Extraction, Evolution, and Sensory Impact of Phenolic Compounds During Red Wine Maceration

L. Federico Casassa[1,2] and James F. Harbertson[2,*]

[1]Wine Research Center, Estación Experimental Agropecuaria Mendoza, Instituto Nacional de Tecnología Agropecuaria (INTA), Luján de Cuyo, 5507 Mendoza, Argentina

[2]School of Food Science, Irrigated Agriculture Research and Extension Center, Washington State University, Prosser, Washington 99350-8694; email: jfharbertson@wsu.edu

Annu. Rev. Food Sci. Technol. 2014. 5:83–109

First published online as a Review in Advance on January 9, 2014

The *Annual Review of Food Science and Technology* is online at http://food.annualreviews.org

This article's doi:
10.1146/annurev-food-030713-092438

*Corresponding author

Keywords

red wine production, anthocyanins, proanthocyanidins, polymeric pigments, color, mouthfeel

Abstract

We review the extraction into wine and evolution of major phenolic classes of sensory relevance. We present a historical background to highlight that previously established aspects of phenolic extraction and retention into red wine are still subjects of much research. We argue that management of the maceration length is one of the most determining factors in defining the proportion and chemical fate of phenolic compounds in wine. The extraction of anthocyanins, flavonols, flavan-3-ols, and oligomeric and polymeric proanthocyanidins (PAs) is discussed in the context of their individual extraction patterns but also with regard to their interaction with other wine components. The same approach is followed to present the sensory implications of phenolic and phenolic-derived compounds in wine. Overall, we conclude that the chemical diversity of phenolic compounds in grapes is further enhanced as soon as vacuolar and pulp components are released upon crushing, adding a variety of new sensory dimensions to the already present chemical diversity. Polymeric pigments formed by the covalent reaction of anthocyanin and PAs are good candidates to explain some of the observed sensory changes in the color, taste, and mouthfeel attributes of red wines during maceration and aging.

1. INTRODUCTION

Among the variables inherent to the maceration process in red winemaking, the management of the amount of contact time that is allowed between the seeds, skins, and stems (when present) and the fermenting must and wine is arguably the most critical factor for defining the phenolic profile and sensory properties of the resulting wine (Berg & Akiyoshi 1956, 1958; Ough & Amerine 1961a,b; Meyer & Hernández 1970; Sipiora & Gutiérrez-Granda 1998; Yokotsuka et al. 2000; Vrhovsek et al. 2002; Zimman et al. 2002; Romero-Cascales et al. 2005; Kelebek et al. 2006; Puertas et al. 2008; Busse-Valverde et al. 2012; Gil et al. 2012; González-Neves et al. 2012; Casassa et al. 2013a,b). Herein lays the major focus of this review. On the basis of collation of historical and current studies on the topic of phenolic extraction during maceration, it is argued that the control of maceration length is the most easily adjustable variable to manage phenolic extraction into wine from seed and skin tissues. The maceration process in itself also plays a critical role in defining the chemical fate and sensory properties of phenolic and phenolic-derived compounds in red wines.

After a short historical perspective, the remainder of this review covers current knowledge on the impact of specific phenolic compounds, by category (**Figure 1**), on wine during maceration.

Due to their relevance to this review, only phenolics of the flavonoid class and some of their reaction products, namely anthocyanins, anthocyanin-derived pigments, flavonols, flavan-3-ols, PAs, and polymeric pigments are discussed (**Figure 1**). The extraction, evolution during winemaking, and main sensory properties of these compounds are discussed as primarily affected by the maceration length. **Figure 2** presents an overview of the extraction of major phenolic classes, color saturation, and polymeric pigments in Cabernet Sauvignon wines during maceration and bottle aging.

2. HISTORICAL BACKGROUND

The first observations pertaining to the extraction of phenolic compounds during red wine maceration are probably attributable to Eugene W. Hilgard, who noted in 1887 that the maximum extraction of color is attained before that of tannins and that maximum color extraction occurred earlier at higher temperatures (Hilgard 1887). During the next 60 years, a significant number of studies characterized the chemical features and reactivity of the most relevant phenolic compounds in plants and food-derived products. However, it was not until 1956 that studies resumed focusing on the extraction of phenolics and color into wine. Berg & Akiyoshi (1956, p. 89), upon analyzing red wine fermentations of Cabernet Sauvignon, Petite Syrah, and Zinfandel for a period of 100 h post-crushing, noted that "the tannin content of the juice is proportional to the contact time of juice with pomace during fermentation. However, the color density reaches a maximum well before the completion of fermentation." Fermentation variables such as ethanol, temperature, SO_2 concentration, and frequency of pump-overs (the operation of pumping the wine up from the bottom of the tank and splashing it over the top of the fermenting must) were then studied in a series of experiments by Ough & Amerine (1961a; 1961b, p. 128), who concluded that "time to press for red varieties will have some effects on color and quality of wine, dependent on the variety in question." Succinctly summarized, maceration length has the predominant effect on the wine's perceived qualities, but the grape cultivar's distinct chemical makeup also impacts what is extracted and ultimately perceived.

Subsequently, the influence of seeds during maceration as determinants not only of the tannin content but also of the evolution of color and astringency was recognized by Vernon Singleton and Diana Draper in their work "The transfer of polyphenolic compounds from grape seeds into wines" (Singleton & Draper 1964). One of the concluding remarks of this pioneering study

was that "the complete extraction of tannin of the grape's seeds into wine would give tannin contents of about 0.2–0.4%. Under the usual conditions of red wine fermentation it is estimated that an amount sufficient for about half of this concentration should be extracted from the seeds" (Singleton & Draper 1964, p. 40). The concept conveyed by the authors is clear: Although the seeds have normally sufficient amount of tannins, standard red wine macerations should be set to extract only a portion of this amount. Singleton & Draper's paper conveys, arguably for the first time, the concept of selective and controlled extraction of phenolics from the grape solids.

In 1979, Nagel & Wulf used high-performance liquid chromatography (HPLC) coupled with detection at 530 nm to study the evolution of anthocyanins during maceration up to 240 days post-crushing during the production of Merlot and Cabernet Sauvignon wines (Nagel & Wulf 1979). Their study appears to be the first to follow 16 monomeric anthocyanins, including monoglucosides and acetyl- and coumaroyl derivatives during wine aging. The authors concluded that "anthocyanin concentration increased to a maximum by the third day [of maceration] and decreased thereafter such that by day 240 post-crush less than 10% of the original amount remained" (Nagel & Wulf 1979, p. 111). Moreover, the authors noted "a large number of compounds absorbing at 280 nm, some of which are undoubtedly flavonols, but have not yet been identified" (Nagel & Wulf 1979, p. 111). Implicit in their conclusion was that the sometimes dramatic loss of monomeric anthocyanins during maceration and aging occurs along with the formation of new products, some of which, as noted by the authors, have absorbance at 280 nm.

Thereafter, a body of studies, including those of Émile Peynaud (1984), Roger Boulton and colleagues (Boulton et al. 1996), and Pascal Ribéreau-Gayon and colleagues (Ribéreau-Gayon et al. 1998), concluded that red wines' main sensory features are set during maceration,[1] and it is during this stage that the relative proportions of anthocyanins, proanthocyanidins (PAs),[2] and other phenols should be adjusted by means of their selective (and sometimes incomplete, as noted by Singleton & Draper 1964) extractions. Several complex variables arise at this stage of winemaking, some attributable to the chemical makeup of the grapes (e.g., cultivar, growing conditions, maturity), whereas others are intrinsic to the maceration process itself. As noted by E. Hilgard in 1887, different phenolic classes are extracted and undergo chemical modifications at specific rates; these rates, however, can be modified to a certain extent by means of selected maceration conditions (Hilgard 1887).

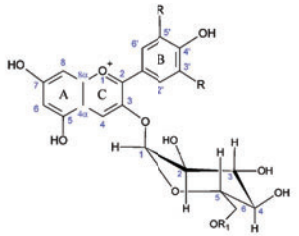
3. ANTHOCYANINS AND FORMATION OF ANTHOCYANIN-DERIVED PIGMENTS

Anthocyanins appear in vivo as C3-heterosides whose aglycone or anthocyanidin is derived from the 2-phenylbenzopyrilium or flavylium cation; the anthocyanidin, together with the glycosyl moiety, is referred to as anthocyanin. Of the 23 anthocyanidins reported in vascular plants (Kong et al. 2003, Andersen & Jordheim 2006), only six have been found in *Vitis vinifera* L. grapes and their wines: pelargonidin, cyanidin, peonidin, delphinidin, petunidin, and malvidin (Cheynier 2006, Castillo-Muñoz et al. 2009, He et al. 2010; see also **Figure 1**). For most *V. vinifera* cultivars, malvidin-3-glucoside is the prevalent anthocyanin, and in grapes malvidin derivatives can represent from 39 to 72% of the total anthocyanin profile (Baldi et al. 1995, Castellarin et al. 2006, Cortell et al. 2007, Downey & Rochfort 2008, Manfra et al. 2011). On the basis of a molar extinction coefficient (ε) of 28,000 M^{-1} cm^{-1} (0.1 N aqueous HCl solution) for malvidin-3-glucoside

[1]The term maceration is heretofore referred indistinctly as skin contact time or maceration.

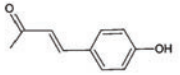
[2]The terms proanthocyanidins and tannins are considered synonyms and thus are used interchangeably in this review.

Anthocyanins

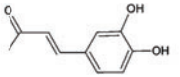


R_1 =

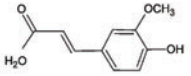
-acetyl



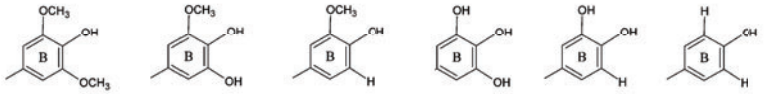
-*p*-courmaroyl



-caffeoyl

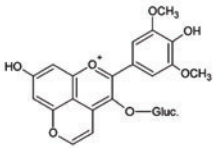


-ferulic

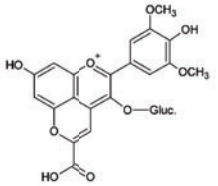


malvidin | petunidin | peonidin | delphinidin | cyanidin | pelargonidin

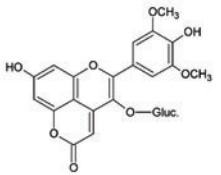
Anthocyanin-derived pigments



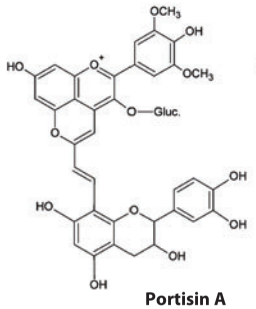
Vitisin B



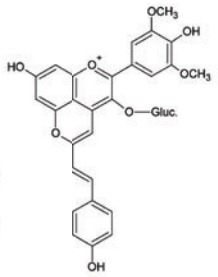
Vitisin A



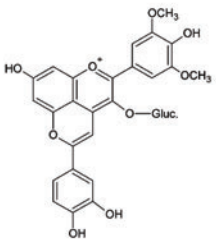
Oxovitisin A



Portisin A

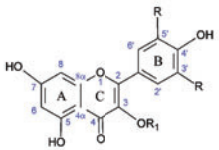


Portisin B

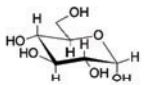


Pinotin A

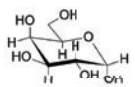
Flavonols



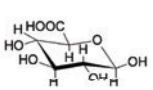
R_1 =



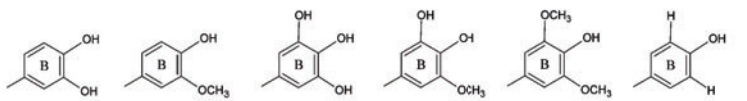
–glucose



–galactose

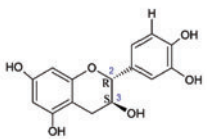


–glucuronic acid

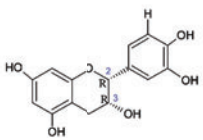


quercetin | isorhamnetin | myricetin | laricitrin | syringetin | kaempferol

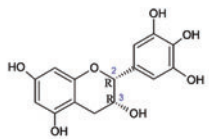
Flavan-3-ols



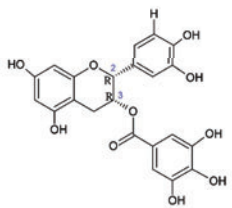
(+)-catechin



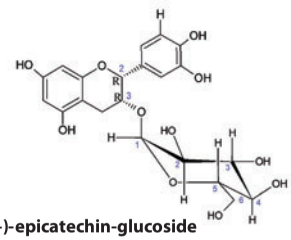
(–)-epicatechin



(–)-epigallocatechin



(–)-epicatechin-3-*O*-gallate



(–)-epicatechin-glucoside

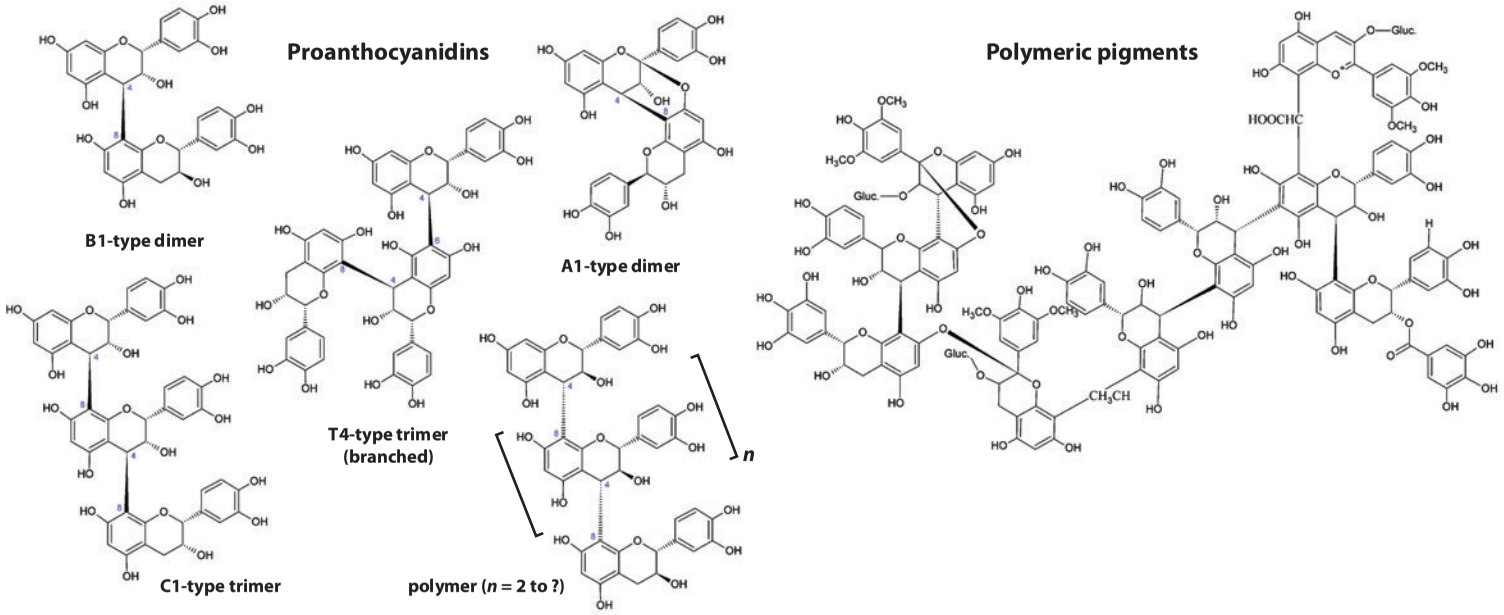


Figure 1

Overview of representative chemical structures of the phenolic classes covered.

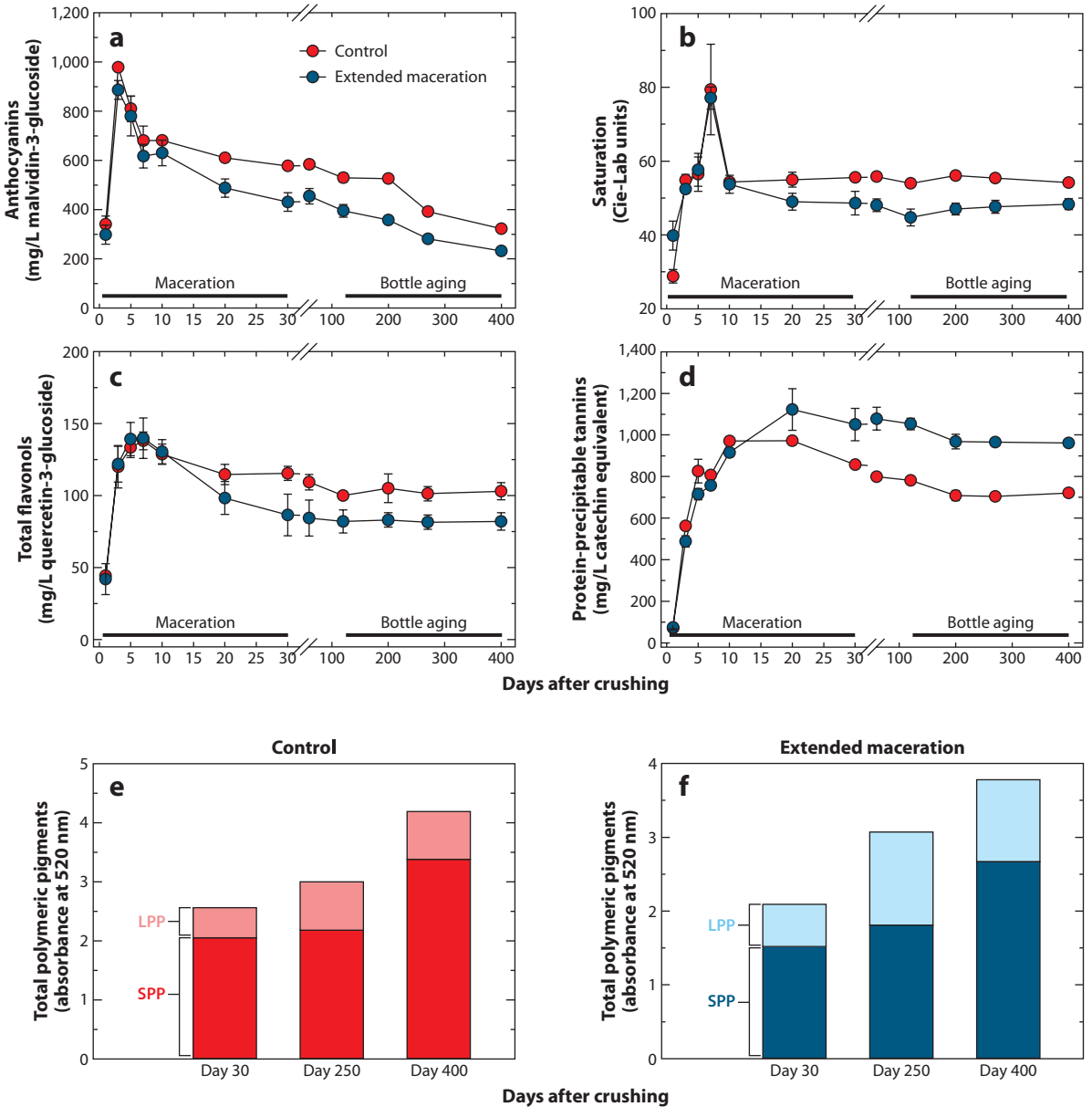


Figure 2

Overview of the extraction of phenolics, wine color saturation, and polymeric pigments during maceration and bottle aging of Cabernet Sauvignon wines processed with a maceration length of 10 days (control) and 30 days (extended maceration). (*a*) Anthocyanins, (*b*) saturation as measured by the Cie-Lab system, (*c*) total flavonols, (*d*) protein-precipitable tannins, (*e*) small (SPP) and large (LPP) polymeric pigments in control wines, and (*f*) SPP and LPP in extended maceration wines. In the extraction plots, each point represents the average and the standard error of the mean of two independent tank replicates. Adapted from Casassa et al. (2013b).

(Niketic-Aleksic & Hrazdina 1972), anthocyanins represent the most important forms exhibiting chromatic properties in red wines (Harbertson & Spayd 2006).

In *V. vinifera* and its hybrids, anthocyanins appear in the epidermal and first subepidermal cells of the skin tissue as free, noncomplexed spherical vacuolar inclusions of 10 to 15 μm in diameter (Moskowitz & Hrazdina 1981, Mizuno et al. 2006). Due to their vacuolar location, the diffusion of anthocyanins into the must requires the concerted breakdown of two biological barriers, namely the cell wall, including the degradation of the pectic substances in the middle lamella, and the tonoplast (Amrani-Joutei et al. 1994). Normal operations during crushing ensure the breakdown of cell walls, and native enzymatic reactions allow for the degradation of pectic substances and polysaccharides in the middle lamella. The diffusion process is favored by the water-soluble nature of anthocyanins, resulting in a peak of extraction within the third to fifth day of maceration (Nagel & Wulf 1979, Somers & Evans 1979, Gil-Muñoz et al. 1999, Gómez-Míguez & Heredia 2004, Canals et al. 2005, Gómez-Plaza et al. 2005, Aron & Kennedy 2007, Harbertson et al. 2009, Casassa et al. 2013a), as can be seen in **Figure 2*a***. Following the peak of anthocyanin extraction, a variable drop in concentration, which can be as high as 60% from the peak concentration, is typically observed (Nagel & Wulf 1979; Cheynier et al. 2006; Harbertson et al. 2009; Casassa et al. 2013a,b). The loss of anthocyanins during the latter stages of maceration has been attributed to a variety of factors, including ionic adsorption by the negatively charged yeast cell wall and yeast lees[3] during post-maceration (Vasserot et al. 1997, Mazauric & Salmon 2005, Medina et al. 2005), adsorption onto bitartrate crystals (Cheynier et al. 2006) and particulate matter (Somers & Evans 1979), incorporation into polymeric pigments (Adams et al. 2004, Harbertson et al. 2009), formation of pyranoanthocyanins (Medina et al. 2005, Rentzsch et al. 2007), and oxidative cleavage of the heterocyclic C ring leading to direct anthocyanin degradation (Morel-Salmi et al. 2006, Lopes et al. 2007). A decrease in copigmentation as a result of an increasing concentration of ethanol in the fermenting must (which increases the hydrophobic character of the medium thereby disrupting the copigmentation complex) also contributes to both the loss of anthocyanins and a decrease in perceived color (Haslam 1998, Boulton 2001, Hermosín-Gutiérrez 2003). Interestingly, longer maceration times (>20 days) appear to accentuate the above factors. At the end of maceration, the amount of anthocyanins recovered in the wine relative to the initial grape content has been reported to vary between 21 and 45% (Cheynier 2006, Casassa et al. 2013a).

As implied above, there is a clear negative relationship between maceration length and anthocyanins retained in the resulting wine (Scudamore-Smith et al. 1990; Sipiora & Gutiérrez-Granda 1998; Vrhovsek et al. 2002; Kelebek et al. 2006; Harbertson et al. 2009; González-Neves et al. 2012; Casassa et al. 2013a,b), and the same relationship seems to apply to wine color saturation (**Figure 2*a*,*b***, respectively). This observation has led to the hypothesis that a portion of the anthocyanin mass may be readsorbed onto the skins and other fermentation solids during prolonged maceration. However, anthocyanins recovered in pomace samples (i.e., skins and seeds) analyzed after extended maceration hardly increased the recovery yield (Cheynier 2006, Casassa et al. 2013a). This suggests that many of the anthocyanins are irreversibly adsorbed on fermentation solids other than skin and seed pomace (e.g., yeast lees) and/or converted to other phenolic species, particularly during extended maceration (Yokotsuka et al. 2000, Casassa et al. 2013a). Enhanced formation of polymeric pigments has been confirmed in wines undergoing extended maceration (Sipiora & Gutiérrez-Granda 1998, Harbertson et al. 2009, González-Neves et al. 2012, Casassa

[3]Yeast lees consist of deposits of dead yeast cells that flocculate to the bottom of the fermentation tank toward the end of alcoholic fermentation.

et al. 2013a). Polymeric pigments resulting from the reaction of monomeric anthocyanins and oligomeric and polymeric PAs are discussed in Section 7.1 of this review.

Anthocyanins are chemically reactive pigments at wine pH (3.4 to 3.9), and upon crushing and afterward during aging they can readily react with a variety of electrophiles and nucleophiles. These include other monomeric anthocyanins (Vidal et al. 2004b, Salas et al. 2005, Alcalde-Eón et al. 2007), flavan-3-ols via direct condensation (Dueñas et al. 2006) or via an acetaldehyde bridge (Timberlake & Bridle 1976, Rivas-Gonzalo et al. 1995, Es-Safi et al. 1999), dimeric or trimeric PAs (Remy et al. 2000, Salas et al. 2003), lactic acid (Alcalde-Eón et al. 2006), glyceraldehyde (Laurie & Waterhouse 2006a,b), acetaldehyde (Bakker & Timberlake 1997, Wang et al. 2003, Oliveira et al. 2009, De Freitas & Mateus 2010), pyruvic acid (Fulcrand et al. 1998, Mateus et al. 2001, Schwarz et al. 2003, Wang et al. 2003), and glyoxylic acid (Fulcrand et al. 1997, Es-Safi et al. 2000b). Anthocyanins also react covalently with numerous other aldehydes, such as furfural, 5-hydroxy-methyl-furfural (contributed by oak barrels), isovaleraldehyde, benzaldehyde, propionaldehyde, isobutyraldehyde, formaldehyde, and 2-methyl-butyraldehyde (Es-Safi et al. 2000a, Pissara et al. 2003, Cheynier 2006). Aldehydes are formed from either the metabolism of *Saccharomyces cerevisiae* during alcoholic fermentation (Asenstorfer et al. 2003, Morata et al. 2003, Monagas et al. 2007) or via the metal-catalyzed oxidation of several wine substrates, including ethanol, glycerol, tartaric acid, and malic acid (Danilewicz 2003, Waterhouse & Laurie 2006, Danilewicz et al. 2008, Elias et al. 2008). These anthocyanin-derived products, some of them generically known as pyranoanthocyanins, also include pigmented structures that have been recently elucidated, such as the vitisins (A and B), portisins (A and B), oxovitisins and pinotins (**Figure 1**).

The anthocyanin-derived products have different spectral features than those of the native anthocyanins; as such, they invariably lead to changes in perceived wine color. Because the formation of these reaction products starts as soon as the grapes are crushed, it is usually during maceration and post-maceration that the most noticeable changes in wine color saturation and hue take place. Ultimately, these reactions, together with the formation of oligomeric and polymeric pigments, account for the evolution of wine color: from deep purple, due to both the presence of monomeric anthocyanins and the occurrence of self-association copigmentation reactions in young wines, to orange, brick-red tones in aged wines, due to the formation of anthocyanin-derived and polymeric pigments.

In addition to their direct impact on color, anthocyanins are also involved in the modulation of astringency. Isolated anthocyanins are tasteless or indistinctly flavored (Singleton & Noble 1976, Vidal et al. 2004a); however, upon reaction with oligomeric or polymeric PAs during winemaking, polymeric pigments are formed, and these can in turn modulate astringency, a concept further elaborated in Section 7.1.

4. FLAVONOLS

In *V. vinifera* grapes and their wines, flavonols exist primarily as 3-glycosides (and less commonly as 3-galactosides and 3-glucuronides) of six aglycones: myricetin, quercetin, kaempferol laricitrin, syringetin, and isorhamnetin (Castillo-Muñoz et al. 2007, Flamini & Traldi 2010; see also **Figure 1**). Due to the diverse combination of glycosidic forms, up to 21 different flavonols have been reported in wines (Monagas et al. 2005, Castillo-Muñoz et al. 2009). Quercetin-3-glucoside, quercetin-3-glucuronide, and myricetin are the most abundant flavonols in both grapes and their wines (Price et al. 1995, Downey et al. 2003, Castillo-Muñoz et al. 2007, Jeffery et al. 2008). From a spectral standpoint, flavonols are yellow pigments, as they strongly absorb light in the visible 325-to-400-nm range (Price et al. 1995, Waterhouse 2002, Castillo-Muñoz et al. 2009).

Flavonols in the glycosidic form are co-located with the anthocyanins in the skin vacuoles of the subepidermal cells (Cheynier & Rigaud 1986). However, free flavonol aglycones are also detected in wines due to the hydrolysis of the glycosidic bond by native enzymes or acidic conditions that release the flavonol's aglycones (Burns et al. 2001, Castillo-Muñoz et al. 2007, Jeffery et al. 2008). Whereas the glycosylated flavonols are partially water-soluble and more soluble in ethanolic wine, the flavonol aglycones are poorly soluble in wine (Jeffery et al. 2008).

Flavonols are extracted following extraction patterns similar to that observed for anthocyanins; however, because of the comparatively lower polarity of the flavonol backbone, their extraction progresses more slowly under standard winemaking conditions (Burns et al. 2001, Morel-Salmi et al. 2006, Gambuti et al. 2009) (**Figure 2*c***). In Merlot and Cabernet Sauvignon grapes, overall extraction efficiencies of flavonols into their respective wines ranged from 50 to 60%, with concentrations remaining steady (in the range of 30 to 80 μM) up to the seventh day of maceration, but increasing from 70 μM up to 213 μM after 9 days of skin contact (Burns et al. 2001). Similar extraction patterns of total flavonols up to day 8 of maceration were reported in a separate study of Cabernet Sauvignon wines, but by day 10, the extraction curves showed an overall decrease of 32% from the peak of extraction for different winemaking treatments, including cold soak and postfermentative heat treatment at 42°C (Koyama et al. 2007). In another study with the cultivars Grenache, Mourvèdre, and Carignan processed with a technology known as flash-release, an early release of flavonols was observed during maceration at day 2 after crushing.[4] In the final wines, reported concentrations of flavonols were between 13 and 36 mg/L for control wines (not treated with flash-release) and between 27 and 68 mg/L in the flash-treated wines (Morel-Salmi et al. 2006). Overall, these studies suggest that flavonols are extracted progressively during the first 5 to 7 days of maceration under standard conditions, and enhanced extraction occurs after 8 or 9 days or when the skin vacuoles are disorganized via specific treatments such as flash-release or thermovinification. From this point onward, acid-catalyzed hydrolysis of the glycoside portion of the molecule leads to the release of the unstable flavonol aglycones, which will be most likely lost by precipitation in the ethanolic medium (**Figure 2*c***).

In addition to their inherent chromatic properties as yellow pigments, flavonols also influence the taste and tactile sensations of the wine. Both quercetin-3-glycoside and its aglycone occur in red wines at concentrations considered of sensory significance, with the former having a reported suprathreshold concentration above 30 mg/L (Gawel 1998). From a gustative standpoint, quercetin derivatives have been generally linked with the perception of bitterness in red wines. For example, as evaluated using an electronic tongue based on potentiometric sensors, quercetin-3-galactoside was found to be partially responsible for the perceived bitterness in a subset of 13 Pinotage wines deemed bitter by their producers (Rudnitskaya et al. 2010); however, no concentration thresholds were provided. Similarly, in a study in which fractionation of Tempranillo wines by semipreparative HPLC on a C18 column was followed by sensory analysis (sip-and-spit procedure), bitterness perception was linked to the presence of quercetin and myricetin glycosides in the bitter fractions (Sáenz-Navajas et al. 2010). From the perspective of tactile and mouthfeel perceptions, syringetin-3-glucoside and quercetin-3-rutinoside were found to participate in the sensation of "velvety astringency" in Italian Amarone red wine (Hufnagel & Hofmann 2008a,b). In terms of their effects on perceived color, quercetin-3-glucoside and its aglycone can be involved in intermolecular copigmentation reactions with the flavylium or quinoidal forms of the anthocyanins, thus causing

[4]Flash-release, also known as flash détente, is a winemaking technology that consists of heating previously crushed grapes quickly at high temperatures (>95°C) with vapor at atmospheric pressure and then placing them under a strong vacuum that causes instant vaporization.

the observed bathochromic and hyperchromic shifts in perceived color typical of young red wines (Boulton 2001).

5. FLAVAN-3-OLS

In *V. vinifera* grapes and their wines, flavan-3-ols appear as four monomeric units: (+)-catechin, (−)-epicatechin, (+)-epigallocatechin, and (−)-epicatechin-3-*O*-gallate (Su & Singleton 1969, Czochanska et al. 1980, Wu et al. 2005). Recently, moreover, the glycosyl derivatives of these same four monomeric units have also been found in Merlot seeds and wines at trace amounts (Delcambre and Saucier 2012; see also **Figure 1**). Flavan-3-ols occur both in grape seeds and skins but the four flavan-3-ol units are distributed differently within the berry tissues. Seeds contain (+)-catechin, (−)-epicatechin, and (−)-epicatechin-3-*O*-gallate (Su & Singleton 1969, Prieur et al. 1994), whereas skins additionally contain (−)-epigallocatechin (Escribano-Bailón et al. 1995) and only trace amounts of (−)-epicatechin-3-*O*-gallate and (−)-epigallocatechin-3-*O*-gallate (Souquet et al. 1996). In the skins, flavan-3-ols are located in the inner thick-walled cells of the hypodermis (Adams 2006). Due to the water-soluble nature of the flavan-3-ols, the release of these compounds from the skins occurs within the first 2 or 3 days of maceration (Sun et al. 1999; González-Manzano et al. 2004, 2006; Morel-Salmi et al. 2006; Aron & Kennedy 2007; Koyama et al. 2007; Gambuti et al. 2009). For example, (+)-catechin and (−)-epicatechin after 5 days of maceration represented between 80 and 85% of the maximum content attained later at pressing in control wines and wines obtained using flash-release, respectively (Morel-Salmi et al. 2006). In another report, release of total flavan-3-ols (catechin + galloylated monomers) occurred between day 3 and day 5 of maceration and remained unchanged during a post-maceration period of 7 days following alcoholic fermentation (González-Manzano et al. 2006). In this same study, (−)-epigallocatechin, exclusive of skins, was extracted rapidly, which allowed the authors to propose that the early extraction of PAs during the first days of maceration is the result of the preferential extraction of flavan-3-ols and small oligomers from skins (González-Manzano et al. 2006).

In the seeds, flavan-3-ols are located in thin-walled cells between the external hydrophobic cuticle and the inner lignified layers. Seeds contain the vast majority of the berry's flavan-3-ols. For example, Cabernet Sauvignon seeds bear up to 96% of the berry flavan-3-ol content on a fresh weight basis (Guerrero et al. 2009). Relative to the skins, the release of flavan-3-ols from the seeds requires longer maceration times. In Cabernet Sauvignon wines, a study found that a concentration of flavan-3-ols close to 40 mg/L was attained only after 10 days of maceration, consistent with the onset of extraction from the seeds (Koyama et al. 2007). Likewise, maximum extraction of flavan-3-ols from seeds (white cv. Viura) occurred after 2 to 3 weeks of maceration in model wines (González-Manzano et al. 2004). Under those conditions, the seeds contributed almost 90% of the total flavan-3-ol content of the final wines. Also, in model wines containing only seeds of the cultivar Monastrel, the concentration of (+)-catechin plus (−)-epicatechin increased from 5 mg/L at day 2 up to 27 mg/L at day 10 (Hernández-Jiménez et al. 2012). This represents a slower rate of extraction relative to that of the flavan-3-ols from skins. Moreover, longer maceration times seem to favor the extraction of epicatechin-3-*O*-gallate from seeds. Accordingly, the percentage contribution of galloylated subunits has been reported to increase along with maceration length (González-Manzano et al. 2006, del Llaudy et al. 2008, Gil et al. 2012, Hernández-Jiménez et al. 2012, Casassa et al. 2013b). The proportion of epicatechin-3-*O*-gallate relative to that of catechin, epicatechin, and epigallocatechin on the wine PA composition has been proposed as an indicator of extraction of seed tannins and thus of the application

of extended maceration (Spranger et al. 2004; González-Manzano et al. 2006; Gil et al. 2012; Casassa et al. 2013a,b).

Flavan-3-ols are well-known bitterants (i.e., compounds known to elicit bitterness) in many food products, including apples, apricots, sour cherries, tea, and cider (Macheix et al. 1990, Yaminishi 1990). Moreover, the chiral difference between the two main flavan-3-ols found in *V. vinifera* berries plays a role in the temporal perception of bitterness: (−)-epicatechin is significantly more bitter and has a significantly longer duration of bitterness than (+)-catechin (Robichaud & Noble 1990, Noble 1994, Thorngate & Noble 1995, Kallithraka et al. 1997a, Peleg et al. 1999). The more planar conformation of the C ring of (−)-epicatechin compared with the less planar (+)-catechin may increase the lipophilic character of the molecule, thus facilitating the diffusion and its attachment to the gustative receptor (Haslam 1982).

In wines, the influence of flavan-3-ols on the development of the bitterness sensation was recognized as early as 1966, when Rossi & Singleton isolated an ether-soluble fraction from grape seeds containing (+)-catechin, (−)-epicatechin, and (−)-epicatechin-3-*O*-gallate (Rossi & Singleton 1966, Su & Singleton 1969). Addition of this fraction at 200 mg/L to a white wine showed no contribution to astringency but significantly increased perceived bitterness. In a recent study in which the taste- and mouthfeel-active compounds of an Amarone della Valpolicella red wine were reconstituted in water adjusted to pH 3.8, the bitterness perception was primarily explained by subthreshold concentrations of catechin, epicatechin, and phenolic acid ethyl esters (Hufnagel & Hofmann 2008b). For catechin and epicatechin, reported taste threshold concentrations were 1,000 and 930 μmol/L, respectively (Hufnagel & Hofmann 2008b), which would be equivalent to 290 and 270 mg/L, respectively. Comparable concentrations of free flavan-3-ols have been reported recently in Cabernet Sauvignon wines (Casassa et al. 2013b).

Although the contribution of flavan-3-ols to bitterness is well established, their influence on astringency under wine matrix conditions remains to be explored. Indeed, in model wines, the astringency elicited by flavan-3-ols has been hypothesized to result from the precipitation of, or the strong binding with, proteins due to the presence of one of the 1,2-dihydroxy or 1,2,3-trihydroxy groups that can form hydrogen bonds with specific functional groups in the protein structure (McManus et al. 1981, Haslam 1998, Peleg et al. 1999). Specifically, (+)-catechin was found to induce higher turbidity upon reaction with salivary proline-rich proteins (PRPs) than (−)-epicatechin, implying a potentially higher astringent response of this monomer (De Freitas & Mateus 2001). Similarly, galloylation has been shown to facilitate the interaction of flavan-3-ols with various proteins, suggesting that substitution of the flavan-3-ol backbone with gallic acid may also enhance astringency (Ricardo da Silva et al. 1991, Cheynier et al. 1997, De Freitas & Mateus 2001, Vidal et al. 2003, Sun et al. 2013). This is because the galloyl ring in epicatechin-3-*O*-gallate and PAs containing this monomer provides a supplementary aromatic ring that may engage in hydrophobic interactions with the proline ring of the PRPs' structure, thus enhancing precipitation (Ricardo da Silva et al. 1991, Zhu et al. 1997, Charlton et al. 2002). Protein-induced precipitation of flavan-3-ols has been confirmed by peptide models of salivary PRPs, whereby these proteins were found to interact with flavan-3-ols having molecular weights below 500 g/mol (Charlton et al. 1996, Baxter et al. 1997). Further confirmation was reported in model wines evaluated using a time-intensity procedure in which both (+)-catechin and (−)-epicatechin, at concentrations of 1,538 and 900 mg/L, respectively, were found to elicit astringency (Kallithraka et al. 1997a, Peleg et al. 1999). Finally, Scollary et al. (2012), in interpreting a study from Pianet et al. (2008), argued that when flavan-3-ols are at high concentration (up to 1,200 mg/L), they may be capable of forming colloidal particles, which can readily interact with and precipitate salivary PRPs. Although current evidence using descriptive analysis and time-intensity procedures for astringency evaluation support the potential role of flavan-3-ols on the perception of astringency,

per the amounts of these monomers normally found in wines, their role in astringency is unlikely to be of sensory relevance. Potential synergistic in vivo effects of mixtures of flavan-3-ols with astringent oligomeric and polymeric PAs, such as they naturally occur in the red wine matrix, remain to be explored.

6. OLIGOMERIC AND POLYMERIC PROANTHOCYANIDINS

Wine PAs, also known as condensed tannins, encompass a heterogeneous family of oligomeric (degree of polymerization[5] 2 ≥ and <5) and polymeric (degree of polymerization ≥ 5) phenolic flavonoids, whose building blocks are the four monomeric flavan-3-ols described in Section 5 (Haslam 1998, Monagas et al. 2005, see also **Figure 1**). In wines, oligomeric and polymeric PAs are primarily responsible for the development of the astringent sensation that arises upon wine ingestion (Gawel 1998, McRae et al. 2013, Sun et al. 2013). Astringency is a tactile sensation that develops as a result of the interaction of PAs with PRPs found in the saliva of humans and other mammals (Mehansho et al. 1987, Jöbstl et al. 2004, Poncet-Legrand et al. 2007). This sensation appears as a feeling of puckeriness and dryness in the palate arising from the lack of lubrication of the oral epithelium (Bate-Smith 1973, Kallithraka et al. 2001, Bennick 2002). As such, astringency is a tactile sensation that is not confined to a particular region of the mouth but is a diffuse surface phenomenon, which takes time, typically 15–20 s, to develop fully (Breslin et al. 1993, Ishikawa & Noble 1995, Valentová et al. 2002). The physiological and molecular bases of astringency in red wines have been reviewed intensively during the past 15 years (Gawel 1998, Jöbstl et al. 2004, Lesschaeve & Noble 2005, Bajec & Pickering 2008, McRae & Kennedy 2011, Scollary et al. 2012). Some controversy has arisen regarding the gustative nature of the astringent sensation, as oligomeric PAs may be able to interact with gustatory receptors (Bajec & Pickering 2008). Furthermore, other taste stimuli such as acidity (e.g., elicited by malic and/or tartaric acid) have been shown to synergistically increase the time-intensity development of astringency in both model wines (Kallithraka et al. 1997b) and actual red wines (Demiglio & Pickering 2008, Hufnagel & Hofmann 2008b). Current evidence suggests that astringency is primarily a tactile sensation; however, for some astringent compounds, the sensation may be the result of both taste and tactile mechanisms working together (Bajec & Pickering 2008).

An empirical observation is that the overall astringency and astringency subqualities (e.g., drying, dynamic, surface smoothness, particulate) change dynamically during maceration. However, direct sensory evidence of this has yet to be reported, and a methodological approach designed to test such empiric observations has to account for the fact that the presence of sugars and acids impairs the effective assessment of astringency. To circumvent this drawback, changes in astringency during maceration have been inferred from the extraction patterns of oligomeric and polymeric PAs into wine during maceration. Experimental evidence suggests that during the first 3 to 5 days of maceration, skin PAs are preferentially extracted (Koyama et al. 2007, Cerpa-Calderón & Kennedy 2008). The diffusion of PAs' dimers and trimers from skins follows extraction kinetics similar to those reported for skin's flavan-3-ols. As such, PA oligomers can potentially be extracted in the absence of ethanol, for example during prefermentative cold soak (Hernández-Jiménez et al. 2012). In Tempranillo wines after a 2-day cold soak, the concentration of dimers, trimers,

[5]The average number of constitutive flavan-3-ol units in the PA structure, which are linked by covalent C4→C8 (or less commonly C4→C6) interflavanic bonds, is referred to as mean degree of polymerization (mDP). The common denomination of extension subunits, to refer to the unit positioned on top of a one-dimensional plane, and terminal subunits, to refer to the unit positioned at the bottom of the plane, is based on the ability of the subunit to generate an electrophilic carbocation (extension subunits) or a free monomeric subunit (terminal subunit) during acid-catalyzed hydrolysis (Kennedy & Jones 2001).

and tetramers increased from 22, 23, and 0 mg/L, respectively, to 27, 30, and 6 mg/L, respectively, after postfermentative maceration for one week (González-Manzano et al. 2006). In another study, the concentration of the B2 dimer and the C trimer increased from ~6 mg/L at day 2 to ~22 mg/L (B2 dimer) and to 11 mg/L (C trimer) after 20 days of maceration (González-Manzano et al. 2004). These findings suggest that as the oligomers increase in size, their extraction into wine progresses more slowly (Pérez-Magariño & González-San José 2004, González-Manzano et al. 2006). Alternatively, the effective retention into wine of higher-molecular-weight oligomers may be lower relative to that of smaller ones, a hypothesis that is elaborated in Section 7.

Extraction of oligomeric and polymeric (mDP $\geq$ 5) PAs into wine during maceration has been followed by different analytical approaches, including protein precipitation (Harbertson et al. 2009) and acid-catalyzed depolymerization in the presence of the nucleophile phloroglucinol followed by HPLC analysis (Peyrot des Gachons & Kennedy 2003, Cerpa-Calderón & Kennedy 2008, Casassa et al. 2013b). Using protein precipitation, protein precipitable PAs were found to increase almost linearly during the first 7 days of maceration in Merlot wines (Harbertson et al. 2009). In the same study, extended maceration for 20 days increased PA extraction from a mean of 469 mg/L in control wines to 985 mg/L in the extended maceration wines, with the concentration of PAs remaining stable up to 185 days post-crushing. Another study of Merlot followed PA evolution up to 540 days post-crushing in wines produced with extended maceration and different ethanol concentrations during maceration (Casassa et al. 2013a). This study reported that differences in ethanol up to 1.2% v/v had no effect on the extraction of protein precipitable PAs, but a 30-day extended maceration increased PA concentration by 65% relative to a control wine provided with 10 days of skin contact (Casassa et al. 2013a). The overall extraction and evolution of protein-precipitable tannins during maceration and up to 400 days post-crushing in Cabernet Sauvignon wines made with and without extended maceration are shown in **Figure 2*d***.

Using acid-catalyzed depolymerization and HPLC analysis, the extraction of skin PAs into wine was fit to a Boltzmann sigmoid model (Cerpa-Calderón & Kennedy 2008). In this model, a lag phase of initially slow extraction was attributed to the period of time required for the PAs to diffuse out of the berry cells and into the fermenting must. The extent of this lag phase was postulated to be modulated by variables such as the degree of berry crushing (Cerpa-Calderón & Kennedy 2008) or ethanol concentration (Hernández-Jiménez et al. 2012). The lag phase is followed by a plateau concentration, which is reached when the PA concentration is at its apparent maximum (Cerpa-Calderón & Kennedy 2008).

Extraction of PAs from the seeds has also been modeled using a Boltzmann sigmoid extraction pattern. In model wine extractions with varying ethanol concentrations and containing only seeds (cv. Monastrel), an initial slow extraction of PAs was reported during the first 2 days of maceration (Hernández-Jiménez et al. 2012). As with skins, this lag period was followed by a PA concentration plateau, which was higher with increasing ethanol concentration, implying an initial effect of the ethanol in the degradation of the outer hydrophobic layers of the seeds (Ribéreau-Gayon et al. 1998, Glories & Saucier 2000). From day 6 to day 10, however, PA extraction into wine increased linearly, indicating a deviation from the proposed Boltzmann sigmoid model. According to this model, the release of flavan-3-ols and PAs from the seeds may only occur after the seeds have attained a certain hydration level (Hernández-Jiménez et al. 2012). Once seeds have reached hydration, the leakiness of the parenchyma cells outside the true seed coat allows the effective release of flavan-3-ols and PAs into the fermenting wine independent of the ethanol concentration (Singleton & Draper 1964, Ozmianski et al. 1986, Adams & Scholtz 2008, Hernández-Jiménez et al. 2012, Casassa et al. 2013a). It is unclear, however, at what level of hydration the

disorganization of the seed parenchyma cell is attained, or if there are factors other than time (e.g., cultivar, maturity level, maceration technique) that can influence this process. Nevertheless, the somewhat abrupt release of flavan-3-ols and PAs from the seeds by the end of extended maceration may be responsible for the observed increase in protein-precipitable PAs registered between day 20 and 30 of extended maceration (Harbertson et al. 2009; Casassa et al. 2013a,b).

7. MATRIX EFFECTS ON PROANTHOCYANIDIN EXTRACTION AND EVOLUTION

It is now apparent that the extraction into wine and the fate of oligomeric and polymeric PAs during post-maceration and aging are modulated by the wine matrix composition. The primary effect of this matrix is exerted by the presence/absence of anthocyanins as well as other compounds known to react with wine PAs, such as mannoproteins from yeast origin, polysaccharides, and other cell wall components.

7.1. Presence of Anthocyanins and Formation of Polymeric Pigments

7.1.1. Overview. The presence of anthocyanins during maceration increases the solubility and retention of PAs via the formation of polymeric pigments (Kantz & Singleton 1991, Singleton & Trousdale 1992, Oberholster et al. 2009). Polymeric pigments encompass a variety of winemaking artifacts formed by a covalent reaction, either direct or mediated by an aldehyde functional group (e.g., acetaldehyde, glyceraldehyde, and/or glyoxylic acid) between the anthocyanins and the PAs (**Figure 1**). Qualitative evidence for the existence of polymeric pigments in wine has been provided. For example, pigmented polymers were isolated from a three-year-old Pinot noir wine using Toyopearl TSK HW 40-F size-exclusion chromatography and subsequently characterized by HPLC, UV-Vis, and ESI-MS techniques (Hayasaka & Kennedy 2003). This polymeric material was composed of a complex mixture of dimers to octamers in which the anthocyanin moiety was linked to the flavan-3-ol by B-type and A-type linkages. In a separate study, ultrafiltration and gel adsorption chromatography combined with 1H, 13C, and 2D NMR were used to characterize a high-molecular-weight PA polymer (>5 kDa) isolated from a Bordeaux red wine (Wollmann & Hofmann 2013). The structural backbone of this polymer consisted of a PA chain composed of (−)-epicatechin, (+)-catechin, and (−)-epicatechin-3-*O*-gallate as extension and terminal subunits. The presence of ethyl bridges, mediated by acetaldehyde, was also observed in the A ring of some subunits, as well as that of pyranoanthocyanins linked to the backbone via C4→C6 or C4→C8 linkages. Interestingly, organic acids, phenolics acids, and polysaccharides were also found to be present within the structure; however, the latter were not covalently linked to the PA backbone. This appears to be the first study to elucidate the heterogeneous structure of these compounds as they naturally occur in the wine matrix.

7.1.2. Chemical properties. Polymeric pigments, although chemically heterogeneous, shared at least four fundamental chemical features. Relative to the native anthocyanins, polymeric pigments are partially resistant to bisulfite bleaching, and their coloration is less dependent on pH changes in the range of pH 2 to 5 (Somers 1971, Somers & Evans 1977). Blockage of the C4 position of the anthocyanin backbone as a result of polymerization reactions with flavan-3-ols and/or oligomeric and polymeric PAs sterically protects the chromophore of the anthocyanin from attack by water and other nucleophiles; oxidation; or other chemical modifications, such as the bleaching effect of bisulfite (Jurd 1969, Somers 1971, He et al. 2012). Polymeric pigments are also less prone to precipitation after incorporation of the anthocyanin molecule(s) and further

polymerization, a condition not observed for intact PAs. Indeed, the polymeric pigment structure necessitates the inclusion of the anthocyanin moiety to ensure an enhanced solubilization in the wine matrix relative to that of the intact PA without the anthocyanin portion (Singleton & Trousdale 1992). It is hypothesized that the glucose moiety in the anthocyanin and the polarity of the flavylium cation may decrease the precipitability of the resulting polymeric pigment (Singleton 1992). This, in turn, may explain the persistence of polymeric pigments after prolonged bottle aging. Finally, polymeric pigments can be fractionated in oligomeric and polymeric subfractions using solid-phase extraction based on various sorbents, including silica-based C18 and divinylbenzene (Pinelo et al. 2006, Jeffery et al. 2008), or on the basis of their ability to precipitate with the bovine serum albumin (BSA) protein (Adams et al. 2004). The last method fractionates the wine's total content of polymeric pigments into small polymeric pigments (SPP, nonprecipitable) and large polymeric pigments (LPP, precipitable). SPP are reportedly composed of a heterogeneous mixture of anthocyanin-derived products, including acetaldehyde cross-linked, direct flavan-3-ol-anthocyanin and cycloaddition products (Adams et al. 2004). LPP are suggested to be composed of anthocyanins that have reacted directly with polymeric PAs or polymeric pigments that have been formed by acetaldehyde cross-linking-mediated polymerization (Adams et al. 2004).

7.1.3. Formation during winemaking. A pioneering study carried out by Singleton & Trousdale (1992) provided the first experimental confirmation that retention of PAs into wine and formation of polymeric pigments increased in the presence of added anthocyanins. In this study, white wines were produced with different portions of added PAs and anthocyanins. The results indicated that polymeric pigment formation in the white must increased almost linearly after addition of seed PAs in the range of 0 to 1,000 mg/L (gallic acid equivalents) and anthocyanins in the range of 0 to 500 mg/L (Singleton & Trousdale 1992). However, this study also found that the stoichiometric addition of anthocyanins relative to PAs approached an ideal proportion; a concentration excess of anthocyanins did not lead to a corresponding increase in pigmented polymer formation. This suggests that the proportion of anthocyanins and PAs during maceration can condition PA retention and stability and thus the formation of polymeric pigments.

Because the molar proportion of anthocyanins and PAs modulates the formation of polymeric pigments, there has been interest in following their evolution during maceration and aging, whereby the proportions of both anthocyanins and PAs change dynamically (**Figure 2**). Using protein precipitation, Harbertson et al. (2009) found that LPP increased by 70% between pressing and 185 days post-pressing in Merlot wines. In this same experiment, wines produced with extended maceration and saignée and containing a higher concentration of PAs gave rise to an enhanced formation of LPP; however, this occurred with a decline in the anthocyanin content of 43% relative to its peak concentration (Harbertson et al. 2009). A similar trend was observed in Merlot wines obtained with extended maceration (30 days), in which a two-fold improvement of the total polymeric pigments (SPP + LPP) was observed from day 4 to day 30, along with significant losses of malvidin, delphinidin, petunidin, and peonidin derivatives (Casassa et al. 2013a). Furthermore, this later work demonstrated that the formation of polymeric pigments alone in extended maceration wines was only partially responsible for the observed anthocyanin loss, because an increase in the polymeric pigment content of 13 mg/L from day 4 to day 30 occurred along with a drop in wine anthocyanins of 231 mg/L. In summary, these results suggest a complex relationship between PA content, anthocyanin extraction (or loss), and polymeric pigment formation during maceration. As shown in **Figure 2*e,f***, a common feature of extended maceration seems to be the formation of polymeric pigments with the ability to precipitate BSA (and by a similar mechanism to elicit astringency), but this occurs at the expense of anthocyanin loss (and, consequently, of wine color saturation), which is generally not fully explained by the formation of

polymeric pigments. Altogether, these findings suggest that the presence of anthocyanins invariably leads to the formation of polymeric pigments; yet, the proportion of anthocyanins and PAs during maceration will condition the amount of pigmented PAs that are effectively retained.

7.1.4. Sensory properties. From a sensory standpoint, oligomeric and polymeric pigments play a critical role in color change, long-term color stability, and possibly in the modulation of the astringency sensation as maceration progresses. Relative to the chromatic properties of intact anthocyanins, the UV-visible spectra of anthocyanin-flavan-3-ol adducts resulting from direct condensation reactions have an absorbance maximum at or below 520 nm. The absorbance maximums of condensation products with aldehydes are bathochromically shifted (i.e., bluish color), relative to that of the intact precursors (Timberlake & Bridle 1976, Pissara et al. 2003). Although a numerical value for the molar extinction coefficient of polymeric pigments at wine pH is not yet available, (indirect) experimental evidence suggests that it should be comparatively lower than that of the intact anthocyanins (Casassa et al. 2013a, McRae et al. 2013, Weber et al. 2013). In addition to the influence of these compounds in color stability and color changes during winemaking and aging, direct sensory evidence of the role of polymeric pigments in mouthfeel and astringency changes during aging has also recently been provided. Nevertheless, an early hypothesis of the sensory role of these compounds was developed in the 1970s. According to this hypothesis, the observed lessening of astringency during wine aging was postulated to be the result of the reaction of monomeric anthocyanins with PAs of various sizes giving rise to polymeric pigments, which were deemed less astringent than the intact PAs (Somers 1971, Singleton & Noble 1976). Unfortunately, the structural complexity and heterogeneity of these pigments prevented their isolation and sensory characterization at the time. With the advent of new analytical, semipreparative, and preparative HPLC approaches, the sensory characterization of polymeric pigment isolates became possible. Work by Vidal and colleagues in 2004 found that polymeric pigments having an mDP of ~3 and 9 and bearing an anthocyanin moiety were less astringent than apple PAs of the same mDP deprived of anthocyanins (Vidal et al. 2004a). Moreover, these authors showed that modifying the molecular structure by introducing an ethyl bridge decreased astringency but also increased bitterness (Vidal et al. 2004a). An explanation for the comparatively lower astringency of polymeric pigments relative to that of intact PAs is that the incorporation of an anthocyanin moiety with its glycoside portion increases the polarity of the polymer, as discussed earlier (Singleton 1992). Since the interaction between salivary PRPs and phenols is at least partially governed by hydrophobic forces, the higher hydrophilic character of the pigmented polymer would decrease the interaction with salivary PRPs and thus the development of the astringent sensation (McRae & Kennedy 2011). Alternatively, highly oxidized polymeric pigments may bear a larger degree of intramolecular bonds, thus reducing the number of binding sites available for interaction with salivary PRPs (McRae et al. 2013). Because polymeric pigments were found to contain noncovalent inclusions of polysaccharides within their structure (Wollmann & Hofmann 2013), the formation of soluble complexes with proteins is also a possibility (Le Bourvellec & Renard 2012, Scollary et al. 2012).

Recently, Weber et al. (2013), using size-exclusion chromatography on Sephadex resin, isolated 14 PA-pigmented fractions from a 2005 Cabernet Sauvignon wine. Anthocyanin monoglucosides, mainly malvidin-3-glucoside, were found in the first 10 fractions, confirming the pigmented nature of the polymeric PAs. Fractions 1 to 3 were composed of LPP as measured by protein precipitation (Harbertson et al. 2002), with low anthocyanin and PA content; fractions 4 to 7 consisted of anthocyanin-rich pigmented polymers with medium PA content; and fractions 8 to 14 consisted of small-sized, PA-like oligomers with very low anthocyanin content but very high PA content. Upon sensory evaluation of each fraction in water (adjusted to pH 4.0) at isoconcentrations of 500 mg/L, fractions with a low amount of incorporated anthocyanins elicited higher astringency than fractions

of higher molecular weight but rich in anthocyanins. This suggests that the incorporation of anthocyanins into polymers attenuates perceived astringency. In another report, a pigmented polymer isolated from a Bordeaux red wine was fractionated into eight fractions of different molecular weight (mDP from 5.8 to 10.1) using gel permeation chromatography (Wollmann & Hofmann 2013). Upon dissolution of these fractions in aqueous 1% ethanol (adjusted to pH 4.5) at isoconcentrations of 500 mg/L, astringency was found not to vary in seven of these fractions in spite of differences in the mDP and in the degree of galloylation. However, one fraction consisted of 50% polysaccharides by mass and was found to be significantly less astringent, suggesting that the incorporation of polysaccharides into PAs decreased the perceived astringency. Overall, these results point out that the empirical observation of decreased astringency along with wine aging may not be related to a change in the total amount of PA present. Rather, the structural modification of wine PAs, primarily resulting from the incorporation of anthocyanins, and, secondarily, from the addition of other metabolites such as carbohydrates, proteins, and polysaccharides, may drive the observed changes in perceived astringency during wine aging.

7.2. Interaction between Proanthocyanidins and Cell Wall Material during Maceration

In apple cider production, it has been long noted that there is a lack of recovery of high-molecular-weight PAs that are present at the beginning of processing (Haslam 1998). It was later found that noncovalent interactions between PAs and cell wall material were responsible for this "natural fining" occurring spontaneously during cider production. These noncovalent interactions include hydrogen-bonding and hydrophobic interactions. Moreover, these interactions increased with increasing PA size, percentage of galloylation, and the presence of (−)-epigallocatechin subunits in the PA structure (Cai et al. 1989; Le Bourvellec et al. 2004, 2005). As PAs increase in molecular weight, each additional flavan-3-ol subunit increases the number of sites able to form hydrogen bonds between PAs and cell wall components (Haslam 1998, Renard et al. 2001, Le Bourvellec et al. 2004, Hanlin et al. 2010), thus increasing the fining capacity of the cell wall components. An increase in the percentage of galloylated subunits also raises the hydrophobic character of the PAs (Plumb et al. 1998, McRae et al. 2013). Highly galloylated PAs may also become encapsulated in the hydrophobic pockets and pores of the polysaccharide network upon extraction into wine (De Freitas et al. 2003; Le Bourvellec et al. 2004, 2005).

In berries of different *V. vinifera* cultivars, the reported mDP of the seed PAs varies from 2 up to 22 subunits, whereas that of skins varies from 5 to 85 subunits (Cortell & Kennedy 2006, Cerpa-Calderón & Kennedy 2008, Chira et al. 2009, Hanlin et al. 2011). These PA polymer sizes observed in fresh tissue are in sharp contrast with the reported mDP in wines, which varies between 2 and 17 subunits (Monagas et al. 2003, González-Manzano et al. 2006, Cerpa-Calderón & Kennedy 2008, Lee et al. 2008, Hanlin et al. 2011, Gil et al. 2012). On the basis of these results, obtained by acid-catalyzed depolymerization techniques, it is apparent that PAs with an mDP >20 subunits are not effectively retained in the wine matrix. As in apple cider production, the failure to recover high-molecular-weight PAs in wine (particularly skin PAs) was hypothesized to be the result of PA–cell wall interactions (Hanlin et al. 2010). A series of studies conducted by Bindon and colleagues (Bindon et al. 2010a,b, 2011, 2012) have confirmed this hypothesis. These studies showed a significant relationship between the PA molecular mass and the proportion of PA adsorbed by skin cell wall polysaccharides, the end result being that higher-molecular-mass PAs (>15,000 g/mol, corresponding to an mDP of ∼51) are not extractable and/or removed from the wine by interaction with cell wall components during maceration (Bindon et al. 2010a,b, 2011, 2012). Expansins constitute the main cell wall proteins in the grape berry, and because they are rich

in hydroxyproline residues, they may also interact favorably with polymeric PAs upon extraction into wine (Hanlin et al. 2010). The observation that the affinity of cell wall components from mesocarp cells toward PAs is comparatively higher than that of skin cell walls has been attributed to a higher protein content of the mesocarp cell walls (229 mg/g nitrogen in mesocarp cell walls versus 99 mg/g nitrogen in skin cell walls) (Bindon et al. 2012). The end result would be that a higher protein content in general and that of expansins in particular may increase the flexibility and porosity of the mesocarp cell walls, thus facilitating the sequestration of high-molecular-weight PAs (Bindon et al. 2012). Furthermore, the binding capacity of the cell walls is influenced by the PA and the polysaccharide/protein structure and composition (Hanlin et al. 2010, Bindon et al. 2012).

As ethanol can effectively disrupt hydrophobic interactions, thereby decreasing the polarity of a hydroalcoholic solution such as wine, it has been suggested that the postfermentation extraction of PAs could be the result of a desorption mechanism mediated by this solvent (Adams & Scholtz 2008, Hanlin et al. 2010). In this model, the disruption of the noncovalent interactions of the extracted PAs that were bound to cell wall material mediated by an increasing concentration of ethanol would be responsible for the observed increase in PA extraction in the latter stages of maceration (Casassa et al. 2013a). This model contrasts with the previously discussed model in which the increase in protein-precipitable PAs registered in the latter stages of maceration was attributed to the release of seed PAs once the seeds reached full hydration. Whether this reported increase of PA extraction toward the end of extended maceration is the result of one or a combination of both mechanisms remains to be clarified.

8. CONCLUSIONS

The present review highlights the critical influence of the maceration length during red winemaking in modulating the retention into wine of phenolic and phenolic-derived compounds. For a wide number of red cultivars, extraction of anthocyanins peaks during the first 4 or 5 days of maceration and a decrease in concentration, which appears to be proportional to the maceration length, is observed. During extended maceration, this decrease in anthocyanin concentration is typically accompanied by the formation of protein-precipitable polymeric pigments. Furthermore, wine color saturation also decreases during extended maceration but this occurs along with the formation of polymeric pigments. Flavanols follow a slower rate of extraction relative to that of anthocyanins, and hydrolysis of the free aglycones may occur during extended maceration. Flavan-3-ols and small PA oligomers from skins are extracted within the first days of maceration, whereas extraction of PAs from the seeds requires longer maceration times to allow for seed hydration and the leakiness of the parenchyma cells located below the true seed coat. Furthermore, specific matrix effects were identified that affect the rate of retention of PAs into wine, particularly at the latter stages of maceration. These include the presence of anthocyanins, polysaccharides, and other cell wall components such as structural proteins, together with the role of ethanol as potential disruptor of the noncovalent interactions responsible for the sequestration of a portion of the extracted PAs.

This review also highlighted that phenolics and nonphenolic compounds are extracted and/or formed during maceration following a dynamic balance, resulting in the formation of new structures not previously found in grapes. Some of these new phenolic classes, which may also contain nonphenolic material of yeast and/or grape origin, are responsible for a variety of new sensory attributes. Polymeric pigments, bearing astringent and bitter properties different from those of intact PAs of equivalent molecular weight, are candidates for the changes in the mouthfeel and textural properties of red wines during maceration and aging. Although the taste and mouthfeel attributes of isolated polymeric pigments are starting to be clarified, their interaction with other

phenolic and nonphenolic materials and the volatile fraction of the wine matrix remain to be explored.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

Dr. Richard Larsen (WSU Prosser) and Dr. Gregory Gasic are gratefully acknowledged for skillful reading, editing, and suggested revisions of this review.

LITERATURE CITED

Adams DO. 2006. Phenolics and ripening in grape berries. *Am. J. Enol. Vitic.* 57:249–56

Adams DO, Harbertson JF, Picciotto EA. 2004. Fractionation of red wine polymeric pigments by protein precipitation and bisulfite bleaching. In *Red Wine Colour: Revealing the Mysteries*, ed. AL Waterhouse, JA Kennedy, pp. 275–88. Washington, DC: Am. Chem. Soc. 314 pp.

Adams DO, Scholz RC. 2008. Tannins – the problem of extraction. In *Proc. 13th Aust. Wine Ind. Tech. Conf., Aust. Soc. Vitic. Oenology, Adelaide, Aust.*, pp. 160–64

Alcalde-Eón C, Escribano-Bailón MT, Santos-Buelga C, Rivas-Gonzalo JC. 2006. Changes in the detailed pigment composition of red wine during maturity and ageing. A comprehensive study. *Anal. Chim. Acta* 513:305–18

Alcalde-Eón C, Escribano-Bailon MT, Santos-Buelga C, Rivas-Gonzalo JC. 2007. Identification of dimeric anthocyanins and new oligomeric pigments in red wine by means of HPLC-DAD-ESI/MS^n. *J. Mass Spectrom.* 42:735–48

Amrani-Joutei K, Glories Y, Mercier M. 1994. Localization of tannins in grape berry skins. *Vitis* 33:133–38

Andersen OM, Jordheim M. 2006. The anthocyanins. In *Flavonoids: Chemistry, Biochemistry and Applications*, ed. M Andersen, KR Markham, pp. 452–71. Boca Raton, FL: CRC Press. 1256 pp.

Aron PM, Kennedy JA. 2007. Compositional investigation of phenolic polymers isolated from *Vitis vinifera* L. cv. Pinot noir during fermentation. *J. Agric. Food Chem.* 55:5670–80

Asenstorfer RE, Iland PG, Tate ME, Jones GP. 2003. Charge equilibria and pKa of malvidin-3-glucoside by electrophoresis. *Anal. Biochem.* 318:291–99

Bajec MR, Pickering G. 2008. Astringency: mechanisms and perception. *Crit. Rev. Food Sci. Nutr.* 48:858–75

Bakker J, Timberlake CF. 1997. Isolation, identification, and characterization of new color-stable anthocyanins occurring in some red wines. *J. Agric. Food Chem.* 45:35–43

Baldi A, Romani A, Mulinacci N, Vincieri FF, Casetta B, et al. 1995. HPLC/MS application to anthocyanins of *Vitis vinifera* L. *J. Agric. Food Chem.* 48:2104–9

Bate-Smith E. 1973. Haemanalysis: The concept of relative astringency. *Phytochemistry* 12:907–12

Baxter NJ, Lilley TH, Haslam E, Williamson MP. 1997. Multiple interactions between polyphenols and a salivary proline-rich protein repeat result in complexation and precipitation. *Biochemisty* 36:5566–77

Bennick A. 2002. Interaction of plant polyphenol with salivary proteins. *Crit. Rev. Oral Biol. Med.* 13:184–96

Berg HW, Akiyoshi M. 1956. The effect of contact time of juice with pomace on the color and tannin content of red wines. *Am. J. Enol. Vitic.* 7:84–90

Berg HW, Akiyoshi M. 1958. Further studies of the factors affecting the extraction of color and tannin from red grapes. *Food Res.* 23:511–17

Bindon KA, Bacic A, Kennedy JA. 2012. Tissue-specific and developmental modification of grape cell walls influences the adsorption of proanthocyanidins. *J. Agric. Food Chem.* 60:9249–60

Bindon KA, Kennedy JA. 2011. Ripening-induced changes in grape skin proanthocyanidins modify their interaction with cell walls. *J. Agric. Food Chem.* 59:2696–707

Bindon KA, Smith PA, Holt H, Kennedy JA. 2010a. Interaction between grape-derived proanthocyanidins and cell wall material. 2. Implications for vinification. *J. Agric. Food Chem.* 58:10736–46

Bindon KA, Smith PA, Kennedy JA. 2010b. Interaction between grape derived proanthocyanidins and cell wall material. 1. Effect on proanthocyanidin composition and molecular mass. *J. Agric. Food Chem.* 58:2520–28

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

Boulton RB, Singleton VL, Bisson LF, Kunkee RE. 1996. *Principles and Practices of Winemaking*. New York: Chapman & Hall. 604 pp.

Breslin PA, Gilmore M, Beauchamp GK, Green BG. 1993. Psychological evidence that astringency is a tactile sensation. *Chem. Senses* 18:273–84

Burns J, Gardner PT, Matthews D, Duthie GG, Lean ME, Crozier A. 2001. Extraction of phenolics and changes in antioxidant activity of red wines during vinification. *J. Agric. Food Chem.* 49:5797–808

Busse-Valverde N, Bautista-Ortín AB, Gómez-Plaza E, Fernández-Fernández JI, Gil-Muñoz R. 2012. Influence of skin maceration time on the proanthocyanidin content of red wines. *Eur. Food Res. Technol.* 235:1117–23

Cai Y, Gaffney SH, Lilley TH, Haslam E. 1989. Carbohydrate-polyphenol complexation. In *Chemistry and Significance of Condensed Tannins*, ed. RW Hemingway, JJ Karchesy, SJ Braham, pp. 307–22. New York: Plenum. 553 pp.

Canals R, Llaudy MC, Valls J, Canals JM, Zamora F. 2005. Influence of ethanol concentration on the extraction of color and phenolic compounds from the skin and seeds of Tempranillo grapes at different stages of ripening. *J. Agric. Food Chem.* 53:4019–25

Casassa LF, Beaver CW, Mireles MS, Harbertson JF. 2013a. Effect of extended maceration and ethanol concentration on the extraction and evolution of phenolics, color components and sensory attributes of Merlot wines. *Aust. J. Grape Wine Res.* 19:25–39

Casassa LF, Larsen RC, Beaver CW, Mireles MS, Keller M, et al. 2013b. Impact of extended maceration and regulated deficit irrigation (RDI) in Cabernet Sauvignon wines: characterization of proanthocyanidin distribution, anthocyanin extraction, and chromatic properties. *J. Agric. Food Chem.* 61:6446–57

Castellarin SD, Di Gaspero G, Marconi R, Nonis A, Peterlunger E, et al. 2006. Colour variation in red grapevines (*Vitis Vinifera* L.): Genomic organisation, expression of flavonoid 3′-hydroxylase, flavonoid 3′,5′-hydroxylase genes and related metabolite profiling of red cyanidin/blue delphinidin-based anthocyanins in berry skin. *BMC Genomics* 7:1–17

Castillo-Muñoz N, Gómez-Alonso S, García-Romero E, Gómez MV, Velders AH, Hermosín-Gutiérrez I. 2009. Flavonol 3-*O*-glycosides series of *Vitis vinifera* cv. Petit verdot red wine grapes. *J. Agric. Food Chem.* 57:209–19

Castillo-Muñoz N, Gómez-Alonso S, García-Romero E, Hermosín-Gutiérrez I. 2007. Flavonol profiles of *Vitis Vinifera* L. red grapes and their single-cultivar wines. *J. Agric. Food Chem.* 55:992–1002

Cerpa-Calderón FK, Kennedy JA. 2008. Berry integrity and extraction of skin and seed proanthocyanidins during red wine fermentation. *J. Agric. Food Chem.* 56:9006–14

Charlton AJ, Baxter NJ, Lilley TH, Haslam E, McDonald CJ, Williamson MP. 1996. Tannin interactions with a full-length human salivary proline-rich protein display a stronger affinity than with single proline-rich repeats. *FEBS Lett.* 382:289–92

Charlton AJ, Baxter NJ, Lokmankhan M, Moir AJG, Haslam E, et al. 2002. Polyphenol/peptide binding and precipitation. *J. Agric. Food Chem.* 50:1593–601

Cheynier V. 2006. Flavonoids in wine. In *Flavonoids: Chemistry, Biochemistry, and Applications*, ed. M Andersen, KR Markham, pp. 443–70. Boca Raton, FL: CRC Press. 1256 pp.

Cheynier V, Dueñas-Paton M, Salas E, Maury C, Souquet JM, et al. 2006. Structure and properties of wine pigments and tannins. *Am. J. Enol. Vitic.* 57:298–305

Cheynier V, Prieur C, Guyot S, Rigaud J, Moutounet M. 1997. The structures of tannins in grapes and wines and their interactions with proteins. In *Wine: Nutritional and Therapeutic Benefits*, ed. TR Watkins, pp. 81–93. Washington, DC: ACS Symp. Ser. 296 pp.

Cheynier V, Rigaud J. 1986. HPLC separation and characterization of flavonols in the skins of *Vitis vinifera* var. Cinsault. *Am. J. Enol. Vitic.* 37:248–52

Chira K, Schmauch G, Saucier C, Fabre S, Teissedre P-L. 2009. Grape variety effect on proanthocyanidin composition and sensory perception of skin and seed tannin extracts from Bordeaux wine grapes (Cabernet Sauvignon and Merlot) for two consecutive vintages (2006 and 2007). *J. Agric. Food Chem.* 57:545–53

Cortell JM, Halbleib M, Gallaguer AV, Righetti TL, Kennedy JA. 2007. Influence of vine vigor on grape (*Vitis vinifera* L. cv. Pinot noir) anthocyanins. 2. Anthocyanins and pigmented polymers in wine. *J. Agric. Food Chem.* 55:6585–95

Cortell JM, Kennedy JA. 2006. Effect of shading on accumulation of flavonoid compounds in (*Vitis vinifera* L.) Pinot noir and extraction in a model system. *J. Agric. Food Chem.* 54:8510–20

Czochanska Z, Foo LY, Newman RH, Porter LJ. 1980. Polymeric proanthocyanidins. Stereochemistry, structural units, and molecular weight. *J. Chem. Soc. Perkin Trans.* 1:2278–86

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

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

De Freitas VA, Carvalho E, Mateus N. 2003. Study of carbohydrate influence on protein-tannin aggregation by nephelometry. *Food Chem.* 81:503–9

De Freitas VA, Mateus N. 2001. Structural features of procyanidin interactions with salivary proteins. *J. Agric. Food Chem.* 49:940–45

De Freitas VA, Mateus N. 2010. Formation of pyranoanthocyanins in red wines: a new and diverse class of anthocyanin derivatives. *Anal. Bioanal. Chem.* 401:1463–73

del Llaudy MC, Canals R, Canals JM, Zamora F. 2008. Influence of ripening stage and maceration length on the contribution of grape skins, seeds, and stems to phenolic composition and astringency in wine-simulated macerations. *Eur. Food Res. Technol.* 226:337–44

Delcambre A, Saucier C. 2012. Identification of new flavan-3-ol monoglycosides by UHPLC-ESI-Q-TOF in grapes and wine. *J. Mass Spectrom.* 47:727–36

Demiglio P, Pickering GJ. 2008. The influence of ethanol and pH on the taste and mouthfeel sensations elicited by red wine. *J. Food Agric. Environ.* 6:143–50

Downey MO, Harvey J, Robinson S. 2003. Analysis of tannins in seeds and skins of Shiraz grapes throughout berry development. *Aust. J. Grape Wine Res.* 9:15–27

Downey MO, Rochfort S. 2008. Simultaneous separation by reverse phase high-performance liquid chromatography and mass spectral identification of anthocyanins and flavonols in Shiraz grape skin. *J. Chromatogr. A* 1201:43–47

Dueñas M, Fulcrand H, Cheynier V. 2006. Formation of anthocyanin–flavanol adducts in model solutions. *Anal. Chim. Acta* 563:15–25

Elias RJ, Laurie VF, Ebeler SE, Wong JW, Waterhouse AL. 2008. Analysis of selected carbonyl oxidation products in wine by liquid chromatography with diode array detection. *Anal. Chim. Acta* 626:104–10

Escribano-Bailón MT, Guerra MT, Rivas-Gonzalo JC, Santos-Buelga C. 1995. Proanthocyanidins in skins from different grape varieties. *Z. Lebensm. Unters. Forsch.* 200:221–24

Es-Safi NE, Cheynier V, Moutounet M. 2000a. Study of the reactions between (+)-catechin and furfural derivatives in the presence or absence of anthocyanins and their implication in food color change. *J. Agric. Food Chem.* 48:5946–54

Es-Safi NE, Fulcrand H, Cheynier V, Moutounet M. 1999. Studies on the acetaldehyde-induced condensation of (−)-epicatechin and malvidin 3-*O*-glucoside in a model solution system. *J. Agric. Food Chem.* 47:2096–102

Es-Safi NE, Le Guernevé C, Fulcrand H, Cheynier V, Moutounet M. 2000b. Xanthylium salts formation involved in wine colour changes. *Int. J. Food Sci. Technol.* 35:63–74

Flamini R, Traldi P. 2010. *Mass Spectrometry in Grape and Wine Chemistry*. Hoboken, NJ: Wiley. 348 pp.

Fulcrand H, Benabdeljalil C, Rigaud J, Cheynier V, Moutounet M. 1998. A new class of wine pigments generated by reaction between pyruvic acid and grape anthocyanins. *Phytochemistry* 47:1401–7

Fulcrand H, Cheynier V, Oszmianski J, Moutounet M. 1997. An oxidized tartaric acid residue as a new bridge potentially competing with acetaldehyde in flavan-3-ol condensation. *Phytochemistry* 46:223–27

Gambuti A, Capuano R, Lecce L, Fragasso MG, Moio L. 2009. Extraction of phenolic compounds from 'Aglianico' and 'Uva di Troia' grape skins and seeds in model solutions: Influence of ethanol and maceration time. *Vitis* 4:193–200

Gawel R. 1998. Red wine astringency: A review. *Aust. J. Grape Wine Res.* 4:74–95

Gil M, Kontoudakis N, González E, Esteruelas M, Fort F, et al. 2012. Influence of grape maturity and maceration length on color, polyphenolic composition, and polysaccharide content of Cabernet Sauvignon and Tempranillo wines. *J. Agric. Food Chem.* 60:7988–8001

Gil-Muñoz R, Gómez-Plaza E, Martínez A, López-Roca JM. 1999. Evolution of phenolic compounds during wine fermentation and post-fermentation: influence of grape temperature. *J. Food Comp. Anal.* 12:259–72

Glories Y, Saucier C. 2000. Tannin evolution from grape to wine. Effects on wine taste. In *The ASEV 50th Anniv. Annu. Meet.*, ed. J Ratz, pp. 353–55. Davis, CA: Am. Soc. Enol. Vitic.

Gómez-Míguez M, Heredia FJ. 2004. Effect of the maceration technique on the relationships between anthocyanin composition and objective color of Syrah wines. *J. Agric. Food Chem.* 52:5117–23

Gómez-Plaza E, Romero-Cascales I, Fernández-Fernández JI, López-Roca JM. 2005. The maceration process during winemaking extraction of anthocyanins from grape skins into wine. *Eur. Food Res. Tech.* 221:163–67

González-Manzano S, Rivas-Gonzalo JC, Santos-Buelga C. 2004. Extraction of flavan-3-ols from grape seed and skin into wine using simulated maceration. *Anal. Chim. Acta* 513:283–89

González-Manzano S, Santos-Buelga C, Pérez-Alonso JJ, Rivas-Gonzalo JC, Escribano-Bailón MT. 2006. Characterization of the mean degree of polymerization of proanthocyanidins in red wines using liquid chromatography-mass spectrometry (LC-MS). *J. Agric. Food Chem.* 54:4326–32

González-Neves G, Gil G, Favre G, Ferrer M. 2012. Influence of grape composition and winemaking on the anthocyanin composition of red wines of Tannat. *Int. J. Food Sci. Tech.* 47:1–10

Guerrero RF, Liazid A, Palma M, Puertas B, González-Barrio R, et al. 2009. Phenolic characterization of red grapes autochthonous to Andalusia. *Food Chem.* 112:949–55

Hanlin RL, Hrmova M, Harbertson JF, Downey MO. 2010. Review: condensed tannin and grape cell wall interactions and their impact on tannin extractability into wine. *Aust. J. Grape Wine Res.* 16:173–88

Hanlin RL, Kelm MA, Wilkinson KL, Downey MO. 2011. Detailed characterization of proanthocyanidins in skin, seeds and wine of Shiraz and Cabernet Sauvignon wine grapes (*Vitis vinifera*). *J. Agric. Food Chem.* 59:13265–76

Harbertson JF, Kennedy JA, Adams DO. 2002. Tannin in skins and seeds of Cabernet Sauvignon, Syrah, and Pinot noir berries during ripening. *Am. J. Enol. Vitic.* 53:54–59

Harbertson JF, Mireles M, Harwood E, Weller KM, Ross CF. 2009. Chemical and sensory effects of saignée, water addition and extended maceration on high Brix must. *Am. J. Enol. Vitic.* 60:450–60

Harbertson JF, Spayd S. 2006. Measuring phenolics in the winery. *Am. J. Enol. Vitic.* 57:280–88

Haslam E. 1982. Proanthocyanidins. In *The Flavonoids: Advances in Research*, ed. JB Harborne, TJ Mabry, pp. 417–47. London: Chapman & Hall. 744 pp.

Haslam E. 1998. *Practical Polyphenolics: From Structure to Molecular Recognition and Physiological Action*. Cambridge, UK: Cambridge Univ. Press. 438 pp.

Hayasaka Y, Kennedy JA. 2003. Mass spectrometric evidence for the formation of pigmented polymers in red wine. *Aust. J. Grape Wine Res.* 9:210–20

He F, He JJ, Pan QH, Duan CQ. 2010. Mass-spectrometry evidence confirming the presence of pelargonidin-3-*O*-glucoside in the berry skins of Cabernet Sauvignon and Pinot noir (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* 16:464–68

He F, Liang NN, Mu L, Pan QH, Wang J, et al. 2012. Anthocyanins and their variation in red wines II. Anthocyanin derived pigments and their color evolution. *Molecules* 17:1483–519

Hermosín-Gutiérrez I. 2003. Influence of ethanol content on the extent of copigmentation in a Cencibel young red wine. *J. Agric. Food Chem.* 51:4079–83

Hernández-Jiménez A, Kennedy JA, Bautista-Ortín AB, Gómez-Plaza E. 2012. Effect of ethanol on grape seed proanthocyanidin extraction. *Am. J. Enol. Vitic.* 63:57–61

Hilgard EW. 1887. The extraction of color and tannin during red-wine fermentations. *Univ. Calif. Agric. Exp. Stn. Bull.* 77

Hufnagel JC, Hofmann T. 2008a. Orosensory directed identification of astringent mouthfeel and bitter-tasting compounds in red wine. *J. Agric. Food Chem.* 56:1376–86

Hufnagel JC, Hofmann T. 2008b. Quantitative reconstruction of the nonvolatile sensometabolome of a red wine. *J. Agric. Food Chem.* 56:9190–99
Ishikawa T, Noble AC. 1995. Temporal perception of astringency and sweetness in red wine. *Food Qual. Pref.* 6:27–33
Jeffery DW, Parker M, Smith PA. 2008. Flavonol composition of Australian red and white wines determined by high-performance liquid chromatography. *Aust. J. Grape Wine Res.* 14:153–61
Jöbstl E, O'Connell J, Fairclough JPA, Williamson MP. 2004. Molecular model for astringency produced by polyphenol/protein interactions. *Biomacromolecules* 5:942–49
Jurd L. 1969. Review of polyphenol condensation reactions and their possible occurrence in the aging of wines. *Am. J. Enol. Vitic.* 20:191–95
Kallithraka S, Bakker J, Clifford MN. 1997a. Evaluation of bitterness and astringency of (+)-catechin and (−)-epicatechin in red wine and in model solution. *J. Sens. Stud.* 12:25–37
Kallithraka S, Bakker J, Clifford MN. 1997b. Effect of pH on astringency in model solutions and wines. *J. Agric. Food Chem.* 45:2211–16
Kallithraka S, Bakker J, Clifford MN, Vallis L. 2001. Correlations between saliva protein composition and some T-I parameters of astringency. *Food Qual. Pref.* 12:145–52
Kantz K, Singleton VL. 1991. Isolation and determination of polymeric polyphenols in wines using Sephadex LH-20. *Am. J. Enol. Vitic.* 42:309–16
Kelebek H, Canbas A, Selli A, Saucier C, Jourdes M, Glories Y. 2006. Influence of different maceration times on the anthocyanin composition of wines made from *Vitis vinifera* L., cvs. Bogazkere and Okuzgozu. *J. Food Eng.* 77:1012–17
Kennedy JA, Jones GP. 2001. Analysis of proanthocyanidin cleavage products following acid-catalysis in the presence of excess phloroglucinol. *J. Agric. Food Chem.* 49:1740–46
Kong JM, Chia LS, Goh NK, Chia TF, Brouillard R. 2003. Analysis and biological activities of anthocyanins. *Phytochemistry* 64:923–33
Koyama K, Goto-Yamamoto N, Hashizume K. 2007. Influence of maceration temperature in red wine vinification on extraction of phenolics from berry skins and seeds of grape (*Vitis vinifera*). *Biosci. Biotechnol. Biochem.* 71:958–65
Laurie VF, Waterhouse AL. 2006a. Glyceraldehyde bridging between flavanols and malvidin-3-glucoside in model solutions. *J. Agric. Food Chem.* 54:9105–11
Laurie VF, Waterhouse AL. 2006b. Oxidation of glycerol in the presence of hydrogen peroxide and iron in model solutions and wine. Potential effects on wine color. *J. Agric. Food Chem.* 54:4668–73
Le Bourvellec C, Bouchet B, Renard CM. 2005. Noncovalent interaction between procyanidins and apple cell wall material. Part III. Study on model polysaccharides. *Biochim. Biophys. Acta* 1725:10–18
Le Bourvellec C, Guyot S, Renard CM. 2004. Noncovalent interaction between procyanidins and apple cell wall material. Part I. Effect of some environmental parameters. *Biochim. Biophys. Acta* 1672:192–202
Le Bourvellec C, Renard CM. 2012. Interactions between polyphenols and macromolecules: quantification methods and mechanisms. *Crit. Rev. Food Sci. Nutr.* 52:213–48
Lee J, Kennedy JA, Devlin C, Redhead M, Rennaker C. 2008. Effect of early seed removal during fermentation on proanthocyanidin extraction in red wine: A commercial production example. *Food Chem.* 107:1270–73
Lesschaeve I, Noble AC. 2005. Polyphenols: factors influencing their sensory properties and their effects on food and beverage preferences. *Am. J. Clin. Nutr.* 81:330S–35
Lopes P, Richard T, Saucier C, Teissedre P-L, Monti J-P, Glories Y. 2007. Anthocyanone A: a quinone methide derivative resulting from malvidin 3-*O*-glucoside degradation. *J. Agric. Food Chem.* 55:2698–704
Macheix JJ, Fleuriet A, Billot J. 1990. *Fruit Phenolics*. Boca Raton, FL: CRC Press. 378 pp.
Manfra M, De Nisco M, Bolognese A, Nuzzo V, Sofo A, et al. 2011. Anthocyanin composition and extractability in berry skin and wine of *Vitis vinifera* L. cv. Aglianico. *J. Sci. Food Agric.* 91:2749–55
Mateus N, Silva AMS, Vercauteren J, De Freitas V. 2001. Occurrence of anthocyanin-derived pigments in red wines. *J. Agric. Food Chem.* 49:4836–40
Mazauric JP, Salmon JM. 2005. Interactions between yeast lees and wine polyphenols during simulation of wine aging: I. Analysis of remnant polyphenolic compounds in the resulting wines. *J. Agric. Food Chem.* 53:5647–53

McManus JP, Davis KG, Lilley TH, Haslam E. 1981. The association of proteins with polyphenols. *JCS Chem. Commun.* 1981:309–11

McRae JM, Kennedy JA. 2011. Wine and grape tannin interactions with salivary proteins and their impact on astringency: a review of current research. *Molecules* 16:2348–64

McRae JM, Schulkin A, Kassara E, Holt EH, Smith PA. 2013. Sensory properties of wine tannin fractions: implications for in-mouth sensory properties. *J. Agric. Food Chem.* 61:719–27

Medina K, Boido E, Dellacassa E, Carrau F. 2005. Yeast interactions with anthocyanins during red wine fermentation. *Am. J. Enol. Vitic.* 56:104–9

Mehansho H, Butler LG, Carlson DM. 1987. Dietary tannins and salivary proline-rich proteins: Interactions, induction and defense mechanisms. *Annu. Rev. Nutr.* 7:423–40

Meyer J, Hernández R. 1970. Seed tannin extraction in Cabernet Sauvignon. *Am. J. Enol. Vitic.* 21:184–88

Mizuno H, Hirano K, Okamoto G. 2006. Effect of anthocyanin composition in grape skin on anthocyanic vacuolar inclusion development and skin coloration. *Vitis* 45:173–77

Monagas M, Bartolomé B, Gómez-Cordovés C. 2005. Updated knowledge about the presence of phenolic compounds in wine. *Crit. Rev. Food Sci. Nutr.* 45:85–118

Monagas M, Gómez-Cordovés C, Bartolomé B. 2007. Evaluation of different *Saccharomyces cerevisiae* strains for red winemaking. Influence on the anthocyanin, pyranoanthocyanin and non-anthocyanin phenolic content and colour characteristics of wines. *Food Chem.* 104:814–23

Monagas M, Gómez-Cordovés C, Bartolomé B, Laureano O, Ricardo da Silva JM. 2003. Monomeric, oligomeric, and polymeric flavan-3-ol composition of wines and grapes from *Vitis vinifera* L. cv. Graciano, Tempranillo, and Cabernet Sauvignon. *J. Agric. Food Chem.* 51:6475–81

Morata A, Gómez-Cordovés C, Colomo B, Suárez JA. 2003. Pyruvic acid and acetaldehyde production by different strains of *Saccharomyces cerevisiae*: relationship with Vitisin A and B formation in red wines. *J. Agric. Food Chem.* 51:7402–9

Morel-Salmi C, Souquet J-M, Bes M, Cheynier V. 2006. Effect of flash release treatment on phenolic extraction and wine composition. *J. Agric. Food Chem.* 54:4270–76

Moskowitz AH, Hrazdina G. 1981. Vacuolar contents of fruit subepidermal cells from *Vitis* species. *Plant Physiol.* 68:686–92

Nagel CW, Wulf L. 1979. Changes in the anthocyanins, flavonoids, and hydroxycinnamic acid esters during fermentation and aging of Merlot and Cabernet Sauvignon. *Am. J. Enol. Vitic.* 30:111–16

Niketic-Aleksic G, Hrazdina G. 1972. Quantitative analysis of the anthocyanin content in grape juices and wines. *Lebensm. Wiss. Technol.* 5:163–65

Noble AC. 1994. Bitterness in wine. *Physiol. Behav.* 56:1251–55

Oberholster A, Francis IL, Iland PG, Waters EJ. 2009. Mouthfeel of white wines made with and without pomace contact and added anthocyanins. *Aust. J. Grape Wine Res.* 15:59–69

Oliveira J, De Freitas V, Mateus N. 2009. A novel synthetic pathway to Vitisin B compounds. *Tetrahedron Lett.* 50:3933–35

Ough CS, Amerine MA. 1960. Experiments with controlled fermentations. IV. Red wines. *Am. J. Enol. Vitic.* 11:5–14

Ough CS, Amerine MA. 1961a. Studies on controlled fermentation. V. Effects on color, composition and quality of red wine. *Am. J. Enol. Vitic.* 12:9–19

Ough CS, Amerine MA. 1961b. Studies with controlled fermentation. VI. Effects of temperature and handling on rates, composition, and quality of wines. *Am. J. Enol. Vitic.* 12:117–28

Ozmianski J, Romeyer FM, Sapis JC, Macheix JJ. 1986. Grape seed phenolics: Extraction as affected by some conditions occurring during wine processing. *Am. J. Enol. Vitic.* 37:7–12

Peleg H, Gacon K, Schlich P, Noble AC. 1999. Bitterness and astringency of flavan-3-ol monomers, dimers and trimers. *J. Sci. Food Agric.* 1128:1123–28

Pérez-Magariño S, González-San José ML. 2004. Evolution of flavanols, anthocyanins, and their derivatives during the aging of red wines elaborated from grapes harvested at different stages of ripening. *J. Agric. Food Chem.* 52:1181–89

Peynaud É. 1984. *Knowing and Making Wine*. Transl. A Spenser. New York: Wiley-Intersci. 416 pp. (In French)

Peyrot des Gachons C, Kennedy JA. 2003. Direct method for determining seed and skin proanthocyanidin extraction into red wine. *J. Agric. Food Chem.* 51:5877–81

Pianet I, André Y, Ducasse MA, Tarascou I, Lartigue JC, et al. 2008. Modeling procyanidin self-association processes and understanding their micellar organization: a study by diffusion NMR and molecular mechanics. *Langmuir* 24:11027–35

Pinelo M, Laurie VF, Waterhouse AL. 2006. A simple method to separate red wine nonpolymeric and polymeric phenols by solid-phase extraction. *J. Agric. Food Chem.* 54:2839–44

Pissara J, Mateus N, Rivas-Gonzalo JC, De Freitas V. 2003. Reaction between malvidin 3-glucoside and (+)-catechin in model solutions containing different aldehydes. *J. Food Sci.* 68:476–81

Plumb GW, de Pascual-Teresa S, Santos-Buelga C, Cheynier V, Williamson G. 1998. Antioxidant properties of catechins and proanthocyanidins: effect of polymerisation, galloylation and glycosylation. *Free Radic. Res.* 29:351–58

Poncet-Legrand C, Gautier C, Cheynier V, Imberty A. 2007. Interactions between flavan-3-ols and poly (L-proline) studied by isothermal titration calorimetry: Effect of the tannin structure. *J. Agric. Food Chem.* 55:9235–40

Price SF, Breen PJ, Valladao M, Watson BT. 1995. Cluster sun exposure and quercetin in Pinot noir grapes and wine. *Am. J. Enol. Vitic.* 46:187–94

Prieur C, Rigaud J, Cheynier V, Moutounet M. 1994. Oligomeric and polymeric procyanidins from grape seeds. *Phytochemistry* 36:781–84

Puertas B, Guerrero RF, Jurado MS, Jimenez MJ, Cantos-Villar E. 2008. Evaluation of alternative winemaking processes for red wine color enhancement. *Food Sci. Technol. Int.* 14:21–28

Remy S, Fulcrand H, Labarbe B, Cheynier V, Moutounet M. 2000. First confirmation in red wine of products resulting from direct anthocyanin-tannin reactions. *J. Sci. Food Agric.* 80:745–51

Renard CM, Baron A, Guyot S, Drilleau JF. 2001. Interactions between apple cell walls and native apple polyphenols: quantification and some consequences. *Int. J. Biol. Macromol.* 29:115–25

Rentzsch M, Schwarz M, Winterhalter P. 2007. Pyranoanthocyanins: an overview on structures, occurrence, and pathways of formation. *Trends Food Sci. Tech.* 18:526–34

Ribéreau-Gayon P, Dubourdieu D, Donèche B, Lonvaud A. 1998. *Traité d' Oenologie. 1. Microbiologie du Vin Vinifications.* Paris: Ed. Dunod. 661 pp.

Ricardo da Silva JM, Cheynier V, Souquet JM, Moutounet M, Cabanis JC, Bourzeix M. 1991. Interaction of grape seed procyanidins with various proteins in relation to wine fining. *J. Sci. Food Agric.* 57:111–25

Rivas-Gonzalo JC, Bravo-Haro S, Santos-Buelga C. 1995. Detection of compounds formed through the reaction of malvidin 3-monoglucoside and catechin in the presence of acetaldehyde. *J. Agric. Food Chem.* 43:1444–49

Robichaud JL, Noble AC. 1990. Astringency and bitterness of selected phenolics in wine. *J. Sci. Food Agric.* 53:343–53

Romero-Cascales I, Fernández-Fernández JI, López-Roca JM, Gómez-Plaza E. 2005. The maceration process during winemaking extraction of anthocyanins from grape skins into wine. *Eur. Food Res. Technol.* 221:163–67

Rossi JA, Singleton VL. 1966. Flavor effects and adsorptive properties of purified fractions of grape-seed phenols. *Am. J. Enol. Vitic.* 17:240–46

Rudnitskaya A, Nieuwoudt HE, Muller N, Legin A, du Toit M, Bauer FF. 2010. Instrumental measurement of bitter taste in red wine using an electronic tongue. *Anal. Bioanal. Chem.* 397:3051–60

Sáenz-Navajas MP, Ferreira V, Dizy M, Fernández-Zurbano P. 2010. Characterization of taste-active fractions in red wine combining HPLC fractionation, sensory analysis and ultra-performance liquid chromatography coupled with mass spectrometry detection. *Anal. Chim. Acta* 673:151–59

Salas E, Dueñas M, Schwarz M, Winterhalter P, Cheynier V, Fulcrand H. 2005. Characterization of pigments from different high speed countercurrent chromatography wine fractions. *J. Agric. Food Chem.* 53:4536–46

Salas E, Fulcrand H, Meudec E, Cheynier V. 2003. Reactions of anthocyanins and tannins in model solutions. *J. Agric. Food Chem.* 51:7951–61

Schwarz M, Quast P, von Baer D, Winterhalter P. 2003. Vitisin A content in chilean wines from *Vitis Vinifera* cv. Cabernet Sauvignon and contribution to the color of aged red wines. *J. Agric. Food Chem.* 51:6261–67

Scollary GR, Pásti G, Kállay M, Blackman J, Clark AC. 2012. Astringency response of red wines: potential role of molecular assembly. *Trends Food Sci. Tech.* 27:25–36
Scudamore-Smith PD, Hooper RL, McLaren ED. 1990. Color and phenolic changes of Cabernet Sauvignon wine made by simultaneous yeast/bacteria fermentation and extended pomace contact. *Am. J. Enol. Vitic.* 41:57–67
Singleton VL. 1992. Tannins and the qualities of wines. In *Plant Polyphenols: Synthesis, Properties, Significance*, ed. RW Hemingway, pp. 859–80. New York: Plenum. 1077 pp.
Singleton VL, Draper DE. 1964. The transfer of polyphenolic compounds from grape seeds into wines. *Am. J. Enol. Vitic.* 15:34–40
Singleton VL, Noble AC. 1976. Wine flavor and phenolic substances. In *Phenolic, Sulfur and Nitrogen Compounds in Food Flavors*, ed. G Charalambous, I Katz, pp. 47–70. ACS Symp. Ser. 26. Washington, DC: Am. Chem. Soc. 215 pp.
Singleton VL, Trousdale EK. 1992. Anthocyanin-tannin interactions explaining differences in polymeric phenols between white and red wines. *Am. J. Enol. Vitic.* 43:63–70
Sipiora MJ, Gutiérrez-Granda MJ. 1998. Effects of pre-véraison irrigation cut off and skin contact time on the composition, color and phenolic content of young Cabernet Sauvignon wines in Spain. *Am. J. Enol. Vitic.* 53:268–74
Somers TC. 1971. The polymeric nature of wine pigments. *Phytochemistry* 10:2175–86
Somers TC, Evans ME. 1977. Spectral evaluation of young red wines: Anthocyanin equilibria, total phenols, free and molecular SO2 and chemical age. *J. Sci. Food Agric.* 28:279–87
Somers TC, Evans ME. 1979. Grape pigment phenomena: interpretation of major colour losses during vinification. *J. Sci. Food Agric.* 30:623–33
Souquet JM, Cheynier V, Brossaud F, Moutounet M. 1996. Polymeric proanthocyanidins from grape skins. *Phytochemisty* 43:509–12
Spranger I, Clímaco MC, Sun B, Eiriz N, Fortunato C, et al. 2004. Differentiation of red winemaking technologies by phenolic and volatile composition. *Anal. Chim. Acta* 513:151–61
Su CT, Singleton VL. 1969. Identification of three flavan-3-ols from grapes. *Phytochemisty* 8:1553–58
Sun BS, de Sá MC, Leandro C, Caldeira I, Duarte FL, Spranger I. 2013. Reactivity of polymeric proanthocyanidins toward salivary proteins. *J. Agric. Food Chem.* 61:939–46
Sun BS, Pinto T, Leandro MC, Ricardo da Silva JM, Spranger MI. 1999. Transfer of catechins and proanthocyanidins from solid parts of the grape cluster into wine. *Am. J. Enol. Vitic.* 50:179–84
Thorngate JH, Noble AC. 1995. Sensory evaluation of bitterness and astringency of 3*R*(−)-epicatechin and 3*S*(+)-catechin. *J. Sci. Food Agric.* 67:531–35
Timberlake CF, Bridle P. 1976. Interactions between anthocyanins, phenolic compounds, and acetaldehyde and their significance in red wines. *Am. J. Enol. Vitic.* 27:97–105
Valentová H, Skrováková S, Panovská Z, Pokorny J. 2002. Time intensity studies of astringent taste. *Food Chem.* 78:29–37
Vasserot Y, Caillet S, Maujean A. 1997. Study of anthocyanin adsorption by yeast lees. Effect of some physicochemical parameters. *Am. J. Enol. Vitic.* 48:433–37
Vidal S, Francis L, Guyot S, Marnet N, Kwiatkowski M, et al. 2003. The mouth-feel properties of grape and apple proanthocyanins in a wine-like medium. *J. Sci. Food Agric.* 83:564–73
Vidal S, Francis L, Noble AC, Kwiatkowski M, Cheynier V, Waters EJ. 2004a. Taste and mouth-feel properties of different types of tannin-like polyphenolic compounds and anthocyanins in wine. *Anal. Chim. Acta* 513:57–65
Vidal S, Meudec E, Cheynier V, Skouroumounis G, Hayasaka Y. 2004b. Mass spectrometric evidence for the existence of oligomeric anthocyanins in grape skins. *J. Agric. Food Chem.* 52:7144–51
Vrhovsek U, Vanzo A, Nemanic J. 2002. Effect of red wine maceration techniques on oligomeric and polymeric proanthocyanidins in wine, cv. Blaufrankisch. *Vitis* 41:47–51
Wang H, Race EJ, Shrikhande AJ. 2003. Anthocyanin transformation in Cabernet Sauvignon wine during aging. *J. Agric. Food Chem.* 51:7989–94
Waterhouse AL. 2002. Wine phenolics. *Ann. N.Y. Acad. Sci.* 957:21–36
Waterhouse AL, Laurie VF. 2006. Oxidation of wine phenolics: a critical evaluation and hypotheses. *Am. J. Enol. Vitic.* 57:306–13

Weber F, Greve K, Durner D, Fischer U, Winterhalter P. 2013. Sensory and chemical characterization of phenolic polymers from red wine obtained by gel permeation chromatography. *Am. J. Enol. Vitic.* 64:15–25

Wollmann N, Hofmann T. 2013. Compositional and sensory characterization of red wine polymers. *J. Agric. Food Chem.* 61:2045–61

Wu X, Beecher GR, Holden JM, Haytowitz DB, Gebhardt SE, Prior RL. 2006. Concentrations of anthocyanins in common foods in the United States and estimation of normal consumption. *J. Agric. Food Chem.* 54:4069–75

Yaminishi T. 1990. Bitter compounds in tea. In *Bitterness in Foods and Beverages*, ed. RL Rouseff, pp. 159–67. Amsterdam: Elsevier. 356 pp.

Yokotsuka K, Sato M, Ueno N, Singleton VL. 2000. Colour and sensory characteristics of Merlot red wines caused by prolonged pomace contact. *J. Wine Res.* 11:7–18

Zhu M, Phillipson D, Greengrass PM, Bowery NE, Cai Y. 1997. Plant polyphenols: Biologically active compounds or nonselective binders to protein? *Phytochemistry* 44:441–47

Zimman A, Joslin WS, Lyon ML, Meier J, Waterhouse AL. 2002. Maceration variables affecting phenolic composition in commercial-scale cabernet sauvignon winemaking trials. *Am. J. Enol. Vitic.* 53:93–98

Annual Review
of Food Science
and Technology

Volume 5, 2014

Contents

From Tomato King to World Food Prize Laureate
Philip E. Nelson 1

Opportunities and Progress
John H. Litchfield 23

Body Weight Regulation and Obesity: Dietary Strategies to Improve the Metabolic Profile
M.J.M. Munsters and W.H.M. Saris 39

Delivery of Lipophilic Bioactives: Assembly, Disassembly, and Reassembly of Lipid Nanoparticles
Mingfei Yao, Hang Xiao, and David Julian McClements 53

Extraction, Evolution, and Sensory Impact of Phenolic Compounds During Red Wine Maceration
L. Federico Casassa and James F. Harbertson 83

Gastric Digestion In Vivo and In Vitro: How the Structural Aspects of Food Influence the Digestion Process
Gail M. Bornhorst and R. Paul Singh 111

New Developments on the Role of Intramuscular Connective Tissue in Meat Toughness
Peter P. Purslow 133

Strategies to Mitigate Peanut Allergy: Production, Processing, Utilization, and Immunotherapy Considerations
Brittany L. White, Xiaolei Shi, Caitlin M. Burk, Michael Kulis, A. Wesley Burks, Timothy H. Sanders, and Jack P. Davis 155

Designing Food Structures for Nutrition and Health Benefits
Jennifer E. Norton, Gareth A. Wallis, Fotis Spyropoulos, Peter J. Lillford, and Ian T. Norton 177

Nanodelivery of Bioactive Components for Food Applications: Types of Delivery Systems, Properties, and Their Effect on ADME Profiles and Toxicity of Nanoparticles
T. Borel and C.M. Sabliov 197

Modern Supercritical Fluid Technology for Food Applications
Jerry W. King 215

Impact of Diet on Human Intestinal Microbiota and Health
Anne Salonen and Willem M. de Vos 239

Applications of Power Ultrasound in Food Processing
Sandra Kentish and Hao Feng 263

Nondestructive Measurement of Fruit and Vegetable Quality
Bart M. Nicolaï, Thijs Defraeye, Bart De Ketelaere, Els Herremans, Maarten L.A.T.M. Hertog, Wouter Saeys, Alessandro Torricelli, Thomas Vandendriessche, and Pieter Verboven 285

Production of Aroma Compounds in Lactic Fermentations
E.J. Smid and M. Kleerebezem 313

Phage Therapy in the Food Industry
Lorraine Endersen, Jim O'Mahony, Colin Hill, R. Paul Ross, Olivia McAuliffe, and Aidan Coffey 327

Public Health Impacts of Foodborne Mycotoxins
Felicia Wu, John D. Groopman, and James J. Pestka 351

Soft Materials Deformation, Flow, and Lubrication Between Compliant Substrates: Impact on Flow Behavior, Mouthfeel, Stability, and Flavor
Nichola Selway and Jason R. Stokes 373

Metabolic Stimulation of Plant Phenolics for Food Preservation and Health
Dipayan Sarkar and Kalidas Shetty 395

Indexes

Cumulative Index of Contributing Authors, Volumes 1–5 415

Cumulative Index of Article Titles, Volumes 1–5 418

Errata

An online log of corrections to *Annual Review of Food Science and Technology* articles may be found at http://www.annualreviews.org/errata/food