several compounds from the hydroalcoholysis of oak wood and the decreasing rate of some compounds that took part in the condensation and browning process were higher in oak chip-treated wines than the barrel-aged ones. Moreover, in the 14-day artificial ageing of Asyrtiko wines using oak chips, the contents of oak-related aromatic compounds, such as furfural and syringaldehyde were much higher in wines treated with oak chips than barrel-aged wines (Arapitsas *et al.*, 2004). Most studies conclude that the use of wood fragments can enhance the extraction rate of wood-related volatile compounds and accelerate the ageing process. On one hand, the small size of wood fragments allows wines to be adsorbed quickly whereas only the inner surface is soaked in barrel ageing systems. In this case, wines can penetrate and soak wood fragments totally, which makes the diffusion of wood-related volatiles from woods to wines easier. On the other hand, the entire surface of wood fragments is usable rather than only 40% of barrel surface (Stutz *et al.*, 1999). Therefore, the extraction rate of oak-related compounds increases in the ageing system in the presence of wood fragments and the length of contact time can be reduced.

However, it should be taken into account that the alternative ageing system in the presence of wood fragments cannot replace the traditional ageing system completely, especially for long-term ageing. For example, in the study of the evolution of aromatic compounds in Monastrell red wines aged both in oak chip systems and American oak barrels, it was found that chips released aromatic compounds into wine rapidly in the first three months of ageing, and significant quantities of *cis*- and *trans*-oak lactones and vanillin were detected (Bautista-Ortín *et al.*, 2008). However, in the following 6 months, the concentrations of these compounds remained constant or decreased while the wines aged in new and used barrels continued to extract aromatic compounds for a long time (Fig. 1). The overall quality of wine aged in new barrels was also better than that aged with chips. In a recent study, the phenolic compositions and sensory characteristics between red wines aged in oak barrels and those aged with oak chips were compared (Ortega-Heras *et al*., 2010). The results indicated that although wines aged with chips for 30 days had the similar phenolic and colour characteristics to those aged in barrels for three months, chip-treated wines created a more astringent mouth-feel sensation and had more grassy and vegetal odours than barrel-aged ones. Furthermore, the evolution of the redox potential, which reflects the oxidation-reduction reactions during wine ageing, is also different in different systems (Álamo *et al*., 2006). The differences in basic enological parameters and phenolic compositions between wines treated with wood fragments and those aged in barrels could augment as the length of wood contact time increases (Álamo *et al*., 2008). From an organoleptic point of view, the application of wood fragments can be regarded as a good alternative to barrels for producing short-term aged wines with satisfied quality. However, in some cases the sensory quality of wines aged with wood fragments cannot be as good as those long-term aged wines in new barrels. On the other hand, during the phase of bottling, barrel-aged wines also behave differently from those aged with wood fragments (Álamo *et al*., 2008). In this sense, a quicker loss of anthocyanins was found during the bottling of red wines treated with wood fragments than those aged in barrels (Sanza & Domínguez, 2006).

Similar to oak barrels, in the alternative ageing system, the characteristics of wood fragments, including size, prior treatment and geographic origin, play an important role in the quality of final wine.

The shape and size of wood fragments are diverse. The shapes of wood include “oak power”, “cubes” or “oak beans”, “granulates” that are granulated pieces, “pencil shavings”, “dominoes” with the shape of domino counters, etc. (Álamo *et al*., 2008). The traditional wood fragments widely utilized are oak chips, staves, tablets and segments. The size of wood fragments is closely related to the extraction kinetics of wood-related volatile compounds. Arapitsas *et al.* (2004) found that guaiacol extraction rate in the wine treated with oak chips of big size (3.4 cm × 2cm × 1 cm) was higher than in wine treated with chips of small size (1cm × 1 cm × 0.1 cm). Bautista-Ortín *et al.* (2008) studied the effect of size of oak chips on aromatic compounds and found that in the same contact surface area, the highest concentrations of *cis*-oak lactones and vanillin were detected in the wine after 3-month ageing when chips were in the format of cubes (10× 6× 4 mm), rather than shavings (8× 3× 1 mm) and powder (<3× <1× <1 mm). By contrast, Simon *et al.* (2010), using oak wood of two sizes (staves, 100 cm× 8cm× 1cm; chips, 1cm× 0.5 cm, approximately) for ageing red wine, found that chips transferred oak-related compounds like furanic aldehydes more rapidly than staves. In regard to the evolutions of both oak-related and oak-no-related compounds, these compounds in the chip-aged wines became stable after 90-day ageing while stave-aged wines evolved slowly throughout the whole ageing period (180 days). As can be seen, since the size of staves is bigger than that of chips, the extraction rate of wood-related compounds in stave-aged wines is slower than that in chip-aged wines. Big size of wood can slow wine permeation in wood and produce a concentration gradient between wine and wood. Due to the great stock of volatile compounds in toasted staves, the extraction can last a long period. On the other hand, when chips are used, the bigger size seems not to affect the extraction rate negatively. Although the small size can promote the toasting effect of chips and more volatile compounds related to wood toasting could be produced, losses of these compounds due to evaporation may happen if the size is less than 5 mm (Bautista-Ortín *et al*., 2008).

Similar to oak barrels, toasting is a conventional pretreatment of wood fragments. It can increase the amounts of aromatic compounds, including furfural, 5-methylfurfural, eugenol, vanillin, guaiacol and its derivatives in wood (Sarni *et al*., 1990). Its effect on whisky lactone depends on species and origin of wood chips (Cadahía *et al.*, 2003). Different toasting pretreatments of wood fragments can affect the final wine quality and its influences on wine chemical compositions and sensory characteristics are even greater than the type of wood used (Guchu *et al*., 2006). By comparing the wine vinegars aged with American oak chips with two different prior treatments (toasted at 180 °C, or boiled and toasted at 180 °C), Morales *et al*. (2004) found that wine vinegars aged with only toasted oak chips showed more significant increases in the concentration of oak-lactone after ageing for 15 and 90 days (Table 2). The *cis/trans* isomer ratio was also different: about 5 for wine vinegars aged with toasted chips and 2 for those aged with boiled and toasted chips. The toasting level of wood fragment is related to the production of wood-related volatile compounds and Bozalongo *et al*. (2007) pointed out that medium and heavy toasting can produce more contents of 5-hydroxymethylfurfural, 5-methylfurfural, furfural, vanillin, 4-methylguaiacol, guaiacol and syringol than light toasting in wood fragments. During wine ageing, wines treated with medium toasted oak chips extracted the highest contents of furfural and *cis* oak lactone followed by those aged with heavily and lightly toasted chips in the study of Koussissi *et al*. (2009). Moreover, the effect of toasting level of wood fragments on sensorial characters of wine is also significant. Koussissi *et al*. (2009) found that heavy toasting gave wines higher wood-related properties, but also made wines more astringent and bitter. Therefore, through controlling toasting level of wood fragments, desired sensory characters of wine can be obtained.

Besides the conventional pretreatment of wood fragments, the microfungal treatment of wood fragments also shows some interesting potentials in increasing the concentrations of some volatile components during wine ageing process. Petruzzi *et al*. (2010) reported that the use of oak chips inoculated with *Penicillium purpurogenum* could increase the concentrations of oak-related compounds, such as furfural, furfuryl alcohol, guaiacol, 2-phenylethanol, and syringol in red wine significantly during a 17-day ageing period. This phenomenon is probably related to the degradation of lignocelluloses and the metabolism of fungi (Dhouib *et al*., 2005). However, due to the possible production of toxins by fungi, the feasibility of the microfungal treatment remains to be demonstrated. Therefore, a selection of suitable strains and toxicity tests should be carried out before its application.

Another factor which should be taken into account during wood fragment selection is the botanical characters and their geographical provenances. As discussed above, there are differences in volatile composition between woods of different species or origins. Besides the size and pretreatments of wood fragments, the contents of aromatic compounds extracted by wines also depend on the species of wood and their origins. For example, the Chardonnay wine treated with Hungarian oak chips (*Quercus petraea*) extracted trace quantities of oak lactones whereas the same wine treated with American oak chips (*Quercus alba*) extracted significant quantities during the 25-day ageing period (Guchu *et al*., 2006). In wine-brandy, higher levels of ethyl 2-methylpropanoate, ethyl butyrate and ethyl octanoate and lower levels of butanoic acid, *cis*-β-methyl-γ-octalactone and syringol were detected in the brandies aged with French oak

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staves and tablets (*Quercus robur* L.) compared to those aged with Portuguese chestnut wood (*Castanea sativa* Mill.) (Caldeira *et al*., 2010). Moreover, a red wine macerated with Spanish chips (*Quercus pyrenaica* and *Quercus petraea*) was richer in furanic aldehydes and eugenol whereas those macerated with American chips (*Quercus alba*) contained higher concentrations of *cis*-whiskey-lactone, vanillin and methyl vanillate (Rodríguez-Bencomo *et al*., 2009). Therefore, wood fragment should be selected with extreme care by considering the whole characteristics of wood.

In the presence of wood fragments, the ageing time can be reduced due to the high extraction rate of aromatic compounds. However, colour evolution commonly requires a longer maturation time and a small amount of oxygen to promote the chemical reactions. However, atmospheric oxygen cannot diffuse through stainless steel tanks. Thus, the chromatic characteristics and colour stabilization of wines treated with wood-fragments may be not similar to those of barrel-aged wines. To solve this problem, caramel colouring additive E-150, which is authorized in the European Union, can be added to wines during ageing. By using this additive, Monedero *et al*. (2000) found that dry *oloroso* wines aged with oak shavings had the similar colour characters to commercial wines. Another solution is to introduce small, controllable amounts of oxygen into wines during ageing, which is called micro-oxygenation. Its application during wine ageing will be discussed later.

3.2 Combination of micro-oxygenation with wood fragments during wine ageing

This technique is based on the introduction of a small amount of pure oxygen into wines over time. At the beginning, the micro-oxygenation process was applied to imitate the barrel ageing during the 1990s. Nowadays, the main purposes of micro-oxygenation are to develop colour stabilization, strengthen red colour in red wine, enhance health of yeasts during alcoholic fermentation, improve the taste and structure of wine, stimulate oak barrel ageing system, modify aromatic characters of wine and remove undesired flavours (Gómez-Plaza & Cano-López, 2010). Micro-oxygenation can start at any phase of the winemaking process. In this review, discussions are focused on the application of micro-oxygenation during wine ageing.

During ageing, micro-oxygenation is currently carried out in the alternative ageing system in the presence of wood fragments to simulate the traditional barrel ageing system. In the absence of wood fragments, Cano-López *et al*. (2010) found that although a red wine treated with micro-oxygenation could have the similar chromatic and phenolic characteristics to barrel-aged wines after three-month ageing, barrel-aged wines showed a more stable colour during bottling. This difference is probably due to the protective effects of compounds extracted from woods during barrel ageing, such as phenolic acids, wood aldehydes and ellagitannins. On the other hand, without micro-oxygenation treatment, the study of Sartini *et al*. (2007) showed wood fragments slightly modified the phenolic composition of wine while the combination of micro-oxygenation and wood fragments could increase wine colour and promote the formation of polymeric pigments. Therefore, the combination of both micro-oxygenation treatment and addition of wood fragments is essential to imitate the barrel ageing process. Gay *et al*. (2010) monitored the ageing of a red wine by chemical analysis and an electronic tongue and found that wines aged using oak barrel and the combination of micro-oxygenation and oak chips/staves showed similar trends in the variations of either chemical parameters or peak potentials associated to polyphenols (Fig. 2). Guerrero *et al*. (2010) confirmed that the treatment with

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micro-oxygenation and oak chips could modify the phenolic and volatile compositions of sherry wine vinegars and made them similar to traditional barrel aged ones in chemical composition. Finally, they proposed a method of ageing using a dose of oxygen around 70 mL/L month and 5 g/L of chips. In this case, wine vinegars similar to traditional aged ones in sensory characters and chemical compositions can be obtained by the combination treatment of micro-oxygenation and chips in 14 days rather than 105 days for barrel ageing. As can be seen, the combination treatment of micro-oxygenation and wood fragments not only benefits the chromatic, phenolic and aromatic characteristics of final products, but also accelerates the ageing process compared to barrel-aging.

Oxygen dosing is a key factor for micro-oxygenation treatment. An excessive oxygen dosage can be very harmful to wine. To better manage the micro-oxygenation process, several variables, including free SO_2, ethanol, colour indictors, phenolic compounds and dissolved oxygen available in wine should be monitored (Nevares *et al.*, 2010). The changes of these variables are related to the micro-oxygenation treatment and can reflect the influence of this treatment on wine. However, free SO_2, ethanol, phenolic compounds must be extracted and measured offline in the laboratory while the content of dissolved oxygen can be detected online. Therefore, it is easy to monitor the content of dissolved oxygen in wine and this variable can indicate the balance between the dissolution and consumption of oxygen in wine during ageing. The diameter and height of the tank for storing wine play a decisive role in oxygen transfer (Adoua *et al.*, 2010), and a gradient in the dissolved oxygen concentrations of wine can be generated by the addition of oxygen at specific points in the tank (Nevares *et al.*, 2010). In these cases, defining the measuring point in the tank is of paramount importance for dissolved oxygen measurement. A representative point of the entire tank could be found through a gentle pumping treatment, since this treatment can homogenize the dissolve oxygen in wine (Nevares *et al.*, 2010).

At present, dissolved oxygen can be measured by means of different systems. The traditional one is the electrochemical system based on Clark's electrode, which is regarded as the most effective and reliable method. Other alternatives are based on dynamic luminescence quenching of the photoluminescence systems and differ in solutions and types of sensors (Xu *et al.*, 1994). The non-intrusive luminescent technology has been proved suitable for measuring dissolved oxygen during the micro-oxygenation process (Nevares *et al.*, 2010).

Through dissolved oxygen measurement, the evolution of oxygen consumption in wine can be studied. The characteristics of wood fragments play an important role in determining the oxygen consumption by wine because, on one hand, micro-oxygenation treatment is usually accompanied with addition of wood fragments and, on the other hand, oxygen consumption is closely related to the compounds released from wood to wine and the evolution of these compounds during ageing (Álamo *et al.*, 2010). First of all, the evolution of oxygen consumption in wine depends on the toasting levels of wood fragments. Nevares *et al.* (2009) found that oxygen was consumed quickly at the beginning of wines aged with lightly toasted chips and a high loss of anthocyanins, a decrease of red tonalities and an increase of brown tones were detected. On the other hand, wines treated with medium-toasted chips consumed more oxygen in the end. Secondly, the oxygen demands in wine enhance if wood fragments with bigger size are used during ageing (Nevares & Álamo, 2008; Álamo *et al.*, 2010). As for the origin of wood fragments, it is reported that wines treated with French oak (Q. *petraea*) need more oxygen than those treated with American (Q. *alba*) and Spanish (Q. *pyrenaica*) oak woods (Nevares & Álamo, 2008; Álamo *et al*., 2010).

Another factor which affects wines' ability to consume oxygen is their initial characteristics. In general, oxygen is mainly consumed by SO_2, phenolic compounds and ethanol (Devatine *et al*., 2007; Gómez-Plaza & Cano-López, 2010). Therefore, together with the characteristics of wood fragments, the concentrations of these compounds in wine can affect the oxygen consumption.

Considering the effects of these mentioned factors on oxygen consumption during ageing, the micro-oxygenation strategy should be carefully selected. The traditional strategy, called micro-oxygenation, is based on adding doses of oxygen successively, which are similar to the average oxygen quantity penetrating through the wood barrel wall (Castellari *et al*., 2004). In this case, the dose of oxygen is constant and small to avoid oxidation problems, but it is not controlled accurately. This strategy does not consider the influence of wood fragments and wine composition on oxygen consumption. To better manage the ageing process, an alternative strategy known as floating dosage micro-oxygenation was proposed, in which an oxygenation is adapted to the needs of different types of wood fragments (Álamo *et al*., 2010). The dosage of oxygen depends on the level of dissolved oxygen desired in wine, which should ensure the best wine-wood integration during wine ageing (Nevares *et al*., 2009). For this strategy, it is necessary to set a level of dissolved oxygen as a reference, such as the content of dissolved oxygen that can meet the demand of wine during the whole ageing process. Thus, the dosage can be regulated by comparing the reading of each dissolved oxygen measurement with the reference of dissolved oxygen level. In the study of Álamo *et al*. (2010), a dissolved oxygen level of 20 μg L^{-1} was selected.

3.3 Wine ageing on lees

Traditionally, lees are used during the ageing of natural sparkling wines, white wines and biological aged sherry wines produced in the presence of flor yeasts. Currently, this technique has been applied in all viticultural areas since it provides high-quality products. From a sensorial point, ageing on lees can not only reduce bitterness and astringency, enhance the structure, roundness and body of wines, but also make the aromatic notes of wines more complex and persistent (Barrio-Galán *et al*., 2011). In red wines, the presence of lees during ageing can improve the colour stability (Escot *et al*., 2001). Generally, lees are mainly made up of yeasts, and in minor proportion, of some inorganic compounds and tartaric acid. This ageing option is coupled with either barrel ageing or ageing carried out in other containers, such as stainless tanks and large cooperage systems.

During ageing on lees, lees undergo a self-degradation process known as autolysis (Leroy *et al*., 1990). The cell wall is gradually degraded over time and several compounds, including polysaccharides, amino acids, peptides, fatty acids and lipids are released. Therefore, the composition of wine is affected by yeast lees. Firstly, the presence of lees during ageing can modify the aromatic properties of wines. On one hand, the contact of wines with lees cell walls can decrease the contents of some volatile compounds due to the sorption phenomenon (Pozo-Bayón, *et al*., 2009). It has been proved that lees are effective in removing 4-ethylphenol and 4-ethylguaiacol, which can reduce the quality of wine at high concentrations (Chassagne *et al*., 2005). Besides undesired volatiles, lees can also bind oak-related compounds and attenuate the impact of wood on wines, with the most affinity components being 4-propylguaiacol, 4-methylguaiacol, eugenol, furfural and 5-methylfurfural (Moreno & Azpilicueta, 2007). The retention intensity is related to the physicochemical characteristics of lees cell wall and the volatile compounds in wines. The amphiphilic character and polarity of cell wall mannoproteins are believed to give yeasts the ability to bind volatile compounds (Lubbers *et al*., 1994) and their sorption is proportional to the hydrophobicity of these compounds (Gallardo-Chacón *et al*., 2010). Moreover, other factors, such as temperature, pH, ethanol content, the autolysis state of yeast lees and presence of other compounds in wines which can be adsorbed on yeast lees, can also greatly affect this behaviour (Pérez-Serradilla & Castro, 2008). On the other hand, during ageing yeast lees can release some nitrogenous substances as precursors of aromatic compounds. As a result, lees can enhance the final bouquet of wines aged on them. For example, Liberatore *et al*. (2010) found that lees enriched flavour active compounds, like lactones, ketones, terpenoids, esters and aldehydes in Chardonnay white wines during ageing. Besides these mentioned effects of lees on aromatic composition of wines, lees may bring some risks due to the production of some sulfur odours and bad volatile compounds (Palacios *et al*., 1997). To reduce the generation of sulfur off-odours and avoid the evolution of low redox potential in lees, periodic stirring is employed during ageing on lees.

On the other hand, lees can modify the phenolic profile of wines. Similar to aromatic compounds, phenolics can also be adsorbed on lees. For instance, yeast cell wall showed retention capacity to flavan-3-ol derivatives and coloured products generated from phenolic condensation and oxidation in white wines (Razmkhab *et al*., 2002). Yeast membrane sterols are believed to be related to the ability of yeasts to adsorb phenolic compounds and mainly, the colorless intermediate compounds of the browning reactions (Márquezt *et al.*, 2009). This potential of lees can be utilized to prevent white wines from browning without changes of sensorial properties. For red wine ageing, yeast lees may adsorb condensed tannins and anthocyanins (Mazauric & Salmon, 2005; Mazauric & Salmon, 2006). In these works, it was found that polar condensed tannins were liable to be adsorbed on yeast lees while the polarity of anthocyanin was unrelated to the adsorption efficiency. Apart from the interaction between phenolic compounds and lees, wine ageing on lees is reported to result in moderate increases in some benzoate derivatives and remarkable increases in their hydroxycinnamate analogues (Karathanos *et al*., 2008). The enhancement of these compounds has a positive impact on the nutritional value of wine due to their antioxidant activities (Fernández-Pachón *et al*., 2005).

Furthermore, lees play an important role in the evolution of polysaccharides and nitrogen compounds in wines. The autolysis of yeast lees enriches the level of polysaccharides in wines. Through stabilization of flavour and modification of tannin astringency, polysaccharides can give wines the sensory characters of fullness, roundness and mellowness. At the same time, polysaccharides can limit the aggregation of unstable substances, and consequently promote wine stabilization (Pati *et al*., 2010). Other compounds released during autolysis include amino acids and peptides that enhance the nutritive value of wines. Taking sparkling wines for example, lees can release hydrophobic peptides during ageing, which are responsible for the angiotensin I-converting enzyme inhibitory activity, thus regulating human blood pressure (Alcaide-Hidalgo *et al*., 2008). However, ageing on lees does not always increase the nitrogen compounds in wines. During the biological ageing of sherry wines, it was reported that amino acid level decreased and some amino acids could not even be detected at the end of ageing (Villamiel *et al*., 2008). This is probably because during yeast autolysis, they continue to grow simultaneously. Another thing that should be taken into account is that lees may produce some biogenic amines during ageing. The presence of lactic acid bacteria is related to the formation of biogenic amines because this kind of microorganism can decarboxylate the corresponding amino acids in wines. The intake of biogenic amines can cause several health problems to wine consumers, such as hypotension, hypertension, nausea and headache (Santos, 1996). Therefore, during ageing on lees, the level of biogenic amines in wines should be reduced to minimum.

In order to fulfill the potential of lees on enhancing wine quality during ageing and avoid the negative effects that they bring, several strategies have been developed. To start with, appropriate yeast selection is helpful to optimize ageing on lees. Either the qualitative composition of yeast cell walls or the formation of their wall polysaccharides varies depending on the yeast strains. Moreover, different yeasts may have different polysaccharide release kinetics (Palomero *et al*., 2007). In yeast selection, the release of polysaccharides is considered as a principal criterion. Other parameters, such as the ageing time and the stability of wine colour also need to be taken into account. The traditional species used for ageing are the *Saccharomyces cerevisiae* yeasts. In recent years, the non-*Saccharomyces* wine yeasts have also been developed. Among them, the osmophilic yeast genera, *Saccharomycodes* and *Schizosaccharomyces* show their potential for rapid autolysis and high polysaccharide release (Palomero *et al*., 2009). The contents of polysaccharides released by *Saccharomycodes ludwigii* and *Schizosaccharomyces pombe* during a 142-day ageing period were 110.51 mg/l and 103.61 mg/l, respectively, which were much higher than that released by *Saccharomyces cerevisiae*. Most importantly, no significant loss of colour was detected together with these benefits. As can be seen, these yeast species can enhance the quality of wine within less time than the traditional yeast and, therefore, the ageing time can be reduced.

A shorter ageing time can not only be achieved by selecting the strains that undergo rapid autolysis, but the addition of commercial enzyme preparations can also be a useful method to accelerate the autolysis process. These products are made up of several enzymes, such as pectinase and β-glucanase that are believed to increase the content of polysaccharide in both white and red wines (Pellerin & Tessarolo, 2001). Palomero *et al.* (2007) studied the effect of adding β-glucanase during red wine ageing and found that yeast autolysis was finished within 2-3 weeks in the presence of this enzyme whereas it took a minimum of five months to detect a large amount of polysaccharide released from yeast lees for conventional autolysis. Besides accelerating the autolysis process, the enzyme preparations were reported to enrich the flavour of wines, particularly those varietal aromas not from grapes (Masino *et al.*, 2008). However, the use of β-glucanase enzymes cannot always benefit wines aged on lees. In the studies of Rodríguez-Bencomo *et al.* (2010) and Barrio-Galán *et al.* (2011) no clear effects were observed. Furthermore, the addition of the enzymes may have some negative effects on wine. Palomero *et al.* (2007) found that the use of β-glucanase significantly reduced the content of total anthocyanins in red wine and promoted a marked decrease in colour intensity, probably due to the β-glucanase contamination with undesired β-glucosidase. On the other hand, the addition of these enzymes during wine ageing on lees leads to a great increase in glucose, which may be utilized by undesirable microorganisms such as *Brettanomyces* as a source of carbon and stimulate their growth in wines (Fernández et al., 2011). Considering the advantages and disadvantages that commercial enzyme preparations may bring, their effects on wine quality should be carefully judged before using them on an industrial scale.

Moreover, based on the drawbacks that the present ageing technique on lees may have, oenologists are also trying to improve it in different ways. On one hand, polysaccharides and mannoproteins commercial preparations, including autolysates, yeast wall, yeast derivatives, extracts, etc., have been developed to replace fine lees. These commercial products are helpful to eliminate possible formation of biogenic amines and acetic acid and the apparition of animal and sulphur off-odours when wines are aged on fine lees. Regarding the influence of these commercial products on the composition of wine, Rodríguez-Bencomo *et al*. (2010) found commercial yeast derivatives could bind some volatile compounds, mainly fusel alcohol acetates and ethyl esters, and consequently modulate the intensity and volatility of volatile compounds in wines. These commercial yeast derivatives are also able to release polysaccharides, but the contents and types of polysaccharides are dependent on the addition and characteristics of commercial products (Barrio-Galán *et al*., 2011). On the other hand, oenologists are trying to develop lysated lees instead of fresh lees. Lysates can be produced by accelerating the lysis of lees using hydrolytic and plasmolytic agents, like β-glucanases and commercial tartaric acid (Fornairon-Bonnefond *et al*., 2002). Parietal polysaccharides and other products from different cell parts are abundant in these lysated lees. During ageing, lysated lees can reduce unpleasant odours and potential microbiological contamination to minimum since these negative effects only appear in a small volume of wine around the lysated lees rather than the whole part of wine aged on lees. In order to understand the effects of lystated lees on wine composition and organoleptic quality, Fernández *et al*. (2011) determined the contents of polysaccharides and main phenolic compounds and the colour parameters of a red wine. They found that the presence of lysated lees during ageing could produce wines with lower tannin content without modifying the content of monomeric anthocyanin compared to traditional barrel ageing without lees. Furthermore, different treatments of lysated lees can influence the sensorial properties of final wine. In the same study, these authors (Fernández *et al.*, 2011) found that the use of an acidification treatment on lysated lees produced wines with strong acid and fresh sensations whereas the presence of lysated lees treated with acids together with enzymes not only enhanced wine colour intensity, but also increased sweetness and fullness of wines and extended the length of the perceptions staying in mouths. In one word, although these novel alternative technologies based upon ageing on lees have their own advantages, the selection process should take into account the type of wine required as well as feasibility and winery management factors.

Another strategy is to combine the use of lees with other ageing techniques, such as the use of wood pieces and micro-oxygenation. Up to now, few works have been focused on the combination of lees, wood pieces and micro-oxygenation on the quality of wines. Only the use of lees together with micro-oxygenation has been proved to have a positive effect on the colour stability and increase colour and red polymeric pigments (Barrio-Galán *et al.*, 2011; Sartini *et al.*, 2007). More detailed studies are necessary to elucidate the effect of the combination of lees and other ageing technologies on the quality of wine.

4. Development of Wine Ageing in Bottles

Apart from ageing in barrels and other vessels, bottling is another important stage for wine ageing. Sometimes wines are directly aged in bottles (Segade *et al.*, 2009; Ancín-

Azpilicueta *et al*., 2009). During storage in bottles, temperature, illumination, position and oxygen content are important to determine the composition of final products.

Storage temperature should be considered carefully during bottling. Generally, wine cellar temperature is between 13ºC to 15ºC, and the storage temperature in the range from 5ºC to 18ºC is also acceptable as long as it keeps constant. Winemakers can store wines at low and controlled temperature whereas wines commonly stay at room temperature after they are put in sale places or purchased by consumers. Therefore, it is necessary to clarify how wine quality evolves at different temperatures during bottling. Zalema and Colombard white wines stored at a low temperature (4°C in the refrigerator) could be clearly distinguished from those stored at the ambient temperature and those stored at a constant temperature from 15°C to 20°C according to the linear discriminate analysis of colour parameters and phenolic and volatile compounds (Fig. 3) (Hernanz *et al*., 2009). Furthermore, Garde-Cerdán *et al*. (2008) pointed out that low temperature (5°C) could enhance the contents of some important aromatic compounds such as ethyl esters of fatty acids and isoamyl acetate during the storage of a white wine without the addition of SO_2. Blake *et al*. (2010) also confirmed that a relative low temperature (12ºC-storage) benefited the quality of final wines compared to a 22ºC-storage condition since the lower temperature bottled wines showed higher retention ability of acetate esters, phenolic compounds (in red wines), free and bound SO_2, and a lower browning index. In some cases, high temperature is useful for accelerating the ageing. Losco *et al*. (2010) found most of aromatic compounds from grape flavour precursors increased significantly in the first week when the wines were heated to 50°C to mimic wine ageing in bottle. Nevertheless, high temperatures should be avoided during wine ageing process in most cases, since they can sharply reduce the contents of aromatic compounds in wine (Zoecklein *et al*., 1999; D’Auria *et al*., 2009) and accelerate the process of browning of white wine (Berg & Akiyoshi, 1956).

The phenolic and aroma profiles of wine can be modified by the wavelengths of the ultraviolet spectrum and the blue portion of the visible spectrum (in the range from 350 nm to 500 nm) during storage. The radiation effect on wine is related to the storage temperature. During storage at 25ºC, “fino” sherry wines lost several polyphenolic compounds when they were exposed to UV-Vis radiation, whereas the volatile compounds, including esters and several acids showed an ascending tendency during irradiation (Benítez *et al*., 2003). However, when storage temperature was set at 45 ºC, the contents of most of esters and acids decreased in these wines (Benítez *et al*., 2006). As can been seen, a high temperature appears to counteract the increases in esters and acids promoted by the application of UV-Vis radiation. Another factor which can affect the radiation effect on wine is the nature of the glass bottle. In the study of Benítez *et al*. (2003), the losses in polyphenolic compounds were greater for the sherry wines bottled in transparent glasses than topaz glasses. The former ones cut off the wavelength at 300 nm while the latter ones cut off the wavelength near 600 nm, but transmit 20% at 350 nm (D’Auria *et al*., 2009). With respect to red wines, coloured bottles can be used to protect wines against photodegradation, despite not sufficiently (D’Auria *et al*., 2009). Therefore, in order to preserve wine quality and prevent photodegradation in both retail and cellar environments, it is essential for winemakers to choose a proper bottle hue. Moreover, the radiation effects on wine differ according to the variety of grape. In the irradiation of red wines at 20ºC, different rates of photodegradation of volatile compounds were observed in the Italian red wines produced by different varieties of grapes (D’Auria *et al*., 2009).

During storage, bottles can be placed either in horizontal position or in vertical position without any moving. Compared to other parameters, wine researchers seem not to pay much attention to bottle position during storage and few papers reported its influences on wine quality. Hernanz *et al*. (2009) found that the position of bottle slightly affected the wine quality while Mas *et al*. (2002) concluded that the wines stored in bottles vertically were more oxidized than those stored horizontally. Sometimes vibration of bottles could be applied to accelerate the ageing process. However, this treatment also induces some negative effects on wine, such as reduction of aromatic components and formation of undesirable flavour and taste in wines (Chung *et al*., 2008). Therefore, to produce high-quality wines, vibration of bottles should be avoided.

Furthermore, during winemaking process, oxygen is introduced at various stages. Gentle oxygenation can contribute to the enhancement of wine quality while excessive oxygenation is detrimental to wine quality. Wines are usually packaged in glass bottles with air-tight cap to avoid any direct contact with air. During bottling, oxygen exposure is low and bottling has been called “reductive ageing” (Jackson, 1994). The oxygen content in bottled wines is dependent on the type of closure and the materials of bottle. There are several types of closure, e.g., cork stopper, synthetic closures, screw caps. The cork system is widely used to seal bottles and limit the permeation of atmospheric oxygen into bottles. Different cork systems are used to modify oxygen permeability (Cook *et al*., 1985). Among them, colmated-cork stoppers and polyurethane-powdered-cork stopper, as well as natural-cork stoppers, have already been proved suitable for bottling (Mas *et al*., 2002). Synthetic closures and screw caps are only valuable for short-term bottling since wines sealed by them could be oxidized quickly (Mas *et al*., 2002).

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Another factor related to oxygen content in bottled wines is the raw material of bottles. Besides the traditional glass bottles, the plastic bottles made of polyethyleneterephtalate with an oxygen scavenger can also isolate wines from air, which could make it suitable for wine packaging (Giovanelli & Brenna, 2007). Moreover, the oxygen permeability can be regulated artificially by using closures of constant oxygen transfer rate and controlling oxygen level diffused in the storage space (Caillé *et al*., 2010). In this way, either excessive exposure or excessive protection is avoided and the quality of final products can be satisfied.

To sum up, bottling is an essential phase for wines. Most wines should be bottled for selling. Better understanding of each factor that affects the quality of wine during bottling is helpful to produce high-quality products.

5. Acceleration of Wine Ageing with Physical Methods

Besides the above-mentioned technologies, there are several physical methods showing great potential for accelerating the wine ageing process, involving ultrasonic waves, gamma rays, electric fields and nanogold photocatalysis. Although these technologies are not widely used and people may be concerned about the safety of novel technologies, present studies have showed that they are promising not only in shortening the ageing time and lowering costs for the winemaking industry, but also in producing fine wines.

5.1 Ultrasonic waves

Ultrasound, especially low frequency high-energy power ultrasound, can be used in different areas of food processing, such as extraction, freezing, sterilization, drying, oxidation, etc. (Zheng & Sun, 2006). Wine ageing using ultrasound is a specific example of ultrasonically enhanced oxidation (Povey & Mason, 1998). The effect of ultrasound on wine ageing process is probably related to the acoustic cavitation, which consists of the formation, growth and collapse of microbubbles. The violent collapse of these bubbles can produce extremely high temperatures and pressures (Saterlay & Compton, 2000). Despite either high temperature or high pressure could be harmful to the ageing process and the wine itself, the controlled ultrasonic energy can modify the chemical reactions in wines positively.

In 1937, for the first time ultrasonic waves were applied to produce thermodynamic changes in fermented and distilled alcoholic beverages to emulate those changes that occur by a natural aged beverage (Bachmann and Willkins, 1937). Since then, ultrasonic techniques have been attempted to accelerate the ageing of several alcoholic beverages (Dudar *et al*., 1980; Tyler & Bailey, 2003). Moreover, the detailed effects of 20 kHz and 1.6 MHz ultrasonic waves on rice wine and maize wines during ageing were studied (Chang & Chen, 2002; Chang, 2005). In both cases, wines were forced to pass an orifice atomizer (10 mm for 20 kHz and 4 mm for 1.6 MHz, respectively) to be exposed to ultrasonic radiation and they were circulated several times. According to the sensory analysis carried out, it was found that the taste of rice wines treated with 20 kHz ultrasonic waves within one week could be equivalent to that of market rice wines whereas the taste of rice wines treated with 1.6 MHz ultrasonic waves was not appreciated by the panelists. These studies indicate that high-frequency ultrasound is not suitable for wine chemical reactions. Combined with the report of Lindley & Mason (1987), it could be concluded that the suitable ultrasonic frequency used for accelerating wine ageing reactions is probably in the range from 20 to 100 kHz. However, more studies about using ultrasonic technology for wine ageing are needed to verify this conclusion. For maize wine, Chang (2004) found that ultrasonic treatment did not produce high-quality products.

Besides the advantage of shortening the ageing time, ultrasonic waves were also reported to keep the quality of treated wine at a high level for a long time (Leonhardt & Morabito, 2007). During the whole ageing process of grape wines, the quality of wine tends to improve gradually. Although wines may loss the aroma and fermentation bouquet, they also gain a bottled-aged bouquet (Jackson, 1994). The wine bouquet is multi-layered, which can be composed of floral, fruit, oak notes, etc. When wines are aged for a certain period, they reach their "peak" and have the most pleasant taste and softening of tannins, most complicate aged bouquet (Robinson, 2006). After that, the wine quality starts to decline irreversibly. Therefore, it is best to consume wines when they reach their respective "peaks". After ultrasonic treatment, wines can rapidly arrive at their "peak" and wine quality can stay at peak level for a much longer time than natural aged wines (Fig. 4). The longer duration of wine quality kept at their peak level is very significant in extending the shelf life of wine (Leonhardt & Morabito, 2007).

There are mainly two types of ultrasonic system used for wine ageing. The first one is a flowing system described by Chang & Chen (2002). In this system, wines are flowing and forced through an orifice atomizer, which is connected to the ultrasonic wave generator. Wines are only treated with ultrasound when they pass through the orifice atomizer. Therefore, in order to obtain ultrasonic wines with the expected quality, wines need to be circulated. Another system is a container with wines stored in it (Leonhardt & Morabito, 2007). In this case, ultrasonic transducers can be either fixed on the bottom of this container or in any position inside it.

5.2 Gamma irradiation

Gamma irradiation was used by Chang (2003, 2004) for accelerating rice wine and maize wine ageing. It was found that gamma irradiation treatment at an appropriate dosage, improved some defects of both wines. The contents of polyols in the two types of wine, which are responsible for a bad, greasy mouth-feel in wines, decreased after gamma irradiation treatment. Gamma irradiation also increased the content of ethyl acetate in rice wines that provides a fruit fragrance. Importantly, the studied wines could be aged to a desired taste quality within only 1 hour by using gamma irradiation, which is much shorter than the traditional maturation process. Therefore, gamma irradiation can be considered as a good choice to produce high-quality wines in a short ageing period.

Although gamma irradiation is very promising in accelerating wine ageing, the safety of this technology should be carefully studied. Chang's study (2003) showed no gamma irradiation residues were detected in all irradiation-treated samples. However, more detailed researches including toxicity tests should be performed to ensure the irradiated wines have no negative effects on human health. Besides, to widely use gamma irradiation for wine ageing, consumer fear of radioactive residues also needs to be considered.

5.3 Electric field

In the winemaking process, the application of pulsed electric fields to grape pomace before the maceration-fermentation step can benefit the extraction of phenolic compounds from grapes (López *et al*., 2008a; López *et al*., 2008b). On the other hand, the AC electric field treatment is also considered as an effective tool to accelerate wine ageing and this technology has already been used in some Chinese wine factories (Zeng *et al*., 2008). Since this technology does not always have a positive effect on wine, a preliminary study of the operational parameters should be carried out. Zeng *et al*. (2008) found an optimum treatment (electric field 600 V/cm and treatment time 3 min) for accelerating young red wines, which produced wines with excellent flavour and taste. The high voltage electric field not only reduced the contents of undesired compounds, such as high alcohols and aldehydes, but also increased the contents of free amino acids and esters, which are linked to high-quality wines.

5.4 Nanogold photocatalysis

Nanogold catalysts, which have a particle size between 80-120 nm, can react with oxygen and water to promote the formation of free hydroxyl radicals when they are exposed to the UV radiation at around 245 nm (Lin *et al*., 2008). Free hydroxyl radicals are quite active, which can accelerate chemical reactions (Majlat *et al*., 1974).

Nanogold photocatalysis has been used to accelerate the maturation of young sorghum spirits (Lin *et al*., 2008). In this study, the nanogold photocatalyzed treatment within 2 h at ambient temperature produced spirits with pleasant sensory attributes. In addition, the matured product was identified to be nontoxic by acute toxicity tests. During the nanogold photocatalyzed process of wine, the free hydroxyl radicals encourage the formation of acetic acid and ethyl acetate that are appreciated by human sensors. Therefore, to obtain high-quality products, the generation rate of free hydroxyl radicals should be carefully controlled by adjusting the content of dissolved oxygen.

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5.5 High pressure

High pressure is an important technology for food processing. It is believed that high pressure could provide the activation energy to initiate chemical reactions in wine and consequently shorten the ageing time (Li *et al*., 2000). The high-pressure treatment in the range from 80 MPa to 120 MPa within 2 hours was found to significantly improve the mouth-feel properties of grape wine (Li *et al*., 2000). In this case, a prior storage of wine for 3 to 6 months could benefit the high-pressure treatment. On the other hand, Li *et al*. (2005a; 2005b) found that 300-MPa pressure treatment for 2 hours produced red wines with good flavour and taste. The application of high pressure not only changed the ultraviolet-visible spectrum (190 nm to 560 nm) of red wine, but also changed its boiling point, relative density, redox potential, electrical conductivity and total acidity (Li *et al*., 2005a; 2005b). However, more detailed researches are needed to understand the effect of high pressure on wine composition.

Although these physical technologies can shorten the wine ageing time greatly and their financial investments are pretty low, whether they are available for the ageing of different types of wine, particularly grape wines, still needs to be demonstrated. Moreover, there are a group of wine consumers who are biased against these innovative technologies and wine regulations vary depending on countries. Some of these regulations may be critical of the introduction of technologies involving radiation during the whole winemaking process. Therefore, there could be still a long way to use physical technologies as a conventional processing for wine ageing.

6. Comparison of Different Ageing Technologies and Future Trends

Generally, fresh wines should be aged to obtain a desired and pleasant flavour. As chemical reactions in wines occur over time, the wine quality is improved. The technologies introduced above have already shown that they could improve wine quality from different aspects and some of these technologies can be combined in further to improve the ageing process (Fig. 5).

To produce high-quality wines, the use of a maturation process before bottling is essential. Therefore, the quality of directly bottled wine is not usually as good as that treated with other technologies and they are less expensive. A comparison of each ageing technology except directly bottling is made in Table 3. As can be seen, wine ageing is mainly carried out with three different equipments: wood barrels, stainless-steel tanks and physical treatment set-up. Although the use of wood barrel to store and age wine is quite old and it is trustworthy to produce high-quality wines, several defects of this technology remain and researchers and winemakers have put great effects to develop novel ageing technologies. Either the use of wood fragments or physical methods can accelerate wine ageing, whereas the introduction of lees to barrels or stainless-steel tanks, as well as the introduction of small, controlled amounts of oxygen to stainless-steel tanks, can improve the quality of wine. Despite that these innovative ageing technologies are promising to replace traditional barrel-ageing technology and produce highly appreciated products, the feasibility of most of them remains to be demonstrated.

Both winemakers and wine consumers are concerned about how to produce high-quality wines in a short ageing period. For winemakers, it means the reduction of financial investment while for wine consumers it means high-quality products at a low price. The technologies that can produce fine wines in a short ageing period are summarized in Table 4 and some combined strategies are also proposed. Besides the strategies reported in literatures, the combination of wood fragments and lees is expected to shorten the ageing process if both of them can fulfill their potential during ageing. Moreover, since wines aged by physical methods could not have the aroma and taste of those obtained from oak barrels or chips and, on the other hand, volatile compounds extracted from oak wood could give extraordinary sensory characteristics to wines, the combination of physical methods and wood fragments should be taken into account. Especially in the combination of ultrasound and wood fragments, the cavitation generation could benefit the release of wood-related volatile compounds from wood to wine. Similarly, the combination of physical methods and lees could accelerate either the ageing process or the release of polysaccharides to wines. However, whether physical methods are harmful to yeast lees or not need to be carefully clarified.

Moreover, as it has already been stated, during ageing wine quality firstly reaches a peak point and then undergoes an irreversible decline. To extend wine shelf life, wine quality should stay at their peak level as long as possible. There are several studies about the influence of different ageing technologies on the quality of wine. However, few of them deal with identifying the peak point of each wine after treatment and extending the period at their peak level. In future, more scientific researches should be performed not only on accelerating wine ageing and making them reach their peak point rapidly, but also on maintaining wine quality at the peak level for a long time. In this way, high-quality wines could be manufactured quickly and their shelf life could be extended.

Currently, a major “Research for SMEs” project “ULTRAFINEWINE” is being carried out by FRCFT in University College Dublin and its partners, aiming to develop a novel technology by using ultrasound to significantly accelerate wine ageing process and produce quality wine resembling many years of natural ageing with extended shelf life. The two-year €1.2m "ULTRAFINEWINE" is being funded by the European Commission's Seventh Framework Programme (FP7) and has the backing of six companies, ranging from wine producers to equipment manufacturers from across Europe.

7. Conclusions

To manufacture high-quality wines, ageing is an essential operation in the whole winemaking process. Wine ageing is a complicated process involving numerous chemical reactions. There are several ageing technologies, each of which has their distinct advantages to improve wine quality and to benefit the whole winemaking industry.

Among the current ageing technologies, oak barrel ageing has the longest history and has proved to be an efficient and reliable method to produce fine wines. In fact, barrel ageing is still the most widely used and recognized technique. Although this traditional technology has several drawbacks, such as lengthy time needed and high cost, the traditional barrel system should not be completely abandoned.

The use of wood fragments and physical methods are considered to accelerate the ageing process and improve the feasibility of the process. Wood fragments provide wood-related aromas to wine whereas the application of micro-oxygenation or yeast lees improves the quality of wines both in physicochemical and sensory properties.

On the other hand, physical methods, involving ultrasonic waves, gamma rays, electric fields, nanogold photocatalysis and high pressure, have proved that they may be used for drastically reducing the ageing time. Furthermore, for extending wine shelf life, ultrasound has shown certain potential in this area. Therefore, if both wood fragments and lees can fulfill their advantages during the ageing process, the combination of these techniques with the physical methods above-mentioned could provide high-quality wines in a very short ageing time.

Finally, although a short ageing time is beneficial to the winemaking industry, the quality of wine should always be considered first. Currently an EU 7FP funded project "ULTRAFINEWINE" is being conducted by FRCFT in University College Dublin and their partners to develop a novel technology that can be used to produce high-quality wines in a short ageing time.

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Table 1 The potential of different types of wood on wine ageing in barrels

Wood type	Potential for wine ageing	References
Acacia (*Robinia pseudoacacia*)	a. The wines were richer in simple volatile phenol compounds than those aged in oak barrels. b. The wines were higher rated in sensory analysis than those aged in oak barrels.	Kozlovic *et al*. (2010)
Cherry (*Prunus, avium*)	Cherry was an alternative to oak for short-term ageing rather than long-term ageing as it promoted a high level of polyphenol oxidation.	Rosso *et al.* (2009)

Chestnut	a. The brandies aged in Portuguese chestnut (*Castanea sativa*) presented similar sensory characters to those aged in oak barrels. b. The oxidation, copigmentation and polymerization reactions of phenolic compounds in wine aged in Italian chestnut barrels and their sensory properties were regulated.	Caldeira *et al*. (2006) Gambuti *et al*. (2010)
Mulberry (*Morus alba*)	The wines presented piceatannol, which has anticancer and anti-Epstein-Bar virus properties.	Rosso *et al.* (2009)
Spanish oak (*Quercus robur*, *Quercus petraea*, *Quercus pyrenaica*)	a. The wines presented similar or intermediate chromatic, phenolicand aromatic characteristics to those aged in French and American oak barrels. b. The wines aged in the Spanish oak barrels (*Quercus pyrenaica*) were preferred over the same wines aged in American and French oak barrels.	Simon *et al*. (2003) Simon *et al*. (2003) Simon *et al*. (2008)

Table 2. Concentration of oak-lactone in wine vinegars (1 alcoholic degree) submitted to accelerated ageing with oak chips (Morales *et al*., 2004)

Ageing Time (day)	Oak chips pretreatment [a]	*trans*-β-Methyl-γ-octalactone (mg/L)	*cis*-β-Methyl-γ-octalactone (mg/L)	*cis/trans* ratio
0	-	0.102±0.003	0.207±0.012	-
15	B-T	0.128±0.000	0.325±0.008	2.5
15	T	0.271±0.012	1.38±0.030	5.1
90	B-T	0.128±0.007	0.309±0.002	2.4
90	T	0.256±0.005	1.35±0.040	5.3

[a] B= boiled, T= toasted.

Table 3 Comparison of different wine ageing technologies

Ageing Technology	Main wine	Wine type	Advantages	Disadvantages	Reference

		chemical modification				
Wood barrel system	Wood barrel-ageing	a. wood-related aromatic compound increase b. polymerization, copigmentation and oxidation of phenolic compounds promotion	Grape wine (eg., red wine, white wine)	a. the longest history b. reliable in producing high-quality wines	a. time-consuming b. expensive c. space-consuming d. limited barrel life e. potential microbiological contamination f. storage-loss due to evaporation	Bozalongo *et al.* (2007) Ortega-Heras *et al.* (2004) Adana *et al.* (2005)
	Wood barrel-ageing + lees	a. similar effects to wood barrel-ageing b. polysaccharides, amino acids, peptides, fatty acids and lipids enrichment c. aromatic and phenolic composition modification d. biogenic amines production		a. same advantages as wood barrel-ageing b. nutritional value enhancement c. structure , roundness and body of wines improvement d. aromatic notes of wines more complex and persistent e. colour stability improvement	a. same disadvantages as wood barrel-ageing b. sulfur off-odours generation c. biogenic amines production	Barrio-Galán *et al.* (2011) Escot *et al.* (2001) Palacios *et al.* (1997)
Other vessels (usually stainless-steel tanks)	Wood fragments	wood-related aromatic compounds increase	Grape wine (eg., red wine, white wine)	a. reducing ageing time b. money-saving	a. wine sensorial quality not as good as long-term barrel-aged wines b. not benefiting colour evolution	Bautista-Ortín *et al.* (2008) Morales *et al.* (2004) Ortega-Heras *et al.* (2010)
	Wood fragments + micro-oxygenation	similar effects to wood barrel-ageing		a. same advantages as wood fragments b. wood barrel-ageing simulation	a. problems of potentially excessive oxidation	Guerrero *et al.* (2010) Gómez-Plaza & Cano-López (2010) Gay *et al.* (2010)

	Wood fragments + micro-oxygenation + lees	a. colour and red polymeric pigments increase b. slightly phenolic composition modification	Red wine	a. same advantages as the combination of wood fragments and micro-oxygenation b. wine colour more stable during bottling	a. same disadvantages as the combination of wood fragments and micro-oxygenation b. more studies are needed to understand this technology	Sartini *et al.* (2007)
Physical methods	Ultrasound (<100 kHz)	a. alcohol content reduction b. acetaldehyde content decrease c. ethyl acetate content increase d. polyol concentration reduction a. accelerating chemical reactions	Rice wine` Grape wine (eg., red wine, white wine)	a. ageing time reduced drastically b. money-saving c. space-saving d. labour-saving e. no storage-loss due to evaporation f. shelf life extended after ultrasonic treatment	a. more studies needed on different types of wine c. critical wine regulations d. people's worry about the security of these technologies, especially gamma irradiation and nanogold photocatalysis	Chang & Chen (2002) Leonhardt & Morabito (2007)
	Gamma irradiation	a. polyol concentration reduction b. ethyl acetate content increase a. acetaldehyde content increase b. polyol concentration reduction	Rice wine Maize wine			Chang (2003) Chang (2004)
	Electric field	a. higher alcohols and aldehydes content decrease b. esters and free amino acids content increase	Red wine			Zeng *et al.* (2008)
	Nanogold photocatalysis	acetic acid and ethyl acetate content increase	Sorghum sprit			Lin *et al.* (2008)

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	High pressure	a. the ultraviolet-visible spectra (190 nm to 560 nm) change b. boiling point, relative density, redox potential, electrical conductivity and total acidity change	Red wine			Li *et al*., (2005a) Li *et al*., (2005b)

Table 4 Current and proposed strategies to produce fine wines in a short ageing period

Number	Strategy	Reference
1	Inducing a liquid motion in barrel ageing system	Eusti (2010)
2	Wood fragments addition	Morales *et al*. (2004)
3	Physical methods	Chang & Chen (2002)
4	Combination of wood fragments and micro-oxygenation	Guerrero *et al*. (2010)
5	Ageing on lees using the osmophilic yeast genera *Schizosaccharomyces* and *Saccharomycodes*	Palomero *et al*. (2009)
6	Combination of wood fragments and lees	Proposed
7	Combination of physical methods and wood fragments	Proposed
8	Combination of physical methods and lees	Proposed

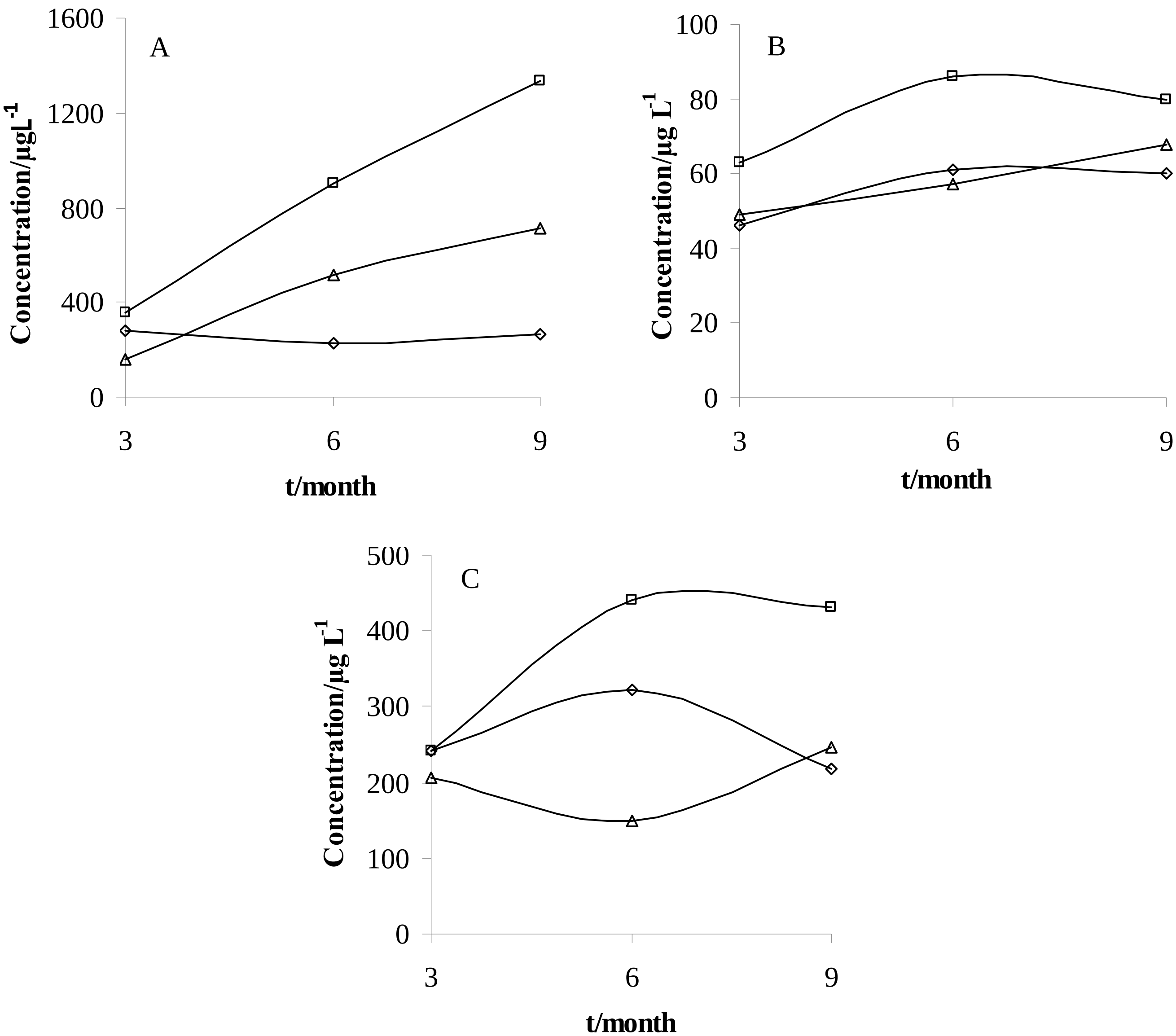

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Fig. 1. Evolution of *cis*-oak lactone (A), *trans*-oak lactone (B) and vanillin (C) in Monastrell red wines during ageing in (□) new barrels; (Δ) used barrels; (□) chip shavings (Bautista-Ortín *et al*., 2008).

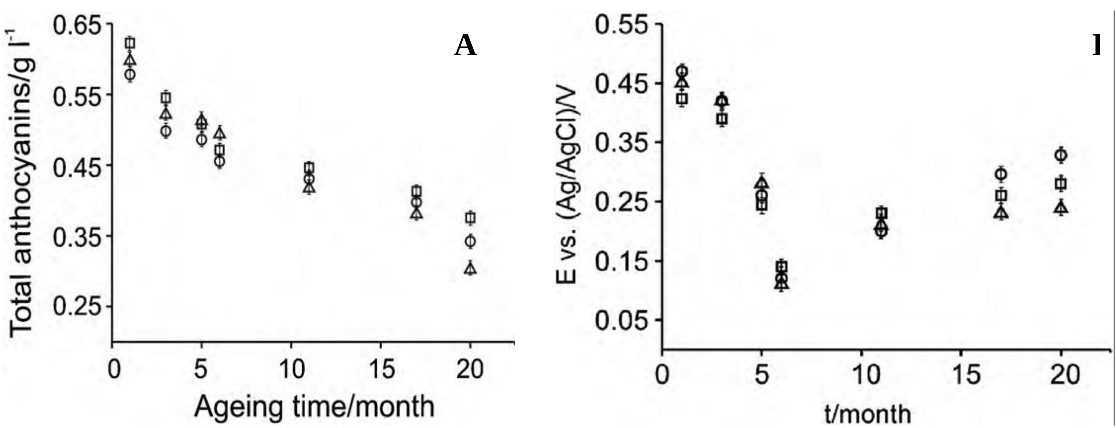

Fig. 2. Variation of anthocyanin content (A) and the peak potential associated to polyphenols (B) during the ageing of wines in (Δ) oak barrels; (O) oak staves; (□) oak chips (Gay *et al*., 2010).

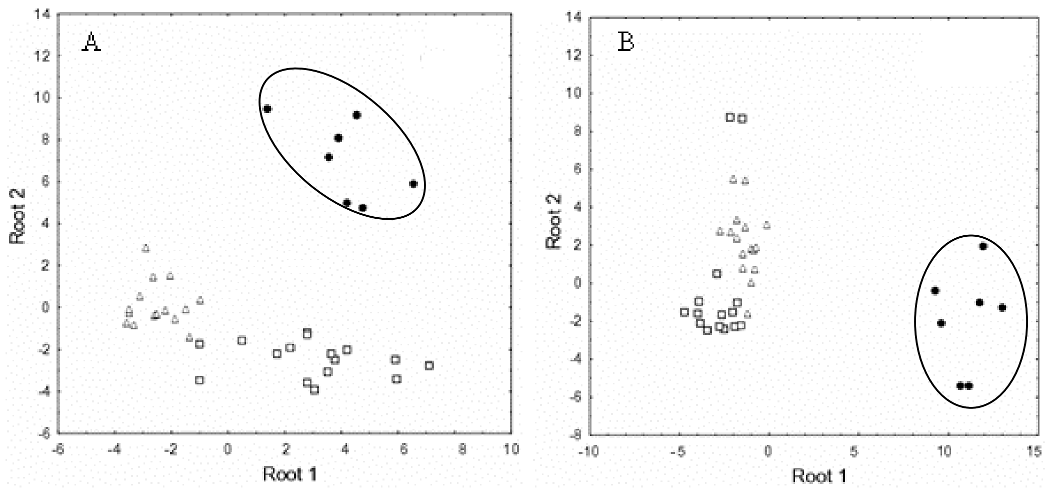

Fig.3. Scatterplot of Zalema (A) and Colombard wine samples in the plane defined by the first two canonical functions based on colour parameters and phenolic and volatile compound concentrations when the storage temperature was considered for discrimination (Δ: constant; □: ambient; ●: cold) (Hernanz *et al*., 2009)

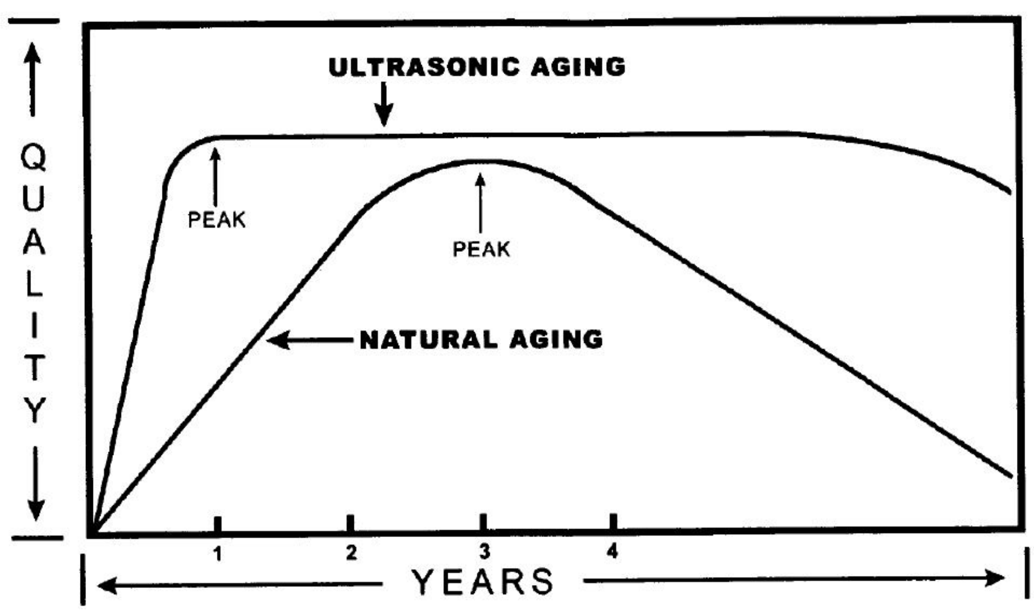

Fig.4. Comparison of the quality evolution of natural aged wines and ultrasonic aged wines (Leonhardt & Morabito, 2007)

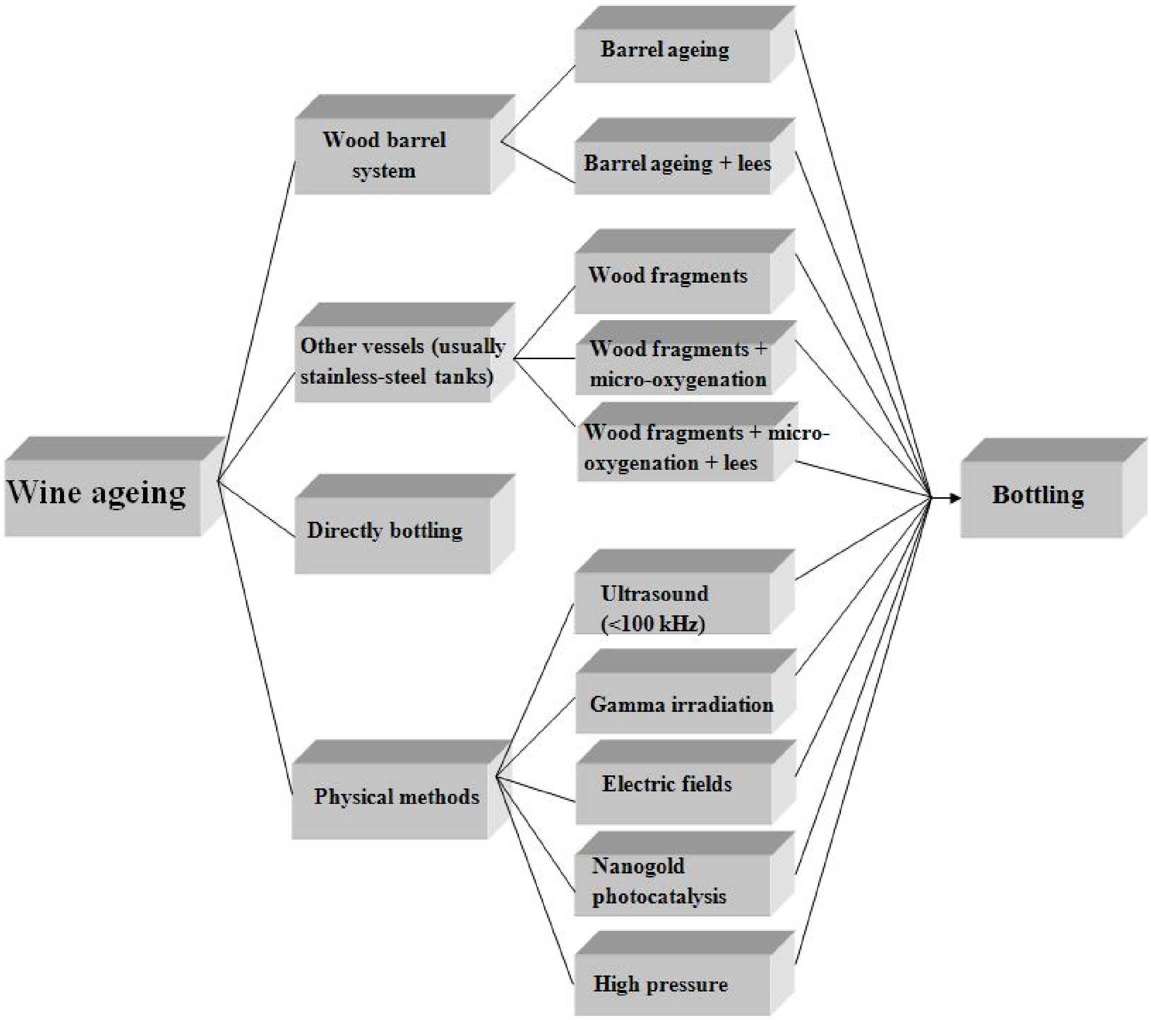

Fig. 5. Current wine ageing technologies reported in literatures