Oxygen in Must and Wine: A review

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Oxygen can play an important role during the winemaking process. It can influence the composition and quality of the must and wine. Phenolic compounds are the main substrates for oxidation in must and wine. Oxygen addition leads to colour changes and the polymerisation of phenolic molecules in wine. Oxygen can, however, also influence the flavour and microbial composition of wine drastically, with certain off-flavours being formed and spoilage micro-organisms able to grow at too high oxygen additions to wine. A state-of-the-art, up-to-date review on the effects of oxygen in must and wine has, however, not been published recently. This review focuses on the effects of oxygen in must, during alcoholic fermentation, extended lees contact and during ageing of white and red wines. The effects it has on acetic acid bacteria and Brettanomyces are also discussed, as well as micro-oxygenation, a relative new technique used in wine production.

The atmosphere consists of approximately 21% oxygen (O2). It plays a crucial role in many metabolic and chemical reactions on earth, thus it is of little surprise that it plays a very important role in the winemaking process. Wine can never be completely protected from it. The general use of sulphur dioxide as an anti-oxidant dates back to the early 18th century and the protection of wine from unwanted oxidative spoilage has been recognised (Ribereau-Gayon et al., 2000a). Oxygen can influence the composition and quality of wine drastically, either positively or negatively, and this will be the focus of this review. This review will also focus on the basic steps involved in oxidation, substrates for oxidation in wine and the evolution of wine constituents during the wine production process when in contact with different concentrations of O2.

Basic reactions of oxygen in wine

Oxidation is the process where electron transfer takes place between reductive and oxidative partners. In wine, O2 is predominantly responsible for this, with it being reduced to certain intermediates and eventually to hydrogen peroxide and then water. Molecular O2 exists as a diradical and is thus in a triplet ground state. This limits the reactivity of O2 and it cannot form bonds by accepting electron pairs. However, the addition of a single electron, originating from reduced transitional metal ions, can overcome this limitation. This leads to an unpaired electron in the resulting negatively-charged superoxide radical, with a second electron transfer resulting in a peroxide anion (Millet et al., 1990; Danielewicz, 2003). This phenomenon results in O2 being involved in various reactions in wine.

Substrates for oxidation in wine

Phenolic molecules originating from grapes can basically be divided into the non-flavonoids and the flavonoids. The non-flavonoids, which are hydroxybenzoic and hydroxycinnamic derivatives, originate from the grape juice, and are normally the principal phenolic molecules in white wines at concentrations ranging from 50-250 mg/L, depending on the cultivar, winemaking techniques, etc. Examples of non-flavonoids are the tartaric esters of caffeic acid, p-coumaric acid and fumaric acids. These molecules have been shown to be the main phenolic molecules in white wine that did not receive prolonged periods of skin contact, because they occur at higher concentrations in the grape juice (Margalit, 1997; Monagas et al., 2005).

The second main group of grape-derived phenolics is the flavonoids. This group of molecules basically consists of two phe-nolic rings attached to a pyran ring. The flavanols have a more complex structure than the non-flavonoids. In a young wine they are normally in a more unpolymerised state, but as wine matures they undergo different polymerisation reactions in which O2 plays an important role. The most important flavonoids in wine are the anthocyanins, flavanols and flavonols. Anthocyanins occur mainly in the skins of red grape cultivars and are responsible for the colour of red wine. In young red wines their concentrations can range from 250 mg/L to more than 1000 mg/L. Different types occur in wine, depending on the -OH and -OCH3 constitution of the B-ring of the molecule, and are esterified with glucose at the C3 position of the molecule. This leads to the occurrence in wine of cyanidin, peonidin, delphinidin, petunidin and malvidin-3-monoglucoside, which can also be acylated with a cinnamic acid derivates (Ribereau-Gayon et al., 2000b; Monagas et al., 2005). Anthocyanins are amphoteric and pH influences their structure in wine. The positively-charged flavylium ion is mainly responsible for the red colour in a young red wine. It is in equilibrium with the chalcone (colourless to yellow), quinodal base (violet), carbinol pseudo-base (colourless) and bisulphate addition product (colourless) (Hrazdina & Franzese, 1974).
The other important group of flavonoids in grapes and wine are the flavanols. These consist of flavan-3-ols (catechins) and flavan-3,4-diols. Different -H and -OH group substitutions on the C and B rings lead to different stereo-isomers being found, viz. (+)-gallocatechin, (-)-epigallocatechin, (+)-catechin and (-)-epicatechin, with the latter two occurring in concentrations of up to 200 mg/L in red wine. These molecules can associate through C4/C6 and C4/C8 bonds to form dimers, trimers and oligomers, and thus form procyanidins. Dimeric procyanidins can be divided into types A and B. Type A has interflavan C4/C6 and C4/C8 bonds, with other bonds between the C5 or C7 carbon units of the terminal unit and the C2 carbon of the upper unit. Type B dimeric procyanidins are characterised by C4/C6 and C4/C8 interflavan bonds. Trimeric procyanidins are divided into Types C and D. Type C has two type B interflavan bonds, and type D has a type A and a type B bond. These molecules can polymerise further to form so-called grape tannins or condensed tannins, which can be classified according to the mean degree of polymerisation (mDP). These molecules are considered oligomers when the mDP is five to ten, and polymers when the mDP is greater than ten. The mDP for stems and pips is about 10, but about 30 for skins, indicating that the flavanoid molecules of skins are more polymerised than those of the pips and stems (Ribereau-Gayon et al., 2000b; Herderich & Smith, 2005). Flavan-3,4-diols can also polymerise in a similar fashion (Monagas et al., 2005). These condensed tannins normally exist at 1-3 g/L in red wine and their concentration depends on the cultivar and wine-making techniques, such as skin maceration time, ageing processes, etc. Other flavonoids that also exist in grapes and wine at much lower concentrations in wine compared to their concentration in red wine are anthocyanins, ellagitannins, hydrolysable and condensed tannins, for example. The total phenolic content of wine is thus no more than 150 mg/L (Singleton, 1987). It is thus no surprise that phenolics act as the principal oxidation substrate for O2 in wine, with especially the vicinal-1,2-dihydroxyphenyl units readily reacting with O2. This leads to the formation of free superoxide (O2-) and peroxide (O22-) radicals. These radicals can be directly reduced by phenolic molecules, and are better oxidants than O2 (Singleton, 1987; Danilewicz, 2003). Wine phenols, however, exist in either the phenol or phenolate anion forms due to the acidic nature. Electron transfer takes place from the phenolate, leaving a free radical of semiquinone, which is further oxidised to the corresponding quinone. The quinone can thus be formed either from phenolate by molecular O2 or ionic free O2 (the intermediate between molecular O2 and H2O2), or from the phenol. The semiquinone can participate in further radical reactions, due to the resonance stabilisation of the delocalised electrons in the ortho and para positions of the aromatic ring (Singleton, 1987; Margalit, 1997).

The constitution of the phenolic molecule will also determine its reduction potential. The phenoxyl radical will more commonly reside on the B ring of catechin than the A ring. The reduction power of a phenolic molecule is determined mainly by the ring constituents, with a lower reduction potential leading to greater reduction power of the reduced component. Electron donating groups (-OME, -Me, vicinal -OH groups) lower reduction potential, but electron-withdrawing groups (-COEt, -COME) have the opposite effect. Methyl gallate is thus a weaker reducing agent than (-)epi-gallocatechin due to its electron-withdrawing carboxylic-ester group. pH also influences this, due to the protonated carboxylic group being electron withdrawing at wine pH levels. This effect is negated at pH 7, where deprenonation takes place and where the reduction potential of methyl gallate becomes comparable to that of (-)epi-gallocatechin. Malvidin-3-monoglisoside, with two -OME groups on the B ring, exists mainly in equilibrium in wine: equilibrium exists between the positively-charged flavylum ion and the carbinol pseudobase, which does not have a charge on the C ring. In the carbinol pseudobase the electron-withdrawing -OME groups on the B ring should make it a strong reducing agent, but an increase in the reduction potential in the flavylum ion is observed. This is due to the positive charge on the C ring of the flavylum ion, which acts as an electron withdrawing system, and which reduces the sensitivity of anthocyanins in the red form to oxidative degradation (Cheminat & Brouillard, 1986; Danilewicz, 2003). The number of O2 atoms consumed per mole of phenol in white wine is about 5.5 times that in red wine. This is mainly due to malvidine derivatives which occur in high concentrations in red wine and which are not directly oxidisable with O2 (Boulton et al., 1996). Quinones, being electrophiles, can also readily react with nucleophilic centres such as phenols, phloroglucinol, SO3- RSH groups, etc. In the same manner, two semiquinone free radicals can also bind by sharing the unpaired electrons in a shared-pair covalent bond. This process, called regenerative polymerisation, leads to the generation of a reoxidisable hydroquinone. This has a lower reduction potential than its original constituents and increases the O2 capacity of wine (Singleton, 1987). It is thus no surprise that phenolics act as the principal oxidation substrate for O2 in wine, with especially the vicinal-1,2-dihydroxyphenyl units readily reacting with O2. These are found in abundance in hydrolysable and condensed tannins, for example. The total phenolic content of a wine can thus be an indication of its ability to consume O2 (Boulton et al., 1996).
Ascorbic acid, which occurs naturally in grapes or is added during the wine production process, can also act as a substrate for oxidation in wine. In the process it reduces quinones back to the corresponding phenols (Peng et al., 1998; Bradshaw et al. 2001). It also undergoes two-electron oxidation. The ascorbate radical exists at wine pH mostly in the anion form. The latter loses a second electron to the quinone, and dehydroascorbic acid is formed. The oxidation rate decreases at lower pH levels, becoming very low below pH 2 (Danilewicz, 2003). Ethanol can also be oxidised in wine by the resulting H2O2 to form acetaldehyde. This can take place in the presence of SO2 because ethanol occurs at relatively high concentrations in wine (Boulton et al., 1996). Acetaldehyde plays an important role in the polymerisation of different phenolic molecules during the ageing of wine (Dallas et al., 1996).

Iron, occurring normally in concentrations of a few mg/L in wine, plays an important role in these oxidation reactions. Fe3+ is reduced to Fe2+ by phenols during oxidation, but oxidised back to Fe3+ in the presence of O2, until all the phenolic substrates have been consumed (Powell and Taylor, 1982). The addition of ferrous ions can catalyse the aerial oxidation of Fe2+; two moles of Fe2+ are produced from one mole of ascorbic acid (Hsieh & Hsieh, 1997). It has also been observed that Fe3+ plays an important role in the oxidation of tartaric acid in wine. The molecular form of SO2 can also react with H2O2, thereby limiting the free sulphur dioxide in wine comprises the molecular, bisulphite and sulphite forms. The O2 consumption rate in must declines drastically with the addition of SO2. This is because the SO2 does not have an anti-oxidative effect in must, but rather inhibits oxidation enzymes. In wine, however, chemical oxidation occurs, and it is mainly the sulphite form of SO2 that can react with O2, but it is still slow under winemaking conditions such as low pH and high ethanol levels. The ascorbate-oxygen reaction is almost 1700 times faster than that between SO2 and O2. First-order kinetics suggests that 4 mg/L SO2 reacts with 1 mg/L O2. The molecular form of SO2 can also react with H2O2 that is formed from the oxidation of phenolic molecules. There seem to be surprisingly few kinetic studies on the interaction between O2, H2O2 and SO2 (Boulton et al., 1996; Ribereau-Gayon, 2000a).

Factors affecting oxygen pick-up and consumption in wine

Winemaking operations

When wine is saturated with O2 it contains about 6-8 mg/L O2 at cellar temperatures. During the normal wine production process wine comes into contact with air, which can result in different O2 concentrations dissolving in the wine. Must can be almost saturated with O2 during the crushing and pressing of fresh grapes (Schneider, 1998). How much O2 dissolves into the wine during fermentation when a pumping over is applied is debatable because the evaporating CO2 probably sparges O2 out of the wine (Boulton et al., 1996). Subsequent winemaking operations add more O2 to the wine. These operations include: pumping (about 2 mg/L), transfer from tank to tank (up to 6 mg/L), filtration (4-7 mg/L), racking (3-5 mg/L), centrifugation (up to 8 mg/L), bottling (0.5-3 mg/L) and barrel ageing (20-45 mg/L/year). During barrel ageing the humidity of the wood and the thickness and the grain of the staves all play a role. Lower humidity, tight grain and thinner staves all allow more O2 to permeate into the wine. In very dry wood of 20 mm thickness it can be up to 0.1 ppm/h, which can lead to oxidation (Vivas et al., 2003). Wine is, however, seldom saturated with O2, due to insufficient contact or the exclusion of air during the production process. The temperature of the wine also influences the dissolved O2 saturation level, with higher concentrations dissolving at lower temperatures. At temperatures between 5 and 35°C the amount of O2 necessary to saturate wine drops from 10.5 mg/L to 5.6 mg/L. The rate of quinone formation, however, increases with an increase in temperature, although the kinetics of this reaction is temperature independent (Margalit, 1997; Ribereau-Gayon et al., 2000b; Vivas de Gaulejac et al., 2001). Oxygen can also be introduced in a controlled manner to wine by a process called micro-oxygenation, which will be discussed later in more detail. The contact of wine with O2 can be minimised by the use of inert gasses, such as N2, CO2 and even argon gas, which can displace the air in a tank or barrel.

The addition of SO2 can also influence the rate of O2 consumption. The free sulphur dioxide in wine comprises the molecular, bisulphite and sulphite forms. The O2 consumption rate in must declines drastically with the addition of SO2. This is because the SO2 does not have an anti-oxidative effect in must, but rather inhibits oxidation enzymes. In wine, however, chemical oxidation occurs, and it is mainly the sulphite form of SO2 that can react with O2, but it is still slow under winemaking conditions such as low pH and high ethanol levels. The ascorbate-oxygen reaction is almost 1700 times faster than that between SO2 and O2. First-order kinetics suggests that 4 mg/L SO2 reacts with 1 mg/L O2. The molecular form of SO2 can also react with H2O2 that is formed from the oxidation of phenolic molecules. There seem to be surprisingly few kinetic studies on the interaction between O2, H2O2 and SO2 (Boulton et al., 1996; Ribereau-Gayon, 2000a).

pH

Wine phenols exist in either the phenol or phenolate anion forms. The negative charge of the phenolate anion is delocalised via the benzene ring from the oxygen atom to the ortho and para posi-
Oxygen in must and wine

Phenolic concentration and composition

Phenolic molecules also differ in their susceptibility to high pH, with caffeic acid and gallic acid becoming less stable towards degradation at high pH, and with (-)-epicatechin and (+)-catechin being much more resistant. The structures of the latter two molecules are not planar and the π electrons of the two benzene rings cannot interact with one another due to conjugation. The spatial arrangements of the -OH groups and the π electrons influence the extent of π orbital overlap and consequently its susceptibility to chemical change. Care should therefore be taken especially when handling white wines with high pH because these are more susceptible to oxidation. They contain caffeic acid derivatives as the main phenolic molecules (Cilliers & Singleton, 1990b; Cilliers & Singleton, 1990c; Boulton et al., 1996). Cilliers and Singleton (1989) found that the amount of phenol consumed per phenol unit at wine pH was about 1.4 to 18 times higher than under alkaline conditions. The rate of the non-enzymatic auto-oxidation of caffeic acid is also enhanced by increasing pH and temperature. Although the oxidation of ascorbic acid by O₂, which is catalysed by Fe³⁺ by ascorbic acid decreases, enzymatic auto-oxidation of caffeic acid is also enhanced by increasing pH and temperature. Although the oxidation of ascorbic acid by O₂, which is catalysed by Fe³⁺, increases with an increase in pH, the reduction of Fe³⁺ by ascorbic acid decreases, with the reaction ceasing at neutral pH (Danilewicz, 2003). Wine thus consumes much more O₂ under slow, acidic conditions than under fast, alkaline conditions.

Phenolic concentration and composition

The phenolic concentration of wine is an indication of its capacity for O₂, with higher phenol-content wines being able to accommodate higher concentrations of O₂. The removal of phenolic compounds from wine with fining reduces the wine's capability to react with O₂. It is calculated that a young, full-bodied red wine can consume 2.4 g or more O₂ under slow acidic conditions (as would happen during barrel ageing when O₂ is added over a long period of time), which is more than its own volume in O₂ or 5-10 times higher than under alkaline conditions. The reaction ceasing at neutral pH (Danilewicz, 2003). Wine thus consumes much more O₂ under slow, acidic conditions than under fast, alkaline conditions.

Numerous studies have reported on the autocatalytic effect of forced oxidation in a wine based medium, with O₂ consumption increasing when two different types of phenolic molecules are involved. The process of regenerative polymerisation, where slow oxidation leads to previously non-oxidisable moieties being incorporated into a re-oxidisable hydroquinone, also leads to an increase in the oxidisable substrates of a wine. However, this seems to be a relatively slow process. The resulting dimeric product has a lower redox potential than its original constituents, and thus buffers the latter against oxidation. At lower pH levels the lower concentrations of phenolate anions will all have time to participate in the regenerative polymerisation reaction to form re-oxidisable hydroquinones with quinones. At high pH levels and when O₂ is added at a fast rate it is not long before no phenols remain to react. This is reflected in the fact that when forced oxidation of wine takes place, browning of the wine follows an autocatalytic pattern, with an initial lag phase. This is due to the dimeric product having a lower redox potential, as mentioned earlier, with two dimeric oxidised semi-quinones reacting with each other to form a tetramer, etc. This process can take place until the molecule becomes too large, and precipitates (Singleton, 1987; Boulton et al., 1996). Cilliers and Singleton (1990a) reported that one molecule of caffeic acid consumed 3.4 atoms of O₂, and this increased to 4.9, 5.5 and 8.5 when phloroglucinol, cysteine and glutathione were added, respectively. The association between catechin and caffeic acid and the addition of cysteine and glutathione increased this further to 13.2 and 19.2 after 9 h. Both cysteine and glutathione act in generating a re-oxidisable product by reducing the quinone back to a caffeic acid and by substituting the quinone to regenerate the hydroquinone form of 2-S-cysteinyl caffeic acid or 2-S-glutathionyl-caftaric acid (Bassil et al., 2005). Depletion of glutathione and cysteine leads to quinone formation and browning. The addition of ferrous sulphate and Fe²⁺ to a model wine solution increased the oxidation of (-)-catechin by O₂ and the rate of O₂ consumption (Vivas et al., 1993; Oszmianski et al., 1996). Ellagic tannins have a much higher capacity for O₂ consumption than condensed tannins do. The rate of O₂ consumption is also faster in the case of ellagittannins, due to more vicinal ortho-OH groups. When ellagic tannins and condensed tannins are added together, the O₂ consumption rate initially increases dramatically, possibly indicating a competition for the O₂ (Vivas & Glories, 1996b).

Desirable levels of oxygen in different wines

Boulton et al. (1996) reported on different levels of O₂ required for certain wine styles. In white wine, about 10 saturations led to the wine becoming oxidised, but it is well known that even fewer additions may lead to a reduction in the fruitiness of wine. Ten saturations led to the minimum concentration necessary to obtain a standard sherry. Red wines differ widely in their capacity, but normally improve with up to 10 saturations (60 mL/L), with others showing improvement even up to 25 saturations (150 mL/L). A value of 10 saturations (or about 60-70 mg/L) is in line with the total amount of O₂ that a red wine can receive in a year because a few rackings and other winemaking procedures can contribute about 20 mg/L, and the barrel ageing regime about 40 mg/L O₂ per year (Vivas et al., 1999a; 1999b; 2003).

Oxygen addition in must, enzymatic oxidation and hyperoxidation

During the crushing, pressing and other processing steps, O₂ comes into contact with the grape juice, leading to the enzymatic oxidation of phenolic molecules. For this to occur the oxidation enzyme, O₂ and the phenolic substrate must be present. The polyphenol oxidases of healthy grapes are known as tyrosinase, cresolase and catechol oxidase, with laccase occurring in Botrytis infected grapes. The latter enzyme is considered a more dangerous enzyme by the winemaker because it is more resistant to SO₂ and has a wider substrate oxidation spectrum. It is not inhibited to the same degree by its oxidation products, as is tyrosinase. Laccase is more active at the low pH values of must and alcohol levels in wine, than tyrosinase. The rate of browning and O₂ consumption is, however, not much different in juices prepared from healthy or rotten grapes (Schneider, 1998; Ribereau-Gayon et al., 2000a).
The main substrates for these oxidation enzymes are the cinnamic acid derivatives, with caftaric acid and coumaric acid occurring at an average of 106 and 10 mg/L respectively in protected white juices (Singleton et al. 1984; Cheynier et al. 1989b). Caftaric acid concentration can also differ dramatically between cultivars, ranging from 40 to 400 mg/L (Singleton et al. 1986). These derivatives occur mainly in the liquid part of the grapes, with flavanoid based phenolics (mainly catechin and condensed tannins) being dominant in the skins, stems and pips. When juice and wine contain higher concentrations of these flavanoids, they also become more susceptible to oxidation and subsequent browning (Schneider, 1998). During oxidation, caftaric acid is oxidised to its corresponding quinone by tyrosinase. Glutathione, with a mercapto group, has a nucleophile centre to substitute into the electrophilic ring of the quinone, leading to regeneration of the vicinal dihydroxy ring of the caffeic acid (Singleton et al. 1985). The product, 2-S-glutathionyl-caftaric acid or Grape Reaction Product (GRP) is no longer a substrate for further oxidation by tyrosinase. Laccase can, however, due to its wider substrate specificity, further oxidise the GRP, with a second addition of glutathione, if available, leading to the formation of GRP2. It does not seem as if laccase can further oxidise the GRP2 under winemaking conditions (Singleton et al., 1985; Cheynier et al., 1986; Cheynier & Van Hulst 1988; Boulton et al., 1996).

Depletion of glutathione and other nucleophiles, which can serve the same role, leads to browning, and the use of cysteine to protect against oxidation should be investigated further. The glutathione to caffeic acid ratio should give an indication of the susceptibility of a certain cultivar to oxidation. This ranges from 1.3 to 12.7 and 0.6 to 10.5 in berries and musts, respectively. Musts can also be divided into three groups according to their hydroxycinamic acid content, with higher concentrations leading to brown colour. A hydroxycinamic acid to glutathione ratio of 0.9 to 2.2, which leads to lightly coloured oxidised must, causes the rapid formation of GRP and high levels of GRP, due to the availability of sufficient glutathione. In medium coloured juices (with a ratio of 1.1 to 3.6) GRP is formed with caftaric acid, and GRP-o-quinone reacts further when glutathione exhaustion has taken place. Small amounts of GRP2 are also formed here. A ratio of 3.8 to 5.9 leads to dark coloured musts, due to glutathione being depleted by the high caftaric acid o-quinone concentration before GRP2 can be formed. This could explain the difference in sensitivity of different musts to oxidation. No correlation between sugar concentration and the ratio could be found (Singleton et al., 1985; Cheynier et al., 1989a; Boulton et al., 1996; Margalit, 1997).

After depletion of the glutathione, the caftaric acid quinone can oxidise GRP and flavanols, and be reduced back to caftaric acid. It can also polymerise with caftaric acid to regenerate a re-oxygenisable phenol. The kinetics of degradation differ between flavanoids, with procyanidin B2 disappearing relatively quickly compared to catechin, but the rate of oxidation between laccase and catechol oxidase did not differ significantly (Oszmianski et al. 1985; Schneider, 1998). Cheynier et al. (1988) found caftaric acid, catechin, epicatechin and epicatechin gallate undergo 70, 50, 46 and 46% decreases respectively after 2 h of oxidation by grape polyphenol oxidase. When the flavanoids were oxidised with caffeic acid their oxidation rate increased, but the condensation reaction of catechin with caftaric acid was still slower than when trapped by glutathione. Catechin also increases the oxidation rate of procyanidin dimers and GRP, but not to the same degree as caftaric acid. Caftaric acid is thus enzymatically oxidised to its quinone, with the consumption of half an atom of O. Catechin is either oxidised to its corresponding quinone in the same manner, with the consumption of one O atom, or by coupled oxidation, by reducing the caftaric acid quinone. The caftaric acid o-quinone with catechin or the catechin o-quinone with caftaric acid can then form a condensation product with a lower redox potential than its monomer constituents and can hence be further oxidised (Cheynier et al., 1988). In a subsequent study, however, Cheynier and Ricardo da Silva (1991a) found that polyphenol oxidase did not degrade procyanidins alone but, in the presence of caftaric acid, the oxidative condensation of the gallloylated procyanidins proceeded more quickly than the oxidative condensation of non-gallloylated procyanidins. This degradation was also influenced by pH, with the nucleophilic addition of a phenolic ring on a quinone occurring between (+)-catechin and its oxidation products occurring at high pH, and semi-quinone radical coupling occurring at low pH. The colour of these products differed; they were colourless at pH <4 and yellow at high pH. Their interflavonic bonds also differed from the original monomer (Guyot et al., 1995; Monagas et al., 2005).

During red winemaking, when an oxidative environment may prevail, and under low glutathione and high hydroxycinamic acid concentrations, anthocyanins can react with caftaric acid quinones, leading to oxidation of the latter through coupled oxidation or condensation reactions. The latter reaction takes place when the nucleophilic C6 or C8 carbon undergoes a condensation reaction with the electrophilic quinone. o-Diphenolic anthocyanins, like delphinidin and petunidin-3-glucoside, usually react rapidly, but malvidin-3-glucoside reacts more slowly due to its condensation with quinones (Monagas et al., 2005).

These phenomena of regenerative polymerisation contribute to the ability of the must to accommodate higher concentrations of O2 than expected, but the O2 accommodation of different musts can differ drastically, ranging from 0.5 to 5 mg/L/min. The consumption of O2 by tyrosinase is very fast, ranging from 30 to 200 mg/L, with 10-15 mg/L being taken up during whole-bunch crushing. The uptake is also faster initially, but decreases as the phenolic substrate is depleted, with laccase, if present, increasing the total uptake further (Cheynier et al., 1993; Schneider, 1998; Ribereau-Gayon et al, 2000a).

The winemaker must apply certain winemaking techniques to prevent oxidation of must during the production process. Oxygen can be excluded by using inert gasses such as N2 or CO2 in presses, pipes and tanks. Oxidation enzymes can also be inhibited by the addition of SO2. Up to 90% decrease in the activity of tyrosinase has been observed upon the addition of 50 mg/L SO2, but higher dosages are necessary to effectively inhibit laccase. SO2 also reduces caftaric acid quinone and enhances the solubility of phenolic molecules. Settling of juice decreases the activity of tyrosinase because it is largely associated with the solid parts of the grape berry. Bentonite fining has also been found to do this, with 100g/L leading to a 30% loss in activity, but it also removes glutathione. Heating of the must to 45 and 65°C will destroy tyrosinase and laccase respectively (Schneider, 1998; Ribereau-Gayon et al., 2000a).

Another strategy to prevent oxidation is to limit the phenolic substrates available for oxidation, especially the flavanoid con-
tent, by soft pressing, no skin contact and removal of stems. A process called hyperoxidation, where large quantities of O₂ are added to the must, can also achieve this (Schneider, 1998). The latter leads to the oxidation of phenolic molecules, which settle, and the juice can then be removed from the precipitate by racking, with no SO₂ added to the must at crushing. To achieve this, O₂ is pumped either in line, while the juice is circulated in the same tank, pumped from tank to tank, added with a diffuser in the juice, or used instead of N₂ before the treatment. Juice that did not receive any skin contact can thus be treated with one saturation, but up to three saturations are necessary to remove sufficient flavanoid molecules from juice that did have skin contact. It is imperative that the subsequent clarification is done efficiently before fermentation starts because the precipitate can redissolve in alcohol. The reductive conditions during alcoholic fermentation and adsorption to yeast cells reduce the brown colour further (Schneider, 1991, 1998).

It is unknown whether must hyperoxidation contributes to the quality of wine. It is however clear that bitterness and astringency decrease markedly with O₂ addition, and that this difference becomes greater during ageing of the wine. These wines are obviously also less susceptible to unwanted browning. In different studies, the aromas of Chardonnay, Riesling, Faberrebe and Parellada were considered more intense in the treated wines. This was more pronounced in the juices that received skin contact before the treatment. This could be due to an increase in fatty acids and esters. Other studies, however, showed a decrease in aroma quality, with more vegetative aromas being formed, possibly due to C₆ aldehydes and alcohols being formed under these conditions. The addition of even H₂O₂ to wine did not decrease the methoxyypyrazine level of white wine (Singleton et al., 1980; Cheynier et al., 1991b; Marais, 1998; Schneider, 1998). Non-volatile flavonoids can, however, indirectly influence the aroma of wine, by yielding acetaldehyde from ethanol during coupled oxidation (Schneider, 1998).

Phenolic molecules can also be removed with fining agents such as PVPP, gelatine and activated charcoal. Charcoal-treated juice made from very rotten Sauvignon blanc grapes had a less intense brown colour than the control (Du Toit, 2003).

**Oxygen addition during alcoholic fermentation and malolactic fermentation**

Completion of the alcoholic fermentation is a crucial step in the winemaking process. During this process yeast transforms sugar into alcohol, CO₂ and energy, and produces flavour compounds such as fatty acids, esters, higher alcohols etc. If this fermentation is not completed successfully then spoilage micro-organisms can use residual sugar to spoil it. Numerous causes for stuck/sluggish alcoholic fermentation have been identified, which include high sugar, low nitrogen, thiamine depletion, excessive clarification, pesticides and a lack of O₂ (Bisson, 1999). Yeast cells need O₂ to produce sterols and unsaturated fatty acids that play a key role in the fluidity and activity of membrane associated enzymes, which influence ethanol tolerance, fermentative capability and viability of yeast (Valero et al., 2001). A dosage of 5 mg/L O₂ is optimal to achieve this when added at the end of the cell growth phase, but when 1 mg/L was added the relative increase in CO₂ production ranged from 10 to 41% between strains. By combining this addition with ammonia addition at the halfway mark of fermentation, it reduced the fermentation by up to 50% in problem fermentations. The maximum O₂ consumption rate was also found to take place at this time (Sablayrolles et al., 1996; Julien et al., 2000). Yeast also assimilates more nitrogen when it is supplied with O₂, but strain differences in fermentation efficiency exist in the absence of O₂. When added before the halfway mark of fermentation, O₂ is assumed to be used in mitochondrial development, ring cleavage of proline and respiration, despite the high sugar content of must. Salmon et al. (1998), however, found that the superfluous O₂ consumption rate during the growth phase of yeast was probably due to mitochondrial alternative respiratory pathways and that O₂ dependent ergosterol biosynthesis accounted for less than 15% of the total O₂ consumption at the beginning of the stationary phase. Blatéryon et al. (2003) found that the addition of 5 mg/L O₂ to fermenting must did not affect the sensory characteristics of the wine compared to the control, but the addition of an excess (50 mg/L) did decrease the quality, with an increase in brown colour. In the absence of O₂ medium chain fatty acids, especially hexanoic, octanoic and decanoic acids, accumulate in the yeast and can be secreted into the wine, contributing to sluggish/stuck fermentations (Bardi et al., 1999). Oxygen has also been found to be depleted from different musts within 2.75 to 4.25 h from the start of fermentation. Its addition may in future serve as a means of proline utilisation by yeast under fermentative conditions (Poole et al., 2002). Buescher et al. (2001) were able to induce S. cerevisiae strain L2226 to produce up to 20.96% alcohol when the yeast fermentation was supplied with O₂ during the first 48 h and nutrients were added together at the start of fermentation. Only 17.89% alcohol was produced when no O₂ was added. Non-Saccharomyces yeast strains can also contribute to the complexity of the wine, by producing certain metabolites. Torulaspora delbrueckii and Kluyveromyces thermotolerans survived longer during fermentation with S. cerevisiae in O₂ rich must (Holm Hansen et al., 2001). The addition of O₂ can be used by the winemaker to ensure a complete fermentation, especially in countries such as South Africa, where grapes have relatively high sugar concentrations. The addition of O₂ to the must also leads to the production of higher concentrations of esters and higher alcohols by S. cerevisiae and S. capensis (Valero et al., 2002). Oxygen can be supplied in large-scale fermentations by sparging air through the tank. This will also help to keep the yeast in suspension.

Certain wines, especially certain white varieties from the Loire valley, Burgundy and Champagne in France and other wine producing countries, are often matured on the yeast lees after fermentation. During this period of time the inactivated yeast undergoes a process called autolysis, which is defined as the hydrolysis of intracellular endohydrolases activated upon cell death. During autolysis the yeast releases different nitrogenous compounds, lipids and polysaccharides into the wine. This process is believed to contribute to the fuller mouth feel and aroma of these wines, while absorbing volatile thiols and anthocyanins. Autolysis can also contribute to a wine’s protein and tartaric stability by releasing manno-proteins. O₂ can be introduced during this period by opening the barrels, transfer of the wine and through a process called battonage, where the lees is stirred periodically in order to mix it uniformly (Fornaire-Bonnefond et al., 2003). It has been observed that yeast lees has a capacity to con-
same this $O_2$, with rates ranging from 3 to 11 fig O2 h$^{-1}$ 10$^9$ from the second month to the sixth month of lees contact. Specific uptake rates also differ between strains, with 100, 50, 42 and 11% of initial $O_2$ concentrations remaining in white wines for strains Su6, Uvaferm, L.2898 and VL.1, respectively, after 3000 h of yeast lees contact. Production of biomass peroxides is directly linked with $O_2$ consumption by yeast lees, with Cu$^{2+}$ additions, serving as auto-oxidation catalysts, increasing this rate. Cell viability of yeast lees decreased faster in the presence of $O_2$, but it did not affect the release of amino acids. These reactions lead to ergosterol levels being reduced in the yeast cell walls, with the formation of 9(11)-dehydro-ergosterol, 5oc6oc-epoxy(22E)-ergosta-8,22-diene-3β-diol or ergosterol epoxidoxide (Salmon et al., 2000; Fornairon-Bonnefond & Salmon, 2003). Yeast has a stronger capacity for absorbing $O_2$ than polyphenols, in the same order as 9 g/L of polyphenols, which is higher than the polyphenol concentrations normally found in wine. However, yeast lees and polyphenols in combination had a much lower capacity of $O_2$ consumption than the theoretical sum of this capacity when tested alone. This is due to the capacity of the yeast lees being reduced drastically after contact with polyphenols. This is probably because of a collapse of cytoplasmic intermembrane space, which lowers the accessibility and reactivity of $O_2$ towards the sterols and unsaturated fatty acids of the membranes. The initial slight decrease and later increase in the capacity of the polyphenols could be due to adsorption on the lees yeast, with gradual release from the lees. The adsorption by the lees of polyphenols follows biphasic kinetics, with no preference for low or high polymeric-size tannins, although epigallocatechin units were adsorbed more by the yeast (Salmon et al., 2002; Mazauric & Salmon, 2005). Therefore yeast lees plays a very important role in the reduction/oxidative potential of wine.

During red wine production the effective mixture of skins with the must is required for extraction of anthocyanin and tannins from the skins. Pre-fermentative $O_2$ addition to red must during skin contact resulted in lower concentrations of red pigments, anthocyanins, caftaric acid and total phenols. The concentrations of total tannins and anthocyanins after six months’ storage were 1220 and 192 mg/L, respectively, in the control, compared to 679 and 150 mg/L in the must, to which most O2 was added. Wines made from the treated musts had more aged characteristics, such as more polymerised colour and a higher colour hue (Castellari et al., 1998). Pumping over in comparison to punch down and rotor tanks may also lead to lower extraction of polyphenols (Marais, 2003), although this could be due purely to this being a softer extraction technique, as Italian researchers did not find any significant difference in polyphenol concentrations after O2 addition during fermentation. It is not known how much O2 is taken up by the yeast, reacts with polyphenols, or simply evaporates with the CO$2$ during a red wine fermentation. More research on this is clearly necessary.

The addition of O2 during fermentation has also been found to affect the subsequent malolactic fermentation. Aeration led to a hundred-fold lower level of lactic acid bacteria than in the anaerobic control after alcohol fermentation, but the former lactic acid bacteria numbers increased more rapidly to 10$^8$ cfu/mL, compared to 10$^4$ cfu/mL in the anaerobic treatment. In the aerated treatment where no temperature control was induced during alcoholic fermentation malic acid was consumed the fastest. This could be ascribed to differences in alcohol levels after fermentation (12 and 13% for the aerobic and anaerobic treatments, respectively) that led to different cell counts (Reguant et al., 2005). Such a significant difference in alcohol levels is uncommon because high concentrations of O2 should be sparged off during fermentation by the resulting CO2 release. Oxygen during malolactic fermentation can also influence the sensory characteristics of wine, especially in Chardonnay where diacetyl contributes to the typical buttery aroma of these wines. Oxygen enhances the conversion of a-acetolactate to diacetyl, with 12 mg/L being produced under semi-aerobic conditions compared to 2 mg/L under anaerobic conditions, however, this was consumed again by the bacteria. Cell growth, malic and citric acid degradation did, however, differ significantly between the semi-aerobic and anaerobic conditions. Limited exposure to air during malolactic fermentation could thus enhance diacetyl production, but this should be followed by SO$2$ addition and filtration to avoid subsequent consumption by yeast and lactic acid bacteria (Nielsen & Richelieu, 2000; Bartowsky & Henschke, 2004). The general effect of O2 on lactic acid bacteria during commercial winemaking is, however, not well understood and should be investigated further.

Effect of oxygen during ageing of wine

Effect of oxygen on white wine colour

The colour of white wine is an important quality parameter. The colour of a young white wine normally has a slight yellow or greenish tint, with white wine that has been aged in barrels achieving a deeper yellow. A brown colour is normally unwanted because this indicates oxidation in white table wine. Brown colour is normally measured at 420 nm in white wine. As previously discussed, brown colouration can be induced by enzymatic oxidation. These enzymes are however normally not very active in wine because their precipitation during alcoholic fermentation occurs and alcohol inhibition of these enzymes takes place in wine. Hence, browning in white wine is a chemical process that is slower than enzymatic-induced oxidation. Browning in white wine can be due to three mechanisms. The first is the oxidation of phenolic molecules to their corresponding quinones, in varying degrees of polymerisation, producing a yellow-brown colouration. This oxidation reaction is influenced by the copper and iron concentrations. The second mechanism is the oxidation of tartaric acid to glyoxylic acid, which leads to the condensation of phenolic molecules due to the glyoxylic acid acting as a bridge between phenolic molecules. Varying degrees of polymerisation of the latter can also contribute to the yellow-brown spectrum. Acetaldehyde, produced during coupled oxidation or fermentation, can also enhance the yellow colour by inducing the condensation of phenolic molecules (Es-Safi et al., 1999c; Lopez-Toldano et al., 2004; Monagas et al, 2005).

The chemical mechanisms involved in the oxidation of phenolic molecules to quinones have been discussed earlier, and only those involved in the oxidation of white wine per se will be mentioned. The main phenolic molecules occurring in white wine that do not receive extensive skin contact or are not aged in oak barrels are the hydroxycinnamic acid derivatives. However, caftaric, coumaric, ferulic and caffeic acid do not seem to play a major role in the browning of white wine because there is little correlation

between their concentrations in white wine and susceptibility to browning. A good correlation does however exist between flavanols and browning sensitivity, especially with (+)-catechin, (-)-epicatechin and dimeric procyanidins B1-B4. The hydroxycinnamic acids may, however, contribute to the browning by being involved in coupled oxidation reactions with these flavanols, as discussed earlier (Simpson, 1982; Fernández-Zurbano et al., 1995). Flavanols also differ in their sensitivity to oxidative degradation. Jorgensen et al. (2004) found that skin procyanidins degraded faster than those from seeds, with flavan-3-ol monomers slowing the degradation of seed procyanidins. After 21 h of oxidation under mildly basic conditions, skin procyanidins, seed procyanidins alone, and seed procyanidins with the added monomers declined to 11.8%, 25.1% and 28.2% respectively. This was also reflected in the rate of degradation of these three substrates. The degradation rates of individual subunits also differ, with (-)-epigallocatechin being degraded faster than (-)-epicatechin. The former constitutes the major part of skin procyanidins, which explains the faster degradation of the skin fraction. It is clear that winemaking techniques that influence the procyanidin concentration in wine also affect sensitivity to browning. The pressing method, skin contact, skin contact time, pasteurisation of the juice and cultivar affect the procyanidin concentration of grape juice. Elvira and Chardonnay were found to have high concentrations of catechins and Seyval and Niagara to have high procyanidin concentrations, especially of B1 and B2 (Fuleki & Ricardo-da-Silva, 2003).

The second pathway of browning, relatively recently described, is that induced by the oxidation of tartaric acid, which yields glyoxylic acid. This acts as a bridging mechanism between flavanol molecules. The oxidation takes place in the presence of catechin and either Fe$^{3+}$ or Cu$^{2+}$. The resulting colourless or yellow products absorb at a maximum between 440 and 460 nm. In these reactions (-)-catechin reacts with glyoxylic acid to produce a (+)-catechin/glyoxylic acid adduct, which reacts with a further (+)-catechin molecule to form a carboxymethine-linked (+)-catechin dimer. This carboxymethine bridge can form between C8-C8, C8-C6 or C6-C6 of the (+)-catechin units. Dehydration of the dimers forms xanthene salts. These salts have a yellow colour and a maximum absorption at 460 and 440 nm for the esterified and non-esterified salts, respectively. Copper and Fe$^{3+}$ catalyse this reaction. Copper enhances the condensation reaction between (+)-catechin and glyoxylic acid and/or the reaction of a (+)-catechin with the (+)-catechin/glyoxylic acid adduct. However, the acid moiety of glyoxylic acid seems crucial for this reaction because Cu$^{2+}$ did not enhance the acetaldehyde induced addition when it was used instead of glyoxylic acid. Iron probably exerts the same type of mechanism. In many wine countries tartaric acid can be added to wine as an acid supplement and it can contain trace amounts of glyoxylic acid, which can influence the colour of white wine in the presence of especially higher concentrations of Cu$^{2+}$ (Es-Safi et al., 2000; Clark et al., 2003; Monagas et al., 2005).

The oxidation of a phenolic molecule produces H$_2$O$_2$, which in turn oxidises ethanol to form acetaldehyde. This can also be produced by yeast during alcoholic fermentation. Acetaldehyde can form ethyl bridges between two (+)-catechin molecules, with carboxymethine-bridged dimers being formed due to the oxidation of tartaric acid, as mentioned earlier. This reaction takes place faster in the case of (-)-epicatechin than with (+)-catechin when each is added alone with acetaldehyde. The degradation product of (+)-catechin has a more reddish hue than (-)-epicatechin. When the two flavanols occur together, (-)-epicatechin also disappears faster than (+)-catechin, with both homo- and heterogeneous ethyl-linked oligomers being formed. The reaction is also faster at lower pH levels, due to more acetaldehyde carboxylation, but the faster reaction of (-)-epicatechin compared to (+)-catechin is enhanced by a pH increase (Es-Safi et al., 1999b; Lopez-Toledano et al., 2002a). Glyoxylic acid or acetaldehyde can be protonated to form an electrophilic C-C+ carboxylation (R1), which undergoes a nucleophilic attack by the C6 or C8 of (+)-catechin to form the corresponding benzylic alcohol (Fig 2). Subsequent protonation, with the loss of H$_2$O, leads to an electrophilic benzylic carboxylation being formed, which can undergo nucleophilic attack from (+)-catechin to form a dimer. This leads to C6-C6, C6-C8 or C8-C8 interactions between two (+)-catechin molecules, with the latter forming at the highest concentrations and the C6-C6 forming at very low concentrations, probably due to steric hindrance. Drinkine et al. (2005) investigated the effect of adding glyoxylic acid and acetaldehyde to (+)-catechin. They found that glyoxylic acid alone led to a three times faster disappearance of (+)-catechin than acetaldehyde alone (t1/2= 2.3+/-0.2 h for glyoxylic acid and t1/2= 6.7+/-0.2 h for acetaldehyde). This was due to structural differences, with glyoxylic acid having both an aldehyde and carboxylic acid group, which has some conjugation associated with its structure, leading to higher aldehyde polarisability. Acetaldehyde, with aldehyde and methyl functional groups, has no conjugation, which thus favours the faster reactions R1 and R2 in glyoxylic acid. However, the rate of the dimer formation was similar, implying that the reaction rate of R3 and R4 is faster with acetaldehyde. For R3(G), as indicated in Fig. 2, the intramolecular hydrogen bonds between the carboxyl functional group and the -OH group of the benzylic alcohol may not favour its protonation and dehydration. The same applies to the carboxyl group and the -OH group of C7, which may hinder nucleophilic addition of the second (+)-catechin. When mixed together, ethyl-bridged dimers appeared and disappeared sooner than carboxymethine-bridged dimers. Polymerisation proceeded further, up to tetramer units, with polymers containing both ethyl and carboxymethine-bridges (Saucier et al., 1997; Drinkine et al. 2005). These reactions were, however, executed in the absence of metal catalysts, which would have induced the formation of xanthyllium salts. The brown colour also increased linearly with an increase in polymerisation (Lopez-Toledano et al., 2004). These interactions between acetaldehyde and glyoxylic acid might influence the colour, state of polymerisation of flavanoids, and ultimately the taste of wine, and they should be investigated further.

An interesting observation made by Bonilla et al. (2001) is that yeast reduces the brown colour of oxidised white wine. The brown colour of an oxidised white wine was reduced with a higher yeast dosage (ranging from 1.5 g/L), which was compatible to PVPP or activated charcoal fining. HPLC analysis revealed that vanillic, syringic, coumaric acids, and especially flavan-3-ol derivatives, were significantly reduced by the yeast addition. Yeast prevents the degradation of (-)-epicatechin and (+)-catechin, exhibiting a stronger inhibition of the degradation of the latter com-
The formation of dimers from glyoxylic acid and acetaldehyde (Drinkine et al., 2005).

This explains the prevention of brown colouration of sherry with flor yeast. The yeast prevents flavanol degradation rather than protecting the wine from air, by growing on its surface. An increase in polymerisation leads to the resulting oxidative degradation product absorbing more in the brown spectrum. Yeast also seems to prefer association with the browner, more polymerised flavanols, compared to monomeric flavanols. This is reflected in 7.7, 36.4, 53.7 and 64.6% of the (+)-catechin, dimer, trimer and oligomers, respectively, being removed by the yeast in a model solution. The yeast thus seems to have a preference for these compounds, which absorb in the yellow/brown spectrum, with the cell walls being the active absorbing area. These reactions proceed very slowly under the acidic conditions in wine and probably play more of a role in browning if the wine contains higher levels of flavanols, and after it has been racked from the yeast lees (Bonilla et al., 2001; Lopez-Toledano et al., 2002b; Lopez-Toledano et al., 2004). The addition of yeast at lower concentrations also improved the aroma of the oxidised wine.
Pinking of certain white wines remains a problem in the wine industry. This happens when wine is made reductively, i.e. when O₂ is kept to a large degree from coming into contact with it by use of inert gases, such as N₂ and CO₂. These wines can then become pink when exposed to small amounts of air, often during bottling, and will become brown when further exposed to O₂ later. Although only aesthetically unacceptable, these bottled wines often have to be opened and treated. Possible compounds responsible for pinking have not been identified but are thought to be phenolic chromophore compounds. Wines made from Sauvignon blanc, Albarino, Garnatxa blanc and Verdejo have been found to be pinking sensitive, although this did not happen in successive vintage years. An assay in which H₂O₂ is added to wine has been developed to test for potential pinking. PVPP alone, PVPP plus bentonite, and PVPP plus ascorbic acid were found to be 74%, 90% and 98% effective, respectively, in reducing tendencies of pinking. These combinations are equally effective in removing already developed pinking. Ascorbic acid alone was also found to be effective in preventing pinking, but new evidence suggests that it can enhance the formation of brown colouration under certain circumstances (Simpson, 1977; Lamuela-Raventó et al, 2001).

Ascorbic acid can also serve as a substrate for oxidation in wine. In the past this anti-oxidant has been used in many wineries for this purpose, especially in white wine, due to its O₂-scavenging ability. The products of ascorbic acid oxidation, dehydro-ascorbic acid and H₂O₂, necessitate the use of SO₂ in combination with ascorbic acid in order to prevent further oxidation by H₂O₂. In recent years evidence has accumulated showing that ascorbic acid can be a pro-oxidant rather than an anti-oxidant in wines under certain conditions, with white wine becoming browner when an air headspace is left in combination with ascorbic acid. Also, sulphur dioxide does not seem to minimise this browning effect (Peng et al, 1998; Bradshaw et al, 2001). When Bradshaw et al (2001 & 2003) oxidised ascorbic acid alone, two phases were observed. The first was the complete oxidation of ascorbic acid, with species being generated that absorb in the visible spectra. The second generated species with a lighter colour, or no colour. They also found that ascorbic acid enhanced the extent of browning in a model wine solution containing (+)-catechin. The onset of browning was, however, first preceded by a ‘lag phase’ when a decrease in browning was observed in comparison with the control containing no ascorbic acid. Pre-oxidised ascorbic acid did not exhibit this lag phase, but O₂ is required only for the initiation of the oxidation of ascorbic acid, with higher concentrations of initial O₂ shortening the lag phase. Higher concentrations of ascorbic acid enhanced the brown colour observed (0.06 for 1000 mg/L and 0.015 for 500 mg/L at 440nm), as well as extending the lag phase and time to reach maximum brown colour. Oxidation of tartaric acid yields glyoxylic acid, generating a colourless xanthene species, which can undergo oxidation to form coloured xanthylum salts. The effective anti-oxidant activity of ascorbic acid initially prevents formation of the coloured xanthylum salts, explaining the initial decrease in colour during the lag phase. As mentioned previously, H₂O₂ is one of the oxidation products of ascorbic acid, but yields were only 21%, as one would expect from a 1:1 production ratio from ascorbic acid. Furthermore, the addition of H₂O₂ to the model solution did not elicit the same extent of browning as ascorbic acid, suggesting that other oxidation products induce the browning. Other oxidation products of ascorbic acid under wine conditions include acetaldehyde, diketo-L-gulonic acid, L-threonine, oxalic acid, L-threo-2-pentulosonic acid, 4,5,5,6-tetrahydro-2,3-diketohexanoic acid and furfural. Dehydroascorbic acid is one of the initial oxidation products. After depletion of ascorbic acid during oxidation its oxidation products can then accelerate the formation of the coloured xanthylum salts, explaining the rapid increase in colour during this period. These oxidation products are not oxidative enough to elicit this in the presence of ascorbic acid. This ‘cross over’ of ascorbic acid as anti-oxidant to pro-oxidant thus depends on the concentration present.

Addition of SO₂ increases the lag phase mentioned above. A decrease was seen in the absence SO₂, the absence of ascorbic acid and formation of the brown xanthylum salts. At an ascorbic acid to SO₂ molar ratio of 0.8:1 the SO₂ increased the lag period to four days, but with a considerable loss in the SO₂ concentration; there was a 100% loss in the SO₂, ascorbic acid, (+)-catechin combination, compared to a 43% loss when the ascorbic acid was omitted. Increasing the SO₂ to a 3:1 ratio inhibited this over the 14-day time period of the evaluation. This ratio, which is 200 mg/L for ascorbic acid and SO₂ in the presence of 100 mg/L (+)-catechine, is quite high in winemaking terms. The ratio of SO₂ consumed to ascorbic acid was 1.7:1, which is higher than the expected 1:1. This is even more surprising considering that the oxidation of ascorbic acid yields only 21% of the expected H₂O₂.

Sulphur dioxide seems to bleach the coloured xanthylum salt, but does not, contrary to popular belief, reduce dehydro-ascorbic acid back to ascorbic acid (Bradshaw et al, 2001; 2004). Flamini and Dalla Vedova (2003) found that Oenococcus oeni reduces glyoxal to glycolaldehyde, which has a 10 times higher browning capacity than ascorbic acid. In the light of these findings wine producers should reconsider the use of ascorbic acid during the wine production process. This is especially relevant for white wines that have higher concentrations of flavanoids and to which tartaric acid, possibly containing glyoxalic acid impurities, has been added. Ascorbic acid has been hailed as a replacement for SO₂, but when it is added to wine it necessitates higher SO₂ additions that can prevent it from turning into a pro-oxidant after exposure to O₂.

**Effect of oxygen on red wine colour**

Red wine obtains its colour from anthocyanins, which are normally extracted from the grape skins during the alcoholic fermentation. Different anthocyanins exist in grapes and wine, as mentioned earlier. The red colour can also be an indication of quality, with deep red wines normally judged as being of superior quality, depending on the other characteristics of the wine. In a young red wine up to 50% of anthocyanins can exist in the colourless carbinol pseudobase. During red wine ageing, the colour of red wine changes from red, in a young red wine, to mauve to brown/red, in the barrel, to eventually brown/orange after prolonged aging in the bottle (Ribèreau-Gayon et al, 2000b). Different chemical reactions induce these changes in colour. These are:

1. Direct anthocyanin-tannin condensation reactions (A-T product). These reactions take place between the nucleophilic C6 or C8 carbons of (+)-catechin, (-)-epicatechin or procyanidins and the electrophilic C4 carbon of the anthocyanin molecule.
The products are colourless flavenes, which can be oxidised to the corresponding flavylium ions, finally developing into yellow xanthylum salts. These reactions take place during fermentation, with subsequent racking from the yeast or lactic acid bacteria lees introducing O\(_2\). This increases the wine’s colour density when the flavene is oxidised (Liao et al., 1992; Santos-Buelga et al., 1999; Ribereau-Gayon et al., 2000).

2. Electrophilic carbocations, formed from procyanidins in a low pH medium such as wine, can react with nucleophilic C6 or C8 carbons of the anthocyanin in its hydrated hemiacetal form (T-A product). The products are colourless, but are rapidly dehydrated into a reddish-orange form. This reaction is stimulated by higher temperatures, and O\(_2\) is not required. It occurs predominantly during bottle ageing. Although the addition of oligomeric procyanidins with the anthocyanins in both A-T and T-A products seems to occur more in wine than anthocyanin polymer additions do, A-T and T-A polymers of up to octamers have been detected (Remy et al., 2000; Ribereau-Gayon et al., 2000b; Hayaska and Kennedy, 2003).

3. Vinyl phenols, normally associated with *Brettanomyces* spoilage, can also associate with anthocyanins. This is due to an electrophilic cyclo-addition of the ethylenic bond of the 4-vinylphenol molecule with the C4 and C5 carbons of the anthocyanin, with subsequent oxidation leading to the formation of a pyrane ring. In aged Pinotage wines the pigment Pinotin A has been discovered. This is formed between the anthocyanin and a hydroxycinnamic acid moiety, especially caffeic acid in Pinotage, with oxidation leading to its formation. Anthocyanin-vinylcatechin products have also been identified, which possibly form from the reaction between a flavylum ion and a catechin molecule with a vinyl group on its C8 carbon, with oxidation leading to pigments having a red-orange colour. These molecules are also more resistant to SO\(_2\) bleaching and pH changes, and they also contribute to the red to tawny change in colour of an older red wine. They can then act as a co-pigment, resulting in higher colour stability (Schwarz et al., 2003; Monagas et al., 2005).

4. The origin of acetaldehyde in wine has been discussed earlier. In wine, which is an acid medium, acetaldehyde can be carboxylated by the addition of a proton. This electrophilic moiety will then react with the C6 or C8 positions on a flavanol molecule, which, after the loss of H\(_2\)O, undergoes nucleophilic attack of the electrophilic C8 position of a colourless carbinol pseudobase anthocyanin molecule. The resulting product, with an ethyl bond, can be protonated to form a coloured compound. This reaction has been confirmed for malvidin-3-glucoside with different procyanidins, and evidence suggests that the same reaction takes place with cyanidin, delphinidin, peonidin and petunidin (Alcâde-Eon et al., 2004; Monagas et al., 2005). (+)-Catechin, (-)-epicatechin and epigallocatechin have all been shown to react in this way with malvidin-3-monoglucoside. Trimers and tetrameric pigments have been identified, but only position C8 of the anthocyanin molecule can be involved in this reaction, with the polymerisation ceasing when the anthocyanin forms the two terminal products of the chain. However, recent evidence suggests that the C6 position of the anthocyanin can also be reactive, as anthocyanins in the absence of flavanols formed dimers, trimers and tetramers via ethyl bonds with each other when acetaldehyde was added (Es-Safi et al., 1999a; Atanosova et al., 2002b). This reaction, which is faster than the previous two, takes place during barrel ageing when controlled oxygenation takes place. Oxygen can come into contact with the wine at this stage through wine-making actions, such as racking or topping up barrels. Oxygen also permeates through the staves of the barrel, with tight-grain oak wood allowing higher O\(_2\) concentrations in the wine. Anthocyanins involved in these polymerisation reactions are less prone to SO\(_2\) bleaching and colour changes due to pH changes. The bisulphite ion, which decolourises the anthocyanin molecule, cannot associate that easily with the polymerisation product due to stearic hindrance. In model solutions containing (+)-catechin, malvidin-3-glucoside, glyoxylic acid and the colourless (+)-catechin dimer, with a carboxymethylene bridge in coloured carboxymethylene-bridged dimers, resulted, although model solutions containing the anthocyanin, (+)-catechin, tartaric acid and ethanol yielded only the flavanol dimer. Clearly, additional research is needed to evaluate the contribution of this to the changes observed in the evolution of red wine colour during ageing (Santos-Buelga et al., 1999; Monagas et al., 2005).

During barrel ageing, the colour intensity (the sum of the brown, red and violet colours) increases. In South African Pinotage and Shiraz wines it was found that the origin of the barrel (American, French or Russian) did not affect the difference in colour intensity, colour hue or total red pigments. The colour density increased from 8-10 to 12-16 between 3-6 months after barrelling. Such a difference in colour density can be observed visually. During this time period the total red pigments decreased, but the percentage of pigments in the red form increased from 15 to 45%. A drop in free and total anthocyanins was thus observed, with the concentration of anthocyanins dropping from about 850 mg/L to 400 mg/L within six months. This transformation of colourless anthocyanins into the coloured form compensates for their loss and leads to the increase in colour density. Oxygen does not seem to influence the total concentration of pigment colour, but does increase the proportion in the red form, as well as increase pigments resistant to SO\(_2\) bleaching (Atanosova et al., 2002a; Fourie, 2005). Colour density can also decrease during ageing in a steel tank over a few months, but O\(_2\) addition prevents this. The storage of red wine in non-aerated vats also leads to lower concentrations of coloured anthocyanins. Temperature plays a very important role in these reactions, as high storage temperature in combination with high O\(_2\) concentration can lead to anthocyanin and tannin breakdown reactions, which can increase the yellow hue of the wine. The oxygen addition should be done in a controlled manner, and not in excessive amounts, because this can lead to excess acetaldehyde formation, excessive polymerisation and precipitation of colour matter. A favourable tannin to anthocyanin ratio is apparently also required, namely in the order of 4:1. Too low a ratio may lead to anthocyanin breakdown reactions and too high a ratio to over-polymerisation and precipitation. These ratios need to be investigated further, under different wine-making conditions (Singleton, 1987; Ribereau-Gayon et al., 2000b; Atanosova et al., 2002a). During oak ageing, ellagitannins, such as vescalagin and castalagin, are extracted from the wood. Vivas and Glories (1996a) and
Vivas (1999a) found that when these tannins oxidise, due to their greater oxidising capacity, they produce larger amounts of acetaldehyde than condensed tannins. This leads to higher levels of polymerisation, which induces tannin-anthocyanin polymerisation, leading to higher colour density. This does not happen in all red wines, and tannin addition can lead to certain wines becoming too astringent. These tannins also seem to buffer catechins from oxidation, by being oxidised themselves, and thus preventing formation of a brick-yellow colour. In these experiments the ellagic tannins were, however, added at 300 to 1000 mg/L to the model solution or wine, and it is not certain if they will react during oak ageing to the same degree because they were isolated at only a few mg/L from oak-aged wines. More of these tannins could probably end up in the wine during ageing because they are easily hydrolysed (Puech et al., 1999). In our own laboratory we found that exposure of a young red wine to O₂ per se had a larger influence on colour development than the addition of commercial tannins according to the supplier’s recommendations (unpublished data).

**Effect of oxygen on red wine taste**

Different phenolic molecules are involved with the bitterness, astringency and fullness of red wine, but it is mainly the flavanols that are responsible for these tastes and flavours. A very young red wine might be harsh, course, very astringent and even bitter. During ageing of red wine in barrels the wine becomes softer and less astringent. The different methods of polymerisation of (+)-catechin and (-)-epicatechin were discussed in the previous section under white wine oxidation, and basically the same reaction mechanisms occur for these compounds in red wine. Polymerisation leads to these molecules becoming less reactive towards mouth proteins, with the wine being perceived as less astringent (Nikfardjam & Dykes, 2003). During ageing, it is mainly the acetaldehyde-induced polymerisation that contributes to the polymerisation of flavanols. The resulting products are not as reactive towards proteins as their constituents. However, direct C4-C8 and C4-C6 polymerisation reactions between procyanidin molecules produce products that are more reactive towards proteins and are hence more astringent than those formed from acetaldehyde-induced condensation reactions. In the case of flavanols, where the C6 and C8 positions can be occupied, polymers larger than trimers have been isolated. Both types of reactions produce procyanidins with a limit of 8 or 10 flavan units. The interaction of anthocyanin molecules with procyanidins can also influence the taste of wine because they can form the terminal subunits, thus preventing further polymerisation (Ribereau-Gayon et al., 2000b; Monagas et al., 2005).

**Effect of oxygen on wine aroma**

The addition of O₂ to white wine is normally undesirable. Even small additions of O₂ to white wine can lead to loss of aroma, especially fruitiness, although the quality of some white wines may increase with a little O₂ contact. Periodical O₂ addition has led to decreasing fruitiness and general quality, with a correlating increase in oxidation character in Sauvignon blanc and Chardonnay wines. In the Sauvignon blanc however, low initial concentrations of O₂ actually enhanced the quality score, by contributing to the complexity of the wine. The addition of H₂O₂ to a neutral Chenin blanc spiced with 2-methoxy-3-isobutylpyrazine did not lead to degradation of this important flavour compound of Sauvignon blanc over a three-month period (Marais, 1998). It thus seems that this compound is resistant to oxidative degradation in wine. At high O₂ additions the formation of unwanted off-flavours will take place, with oxidised white wines being described as caramel, overripe fruit, crushed apple, acetaldehyde, woody, rancid, farm-feed, honey-like and cooked vegetables (Escudero et al., 2002; Silva Ferreira et al., 2003b). After ten O₂ saturations white table wine normally becomes completely brown and maderised, and aromatic degradation can occur before it can be identified by colour change (Singleton et al., 1979; Boulton et al., 1996; Silva Ferreira et al., 2003a).

Simpson (1978) reported on the effect of O₂ addition and enhanced ageing at 50°C for 28 days on the composition of Riesling. The concentrations of ethyl n-hexanoate, hexyl acetate, acetic acid, ethyl n-octanoate, vitispirane, 1-hexanol, ethyl furonate and ethyl lactate did not differ significantly between the treatments. Benzaldehyde, diethyl succinate and 1,1,6-trimethyl-1,2-dihydropthalene (TDN), however, increased from 0, 3,8, 0.066 mg/L to 0.18, 4.4 and 0.09 mg/L, respectively. The concentration of 2-phenylethanol was however lower in the oxidised wine. Enhanced ageing under anaerobic conditions increased ethyl n-octanoate, vitispirane, ethyl furonate, ethyl n-decanoate, TDN and 2-phenethanol concentrations. Marais et al. (1992) found that TDN, trans-vitispirane, 2,6-dimethyl-7-octen-2,6-diol and trans-1,8-terpin concentrations, and the intensity of the bottle-aged kerosene-like character, increased significantly with ageing in Weisser Riesling wines. However, decreases were observed in diiodiol-1, linalool, isomyl acetate, ethyl caproate, hexyl acetate, 2-phenethyl acetate, hexanol, 2-phenyl ethanol, and in the intensity of young wine character, with higher storage temperatures accelerating these changes. This study clearly showed that lower storage temperatures (15°C) were more favourable for the sensory development of Weisser Riesling wines during ageing.

Ferreira et al. (1998) developed a GC-MS method to simultaneously measure compounds in oxidised wine, including t-2-hexenol, t-2-octenal, t-2-nonenal, furfural, 5-methyl-furfural, hexenal, benzaldehyde, furfural and eugenol. In subsequent studies phenylacetaldehyde, TDN, 3-hydroxy-4,5-dimethyl-2(5H)-furanone (sotolon), methional (see Table 1) and other compounds were also isolated from oxidised white wines. The cooked vegetable aroma could especially be predicted from the t-2-nonenal, eugenol, benzaldehyde and furfural concentrations. The honey-like and boiled potato aromas could be predicted from the phenylacetaldehyde and methional concentrations. The woody aroma of oxidised wines, even in those that did not receive any wood contact, could be attributed to an increase in eugenol. Surprisingly, acetaldehyde did not seem to play a role in oxidised white wine aroma because its concentration did not vary significantly during the oxidation process, but other unidentified compounds probably influenced the aroma (Escudero et al., 2002; Silva Ferreira et al., 2002).

The oxidative aroma formation of white wine is dependent on several parameters, which include: O₂ concentration, pH, storage conditions, SO₂ concentration, phenolic composition and ascorbic acid concentration. The floral aroma of white wine seems to degrade faster at higher temperatures, with O₂ additions, and with lower pH values increasing this trend. Sulphur dioxide additions decrease this degradation. At lower temperatures (15°C), however,
TABLE 1

Certain compounds isolated from oxidised white wine (Compiled from Simpson, 1978; Margalit, 1997; Silva Ferreira et al., 2002; Silva Ferreira et al., 2003a).

<table>
<thead>
<tr>
<th>Compound</th>
<th>Associated flavours</th>
<th>Concentration (ug/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furfural</td>
<td>Woody, cooked vegetables</td>
<td>90.2</td>
</tr>
<tr>
<td>t-2-nonenal</td>
<td>Cooked vegetables, woody</td>
<td>62.6</td>
</tr>
<tr>
<td>Eugenol</td>
<td>Cooked vegetables, woody</td>
<td>6.2</td>
</tr>
<tr>
<td>5-M-furfural</td>
<td>Woody</td>
<td>40.5</td>
</tr>
<tr>
<td>Benzaldehyde</td>
<td>Cooked vegetables, woody</td>
<td>165</td>
</tr>
<tr>
<td>Hexenal</td>
<td>Punent</td>
<td>62.3</td>
</tr>
<tr>
<td>Phenylacetaldehyde</td>
<td>Honey-like</td>
<td>80-120</td>
</tr>
<tr>
<td>Methional</td>
<td>Farm-feed</td>
<td>30-40</td>
</tr>
<tr>
<td>TDN</td>
<td>Spicy, kerosene-like</td>
<td>90</td>
</tr>
<tr>
<td>Vitispirane</td>
<td>Camphor, eucalyptus</td>
<td>360</td>
</tr>
</tbody>
</table>

The quinones generated can easily react with thiols from Simpson, 1978; Margalit, 1997; Silva Ferreira O2 greater decrease, with H2O2 also enhancing this decrease, compared to O2. The quinones generated can easily react with thiols according to a Michael addition reaction or generate H2O2, which can further oxidise 3-mercaptobenzoic acid. In a model solution containing (+)-catechin, the 3-mercaptobenzoic acid decreased from 1000 ng/L to 238 ng/L. When 30 g/L SO2 was added to the sample, the 3-mercatohexanol level fell to only 647 ng/L. Anthocyanins and SO2, as observed with 3-mercaptohexan-1-ol, seem to play a synergistic role in reducing the concentration of 3-mercaptobenzoic acid. It is thus clear that the transport of wine can also lead to the reduction of the concentration of these sulfur-containing compounds and that SO2 plays a critical role in protecting them from oxidation (Murat et al., 2003; Blanchard et al., 2004). The oxidative environment inside an oak barrel also stimulates the formation of sotolon, which forms due to the oxidation of threonine. The oxidative degradation of phenylalanine and b-phenylethanol in a barrel also leads to higher concentrations of phenylacetaldehyde, reminiscent of an old oak oxidation flavour (Jarauta et al., 2005). In a study conducted by Cerdan et al. (2004), the concentrations of ethyl butyrate and ethyl octanoate decreased in red wine during a period of 18 months in barrels, while those of ethyl hexanoate and ethyl decanoate increased. Du Toit (2006) found that in South African Pinotage wine excessive oxidation led to a decrease in the coffee aroma and banana aromas. This was also reflected in a decrease in the isoamyl acetate concentration, which imparts the banana character to Pinotage wines. Decreases of these compounds were also correlated with an increase in first a potato skin and later an acetaldehyde-like flavour. It is clear that the effect of O2 on the aroma composition of red wine should be investigated further.

Port sometimes acquires aromas reminiscent of truffles, quince or meats during ageing, which can be ascribed to dimethyl sulfide. This is due to the formation of this compound with oxidation, with low pH levels accentuating this phenomenon. Dimethyl sulfide follows the same pattern. Methional also decreases in concentration in the presence of O2, but no methionol is formed. Another off-flavour, 2-mercapto-ethanol, also decreased; it is oxidised to bis(2-hydroxyethyl) disulfide, which does not have an odour. This explains why older ports never have sulphur off-flavours associated with cauliflower (methionol), rubber/burnt (2-mercapto-ethanol) or cooked potato (methional) (Silva Ferreira et al., 2003c). Low pH and high storage temperature are two parameters that increase the formation of TDN in port during ageing, with O2 additions initially stimulating its formation. High O2 additions lead to its breakdown. Vitispirane, with a camphor or eucalyptus aroma, follows basically the same trend as the other parameters mentioned. Excessive O2 also leads to the degradation of 3-ionone and 3-damascone, which have a flavourful violet and ripe fruit aroma, respectively. The degradation of these molecules can be effectively prevented by the use of SO2, illustrating this preservative's anti-oxidative effect in even a product such as port, in which concentrations are normally kept low during ageing. Concentrations of SO2 that are too high can also lead to the degradation of P-damascone (Daniel et al., 2004; Silk Ferreira & De Pinho, 2004). Oxygen exposure in sweet fortified wines leads to the formation of sotolon and 5-(ethoxymethyl)-furfural that impart the characteristic aromas to mature sweet white and red wines, respectively. The presence of polyphenols in fortified red wines also leads to less oxidation of aroma compounds than in sweet white wines, due to the polyphenols' anti-oxidative characteristics and their capability to react with aldehydes (Cutzach et al., 1999).

Micro-oxygenation

Micro-oxygenation is the process whereby O2 is added to wine, by means of an apparatus, in a controlled manner. This is

achieved by filling a known volume with gas at a high pressure. The volume is then transferred via a low-pressure circuit to the diffuser and into the wine. The latter normally consists of a ceramic or stainless steel sparger that produces small bubbles that can dissolve in the wine. The aim of micro-oxygenation is to introduce O2 into the wine at a rate equal to or slightly less than the wine’s ability to consume that O2. It has to be managed in such a way that, after addition, all O2 has been used up, while sufficient SO2 is still left to protect the wine against oxidation. Different reasons for the application of micro-oxygenation are advocated by the producers of the apparatus. These include: higher colour density, decreases in astringency, sulphur off-odours, green, vegetative aromas, and production costs. Stainless steel tanks in conjunction with micro-oxygenation and alternative wood products can be used to simulate an oak barrel. Wine is also supposed to be market-ready sooner.

Oxygen can be supplied during different stages of the wine-making process. It can be supplied at 1-4 mg/L/day just after malolactic fermentation, especially to press wine fractions, which are rich in polyphenols. The stage at which micro-oxygenation is normally applied is during the ageing period, after malolactic fermentation, when between 1-6 mg/L/month is introduced into the wine (Parish et al., 2000; Sullivan, 2002). The wine’s temperature must be about 15°C because temperatures that are too high will lead to poor solubility of O2 and temperatures that are too low to possible accumulation of O2 in the headspace of the tank. Chemical reactions will also take place too slowly at low temperatures. With certain systems, which dose the O2 according to mL/L, a tank of at least 2.2 m is required for sufficient pressure on the sparger to operate correctly.

Ribéreau-Gayon et al. (2000b) reported on a wine of which the colour intensity increased from 0.82 to 1.67 OD units in 5 months during micro-oxygenation. Anthocyanins and tannins also decreased in concentration, with an increase in the HC1 index (polymerisation index), although a control receiving no O2 was not included in this report. Du Toit (2006) found that the colour density and SO2 resistant pigments increased in South African red wines when the micro-oxygenation treatment started just after the completion of malolactic fermentation, but this did not happen in wines where it started seven months after malolactic fermentation. Micro-oxygenation and the maturation of Pinotage wines matured in oak barrels also led to lower concentrations of catechin and the proanthocyanin B1 compared to the untreated control, with a corresponding increase in polymeric pigment and polymeric phenols. McCord (2003) found slight increases in the red and brown colour intensity of a Cabernet Sauvignon that received micro-oxygenation with a concurrent increase in polymerised anthocyanin level and a decrease in the free anthocyanin level in the wine that received O2 compared to the control. The decrease in anthocyanin level was also higher when oak was added to the wine, possibly due to ellagittannin-induced condensation. No conclusive results could be found concerning the effect of micro-oxygenation on oak compounds. The micro-oxygenation did, however, significantly reduce the unwanted sulphur compounds methyl and ethyl mercaptan to below their aroma threshold of 1 part per billion. Dimethyl sulphide concentration did not increase with micro-oxygenation.

The effect of micro-oxygenation on the taste of wine has not been fully elucidated. Wine receiving micro-oxygenation can apparently go through structuring and harmonisation phases. The former leads to the wine actually becoming more astringent and harsh and can last from one to six months. During the subsequent harmonisation phase a decrease in astringency is observed, with the wine becoming more complex, although this has not been fully scientifically elucidated. This is then the ideal time to terminate the micro-oxygenation because over-oxidation might lead to a mean degree of polymerisation of procyanidins that is too high, with a resulting increase in bitterness and with tannins becoming too dry (Parish et al., 2000; Nikfardjam & Dykes, 2003). Micro-oxygenation also leads to vegetative, green wines becoming fruitier (Sullivan, 2002). Du Toit (2006) found that a tasting panel statistically preferred micro-oxygenation-treated wines compared to the control in younger red wines, but in older red wines it should be applied with care as prolonged treatment led to the wine becoming over-aged, with an increase in the barnyard/medicinal character, which corresponded with an increase in Brettanomyces counts. Micro-oxygenation also led to higher acetic acid bacteria counts, although no increase in volatile acidity was observed in these wines. Taste, however, is still the main parameter by which to measure the progression of micro-oxygenation, but since it is a subjective procedure, it should be supplemented with other techniques. Oxygen can also be introduced by a sparger into barrels, which introduces higher concentrations into the wine. This can lead to savings on racking costs (Vivas, 1999b). It is clear that additional research is needed on micro-oxygenation because little has been published on this process. This is probably due to the relatively large volumes needed for adequate research on micro-oxygenation.

Effect of O2 on acetic acid bacteria and Brettanomyces

Acetic acid bacteria are Gram (+), catalase negative aerobic micro-organisms that occur in wine. They are notorious for wine spoilage due to the conversion of ethanol to acetic acid, which leads to acidification of the wine and an increase in the volatile acidity. Ethanol is transformed into acetaldehyde and the latter to acetic acid by alcohol dehydrogenase and acetaldehyde dehydrogenase, respectively. Low O2 concentrations lead to the inhibition of acetaldehyde dehydrogenase, resulting in acetaldehyde accumulation in the wine. Gluconobacter oxydans normally dominates on healthy grapes, with Acetobacter aceti and A. pasteurianus dominating in wine. Recently, there is renewed interest in the metabolism and survival of acetic acid bacteria in wine, due to the fact that they survive under the relative anaerobic conditions often found in wine. Acetic acid bacteria have been isolated in high numbers from fermenting must and have been proven to be able to cause sluggish alcoholic fermentation (Du Toit & Lambrechts, 2002; Du Toit & Pretorius, 2002). The transfer and racking of wine after alcoholic fermentation and during ageing introduces O2 into the wine, that can lead to a 10-102 cfu/mL increase in acetic acid bacteria numbers. A 30-40-fold increase in acetic acid bacteria numbers was also noticed after the introduction of 7.5 mg/L O2. Drysdale and Fleet (1989) found rapid growth of A. pasteurianus and A. aceti from 107 to 109 cells/mL in wine that was saturated with O2. At 70% saturation, cell counts increased to 108-109 cells/mL, with 50% saturation contributing to the survival of the strains. Du Toit et al. (2005) found that acetic acid bacteria go into a viable, but non-culturable state in wine, especially under limited O2 conditions. This can be negat-
ed by the addition of O2, with plate and epifluorescence microscopy counts being the same after aeration. The O2 permeating through oak staves during maturation probably also supports the survival of acetic acid bacteria in wine. Certain acetic acid bacteria strains also seem to be resistant to high concentrations of SO2.

Brettanomyces are yeast able to spoil wine by production of 4-vinylphenol and 4-vinylguaiacol by the enzyme cinnamate decarboxylase from p-coumaric and p-ferulic acids, respectively. The vinyl groups can then be further reduced to 4-ethyl phenol and 4-ethyl guaiacol by vinyl phenol reductase. These volatile phenols have flavours reminiscent of horse sweat, farmland and medicine. At lower concentrations they can contribute to the complexity of the wine, but become unwanted at excessive concentrations. Brettanomyces have been found to survive especially in oak barrels, probably due to the b-glycosidase activity these microorganisms have, that can release some glucose from the oak for their growth. Oxygen has been found to contribute to the rapid growth of Brettanomyces in wine. Oxygen also stimulates the growth of Brettanomyces in must and induces acetic acid production. Faster production of 4-ethylphenol in the presence of O2 has been observed, correlating with cell growth in red wine. The addition of SO2, however, rapidly kills off Brettanomyces cells, with a 45-min exposure of cells to 0.64 mg/L molecular SO2 being sufficient to achieve this. Brettanomyces also seem to be more sensitive to SO2 than acetic acid bacteria, with only 0.25 mg/L molecular SO2 inducing rapid cell death in certain strains. Bound SO2 does not seem to affect Brettanomyces (Ciani & Ferraro, 1997; Du Toit et al., 2005).

The effect that winemaking practices such as micro-oxygenation have on acetic acid bacteria and Brettanomyces numbers should be investigated. It is clear that the wine producer should avoid O2 pickup and use SO2 effectively when suspecting possible infection with either acetic acid bacteria or Brettanomyces.

Role of oxygen in bottled wine

Oxygen pick-up during bottling

The final step in the winemaking process is that of bottling. During this process the wine must be transferred into the bottles with minimum exposure to micro-organisms and O2. The choice of bottles as a storage container is probably due to the inert characteristics of glass and it not being permeable to air. Before bottling, the wine should also be in the right state. This includes protein, temperature and SO2 stability as well as a low dissolved O2 level (below 0.5 mg/L, but ideally close to 0.3 mg/L). White wine especially should be transferred into the pre-bottling tank under an inert gas. Nitrogen or argon gas can be used, with the latter having a higher specific gravity. Pipes and the filler also need to be filled with an inert gas before bottling starts. The headspace in tanks that is not completely full must be replaced with an inert gas (Allen, 1994). During the bottling process the filler should ideally not add much more than 1 mg/L of O2 to the wine, but this can go up to 3 mg/L. During filling, a vacuum is often drawn inside the bottles, the wine flows inside and the headspace is filled with CO2 (Lewis, 1991, Vivas & Glories, 1996b).

Oxygen diffusion as influenced by the bottle closure

The type of closure can play a critical role during the ageing of wine. Oxidative spoilage of bottled wine has been observed in both white and red wines. Corks differ in their permeability to air. Initial studies indicate that compounds within the cork are responsible for this phenomenon (Waters et al., 1996; Caloghirits et al., 1997). In an in-depth investigation, Godden et al. (2001) looked at the performance of a screw cap, two natural corks, two technical corks and nine synthetic corks used to bottle the same Semillon wine. The wines bottled with the screw cap retained the most SO2 and exhibited the least browning over the 20-months ageing period. Compared to this, the SO2 loss was highest with most of the synthetic corks, intermediate with the natural corks and least evident with the technical corks. Sulphur dioxide concentrations actually decreased from 7 and 61 mg/L free and total for a synthetic closure, compared to 20 and 84 mg/L and 24 and 90 mg/L for a technical cork and the screw cap, respectively, after six months bottle ageing. This was also reflected in the colour of the wines, with wines closed with synthetic corks generally becoming browner sooner. These wines also had an oxidised aroma and lost a high percentage of fruity character. The wine bottled with the screw cap however developed a higher reduced aroma, reminiscent of struck flint or rubber after 36 months, compared with the other treatments. At this stage, only the screw cap and cork based products had an acceptable aroma (Francis et al., 2003).

Lopes et al. (2005) measured the amount of O2 permeating through different types of corks. Technical corks had very low O2 diffusion after the first month (1.4-2.8 mg/L). Natural corks had rates between 2.3 and 3.8 mg/L and artificial corks 3.6-4.3 mg/L in the first month, respectively. The diffusion rates then dropped, with technical corks having between 0.01 and 0.10 mg/L O2 diffusion per month after the first month. Natural corks had 0.24-0.5 mg/L O2 diffusion/month and synthetic corks 0.85-1.5 mg/L O2 diffusion/month during this period. Synthetic corks do not absorb wine as cork based products do, which probably contributes to the sealing capability of the latter. The exact method of O2 diffusion into the bottles is unknown, but it could be that O2 inside the corks initially permeates into the wine, with atmospheric O2 permeating later. This may explain the high initial rate of O2 diffusion in the first month. The large variability observed between natural corks might also explain the random oxidation phenomena of individual bottles. The way bottles are stored also influences air diffusion, with upright bottles, especially those sealed with agglomerated cork stoppers, permitting more O2 to come into contact with the wine (Godden et al., 2001; Mas et al., 2002; Lopes et al., 2005).

Measuring and evolution of oxidation or redox potential in wine

The measurement of O2 in wine can be conducted with an O2 meter. It consists of two electrodes with a membrane permeable to O2. The O2 causes a change in potential between the two electrodes that can be measured. The oxidation-reduction potential of wine can also be measured with a similar electrode. The potential is especially influenced by the O2 concentration, metals, ethanol, phenolic compounds, type of container and temperature, with glycerol having little effect. Winemaking operations, especially those that introduce O2 such as racking, topping up of barrels, filtration and tannin addition also influence this. The effect of different winemaking operations on this potential can be seen in Fig. 3. It is clear that during alcoholic fermentation the potential drops due to the reductive conditions. It increases again with O2 pickup.
Oxygen in must and wine

at racking after malolactic fermentation and racking of the wine (Vivas & Glories, 1996b; Ribèreau-Gayon et al., 2000b).

The progression of oxidation can be measured, especially in white wine, with a spectrophotometer. Absorption at 420 nm measures the brown spectrum of light and can serve as an indicator of oxidation. However, aromatic degradation can occur before it can be identified, by an intense yellow-brown colour (Silva Ferreira et al., 2003b). Other methods of measuring oxidation in wine should thus be developed. This is especially true for red wines, where a colour change is even less indicative of oxidation than in white wines. Du Toit (2006) found that Fourier-transform infrared spectroscopy could distinguish between oxidised and control Pinotage wines, and should be investigated further as a possible means by which to follow oxidation in red wines.

CONCLUSIONS

It is clear that O2 can play an important role during the winemaking process. The main substrates for oxidation in wine are phenolic compounds, but other compounds such as ascorbic acid and tartaric acid can also be oxidised. These oxidation reactions produce quinones, acetaldehyde, H2O2, glyoxylic acid, etc., which can induce polymerisation reactions in the wine. Oxygen can be introduced by the winemaker into the must, during fermentation, and especially during ageing of red wine, to induce favourable chemical changes in the wine. This should be done with care however, as different off-flavours can also be produced in the wine when too high O2 concentrations are introduced. There are still many aspects regarding the reactions of O2 in wine that remain unknown. These include the effect of O2 on red wine aroma and sensory development, and should be investigated in the future.

LITERATURE CITED


FIGURE 3

Evolution of the oxidation-reduction potential of a red wine during the production process. AF: alcoholic fermentation, MLF: malolactic fermentation (Ribèreau-Gayon et al., 2000a).


Oxygen in must and wine


