WHITE

WINE

ENOLOGY

BY THE SAME AUTHOR AND CO-AUTHORS

Red Wine Enology

Tannin and Redox Management of Red Wines

Board & Bench Publishing, 2021

Acidity Management in Musts and Wines

- 2nd edition -

Acidification, deacidification, crystal stabilization, and sensory consequences

Board & Bench Publishing, 2021

Cool-Climate White Wine Oenology

The Crowood Press, 2024

White Wine Enology

OPTIMIZING SHELF LIFE AND FLAVOR STABILITY OF WHITE WINES

- 2nd Edition -

Volker Schneider

tredition, Ahrensburg, Germany

White Wine Enology

2nd edition 2024

Printing and distribution by order of the author:

tredition GmbH, Heinz-Beusen-Stieg 5, 22926 Ahrensburg, Germany

The author is responsible for the content. Publication and distribution are carried out on behalf of the author, to be contacted at: tredition GmbH, Impressumservice, Heinz-Beusen-Stieg 5, 22926 Ahrensburg, Germany.

ISBN: 978-3-384-01615-7

Table of Contents

Preface to the 1st Edition

The enological literature tends to put emphasis on red wines; comprehensive treatises on the enology of white wines are scarce. When such treatises appear, they tend to focus upon maximizing aroma and quality in the widest sense. This book takes a different approach. It deals primarily with the preservation of quality. Therefore, the reader should not be disappointed when he finds other topics such as acidity management and fermentation strategies are only marginally dealt with. And as a highly specialized book, it is dedicated exclusively to fruity white wines regardless of whether they are dry or off-dry. Ultimately, it shows that the enology of white wines is quite different from that of red wines in many aspects.

Fruity white wines are usually unoaked or have undergone only limited barrel aging, which does not detract much from the original freshness and varietal character of young wines. They are the opposite of wines that are characterized by deliberate aging in oak barrels and the typical flavors they impart. They constitute the largest share of the global white wine market. However, their rapid and often premature aging in one or another way is a problem almost all wineries are concerned with. This applies despite the fact that some of these wines might undergo what is considered graceful aging. In an innovative approach to address these concerns, this book deals with flavor preservation rather than with vinification strategies aiming at obtaining short-lived quality benefits. In doing so, it addresses one of the key issues of white wine enology, which is the limited shelf life and poor flavor stability of most of these wines. However, it does not address the hedonic question of 'good' or 'bad', which is well known to be subjective and one which countless opinion leaders feel called upon to answer.

By definition, wine aging is not related to common wine faults of microbial origin, which might accidentally arise during aging or be detected only after some time of storage. In contrast, it is based on chemical reactions occurring at variable rates. As will be shown in chapter 4, these rates and their sensory outcome can be affected by global climate change, which introduces new challenges past generations did not experience.

As a chemical process, white wine aging comprises much more than the commonly known oxidative aging, frequently referred to as premox. Thus, discussing adverse aging means, firstly, differentiating the various kinds of aging according to sensory criteria, specifying the flavor-active compounds responsible for them, and identifying the chemical mechanisms of their formation. That's why this book has a strong sensory focus. In a second step, there are clear definitions of enological measures to be taken or avoided in order to mitigate the aging reactions and, hence, to improve flavor stability. These measures start as early as on the crush pad and continue throughout all phases of juice processing, wine stabilization, bottling, and storage.

In response to these complex challenges, this book covers one of the key areas of enology hardly ever embraced in a single volume. It aims at providing a valuable insight into the inherently cross-disciplinary nature of fine white wine making, unifying knowledge scattered across chemistry, technology, and microbiology. All issues it raises are traced back to their scientific fundamentals and illustrated by original data, most of them obtained under commercial winemaking conditions. The listing of comprehensive bibliographical references allows for deepening up-to-date expertise on specific subject areas.

Nevertheless, this book is not intended to be a merely scholarly one written like so many others in this field from a purely academic perspective, but rather reflects the industry background of the author. It is aimed at professional winemakers, lecturers of enology and consultants without experience in practical winemaking, lab staff, students willing to look behind theory, and amateur winemakers with some scientific background. In light of their frequent questions, it also suggests solutions to typical engineering issues in winery operations. Thus, numerous practical hints and technical details of hands-on winery work round up the picture and provide a holistic view of one of the most fascinating fields of contemporary winemaking.

However, winemaking is more than process technology. After decades of a tendency to technocracy and even over-processing, a growing number of winemakers embrace a trend toward minimal or non-interventionist winemaking in an attempt to respect consumer expectations and traditions. Recent research has allowed us to understand why some traditional techniques, evolved through experience, can be beneficial. It has provided knowledge, insights, and carefully selected techniques that can even improve the fine heritage of traditional winemaking. Examples such as the utilization of oxygen in must or working with yeast lees after fermentation are discussed in detail.

As a guidance for readers and in order to make reading easier, each major chapter designated by a two-digit number is preceded by a short introduction summarizing the contents. Cross-references within the text provide additional guidance.

The author has many friends and colleagues to thank for being willing to critically review and comment the manuscript of this book before publication. He accepts liability for any errors it might contain. Their disclosure will be taken into account in a future edition.

The author

Preface to the 2nd Edition

In the five years following the publication of the first edition of this book by Board & Bench Publishing, there was a lot of feedback from interested readers, which in turn led to many stimulating discussions. Simultaneously, many new insights have emerged, both from the scientific side and on the basis of practical experience from a wide range of wine growing countries and climatic regions. All this constituted a significant expansion upon the book's content, thus justifying a new edition.

Whilst the original approach of combining science with practice has been preserved, there have been significant additions to the content on must processing, the issue of reduction flavor and protection from oxygen uptake after fermentation. Additional real-world examples have been included.

It is important to note that this book was written without any support or involvement from the wine supply industry. It is imperative, however, to thank Mark Tracey, England, for the fruitful discussions without which the book would not have reached this level of completeness.

The author

1. Introduction

The quality and market value of white table wines strongly depend on their distinctive flavor, which may be varietal, origin-related, or fermentation-derived to a variable degree. Much effort and enological knowledge is dedicated to its production, but much less attention is paid to its preservation. However, white wines are sensitive products. They are subject to a far more dynamic aging than red wines. In the majority of cases, the sensory outcome of this aging process is opposed to current understanding of quality; white wines aged in a positive way are rare exceptions. The limited shelf life of white table wines after bottling is a global problem.

All wines change during storage. These changes are driven by intrinsic and extrinsic factors. A gradual decay of fruity aroma attributes, particularly of those produced by the fermentation metabolism of yeast, is common to all kinds of wine and considered unavoidable. This process is referred to as maturation. In a second phase, distinctive aging flavors appear in white wines, usually after bottling. Their occurrence adversely affects the sensory profile and quality patterns initially intended by the winemaker.

In order to take targeted measures for optimizing white wine shelf life and flavor stability, it is indispensable to differentiate the various kinds of aging flavor according to their sensory characteristics and chemical pathways. For this purpose, there is a need of specific terms applied in descriptive sensory analysis. Their precise use depends on sensory training, experience, and linguistic expertise of the tasters involved. Unfortunately and much to the disadvantage of wine quality control, sensory terms are frequently misused, abused, or exchanged among themselves. The term "oxidized" is a good example of linguistic confusion. It gives no information about whether there is the typical smell of free acetaldehyde involved in the aroma pattern as it might only occur in the absence of free sulfur dioxide, or whether the smell is elicited by other oxidation products generated despite the presence of free sulfur dioxide. Misunderstandings caused by imprecise language use often lead to erroneous decisions when it comes to choose enological countermeasures for preventing or remedying premature aging flavors.

According to prevailing sensory criteria, there are four different kinds of white wine aging:

- **Typical aging**, driven by temperature and/or oxygen, gives rise to a wine commonly called maderized, evolved, or simply oxidized. It is reminiscent of cooked vegetables, boiled potatoes, wet soil, black tea, honey, nuts, hay, and straw. Additionally, the odor of free acetaldehyde reminding one of bruised apples may appear and mask these olfactory descriptors when free sulfur dioxide has been decreased to nil by oxygen uptake. An intensification of color and an increase of astringency on the palate may occur simultaneously, but must not do so.

- **Reductive aging** leading to the formation of volatile sulfur compounds, particularly thiols and hydrogen sulfide, whose stinky smell is reminiscent of burnt rubber, cooked cabbage, rotten eggs, and garlic. Its appearance is fostered when wines prone to produce it are stored under anoxic conditions or bottled using bottle closures with a low oxygen ingress rate. Therefore, it is also known as post-bottling reduction flavor.

- **Atypical aging** resulting essentially from the conversion of a phytohormone called indole-3-acetic acid into 2-aminoacetophenone and some by-products reminiscent of mothballs, soap, floor polish, acacia blossom, and laundry in wines produced from stressed or underripe fruit.

- **Petrol flavor** calling to mind gasoline, kerosene, and dry apricots. It is related to an acidic hydrolysis of grape-derived precursors found in wines obtained from a very limited number of grape varieties, Riesling in particular. It is not affected by reactions of oxidation or reduction.

Typical aging due to oxidation with its familiar sensory pattern has always been known and is still the most common form of aging of white wines. Therefore, it is also considered as aging per se. The other variants of aging are considered abnormal or faulty deviations from typical white wine evolution. The frequently encountered confusion between typical and atypical aging is a particularly serious problem in enology with far reaching consequences.

As a matter of principle, any white wine is subject to one or another kind of aging. The only question is which specific form of aging will occur, and how fast it will do so. It is also possible that two forms of aging appear concomitantly. Combinations of aging flavors that are frequently observed include:

- typical aging + atypical aging,
- petrol flavor + typical aging,
- atypical aging + reductive aging,
- reductive aging + petrol flavor.

The sensory identification of these combinations of concomitantly occurring types of aging places high demands on sensory training and enological expertise.

2. Typical and oxidative aging

2.1. Chemical pathways, reaction products, and sensory results

Introduction: This chapter commences by describing the flavor-active compounds generated during what is considered typical aging, the odor profile they elicit, their precursors, and the most important reaction pathways responsible for their formation. It distinguishes between products always formed under oxygen-free conditions and those relying on oxygen uptake. To understand these issues, we will make a small excursion into the broad field of organic chemistry responsible for what we smell and taste in white wines. Footnote explanations facilitate understanding for those who do not deal with chemical terminology on a daily basis. Those who want to turn immediately to the more practical aspects can start reading with section 2.3. However, when too much school chemistry has fallen into oblivion and questions about it arise, then it is advisable to return to the beginning of this book.

2.1.1. Non-oxidative aging reactions

Under standard winery conditions, wine picks up oxygen before, during, and after bottling. The amounts picked up are highly variable and hardly ever checked.

Based on a given amount of oxygen picked up by the wine, oxidation of white wines leads to a substantially different outcome than that of red wines. It is standard knowledge that a certain amount of oxygen is required for maturation of red wines. Oxygen uptake, however, rarely improves the sensory quality of white wines that are produced to display fruity, floral, vegetative, or mineral aromas considered prerequisite for the sensory expression of their cultivar or origin.

From a chemical point of view, typical wine aging is a complex process that is not only driven by oxidation. Before going into details about how typical aging can be mitigated by enological measures, an up-to-date overview of the underlying reactions and compounds is useful.

Non-oxidative aging reactions in any wine

Whilst a considerable part of typical aging is driven by oxygen-related reactions in most wines, it is obvious that there are also non-oxidative reactions taking place simultaneously. They occur in any wine regardless of its oxygen exposure, albeit their significance is often underestimated. For a better differentiation and understanding of oxidative aging's nature as the very traditional problem in white winemaking, they are covered at first.

Every winemaker is familiar with the rather unspecific decay of fruity aroma attributes of any kind of wine during the very first weeks and months after alcoholic fermentation. It is basically related to a gradual loss of fermentation-derived aromatics, which are not specific to the grape variety the wine originated from but rather to the yeast strain it was fermented with. The hydrolytic breakdown[1] of acetic acid esters with higher alcohols resulting from yeast fermentation metabolism plays a major role in this process (Rapp and Mandery 1986, Garofolo and Piracci 1994). Depending on storage temperature, this reaction comes to a complete halt after some months or years, when hydrolysis achieves an equilibrium between esters and their corresponding alcohols. It is unavoidable in very young wines, but not necessarily considered as a kind of aging detrimental to quality.

A striking example of non-oxidative losses of fruity varietal aroma by hydrolysis can be found in Sauvignon blanc wines stored in thoroughly topped stainless steel tanks or screw capped bottles, in which oxidative losses are negligible. These wines, when obtained from ripe fruit, contain various polyfunctional thiols[2], which are responsible for their varietal aroma of tropical fruits. One of these thiols is 3-mercaptohexan-1-ol acetate (3-MHA), an ester with considerable sensory impact in young Sauvignon wines and responsible for their passion fruit and grapefruit aroma. This ester undergoes hydrolysis and declines steadily in concentration, originating 3-mercaptohexanol (3-MH) and acetic acid (Herbst-Johnson et al. 2011). As 3-MH has an approximately 15-fold higher perception threshold than 3-MHA (Coetzee and du Toit 2012, 2015), this hydrolysis results in a lower aroma intensity and a different aroma profile within a few months post-fermentation.

However, there is more. In an early work, several lactones produced by multifarious reaction mechanisms have been identified as partially responsible for an off-odor of white wines aged under anoxic[3]aging conditions (Muller et al. 1973).

---

[1] A hydrolytic breakdown, also denominated as hydrolysis, is a chemical reaction in which water is used to break down a larger molecule into two smaller ones.

[2] Thiols are sulfur-containing organic molecules with one or more -SH functional groups. Most of them display strong odors, which can be pleasant or repulsive. Refer to section 3.1.1 for details.

[3] anoxic = in the absence of oxygen

At a later stage, the formation of odor-active compounds by reactions between amino acids on one hand and dicarbonyl compounds (as diacetyl) or ketones (as acetoin) on the other hand was proven. Thus, in the presence of amino acids such as methionine, leucine, isoleucine and phenylalanine, the production of higher aldehydes, pyrazines, thiazoles, thiazolidines, and oxyzoles by the Maillard and Strecker reactions was observed at relatively low temperature and wine pH. These strong-smelling compounds display odors of corn, roasted hazelnuts, popcorn, sulfur, and ripe fruits (Marchand et al. 2000, Pripis-Nicolau et al. 2000). As might be expected, the synthesis of these compounds strongly increases with temperature (Section 2.7).

It will be shown subsequently that the aroma attributes referred to above are not very different from those produced under conditions of oxidative aging. Therefore, it can be fairly difficult to distinguish by sensory means whether typical aging has been caused by oxidation, by mere thermal load under anoxic conditions, or by both. Clearly, oxidation accelerates typical aging as perceived by smell, but exclusion of oxygen does not totally prevent it.

The aforementioned reactions of non-oxidative aging occur in any wine since the compounds responsible for it are not specific to a particular type of wine. In some wines, however, their detrimental sensory expression is not perceived because it is masked and superimposed by other kinds of white wine aging that are not considered as 'typical'. They comprise

- petrol flavor, which can occur predominantly in Riesling wines (Chapter 5),
- empyreumatic flavors affecting some wines of certain varieties grown in particular areas (Section 3.1.2).
- reductive taints, also known as reduction flavor, imparting a stinky odor in wines that are prone to develop it (Chapter 3).

The relative share of non-oxidative reactions has gained in importance since almost air-tight metal-lined screw caps (Section 3.5) were adopted in many countries such as Australia, New Zealand, and Central European ones for sealing bottled wines. These seals are able to create an anoxic environment excluding oxidative aging reactions, but cannot avoid a rapid decay of fruity varietal aromatics and the appearance of a roasted or nut-like aging aroma when the storage temperature is inadmissibly high. In particular, they foster the appearance of reduction flavor even at low temperatures.

Sensory studies concerning the impact of temperature on the rate of typical aging and petrol flavor are available (Sections 2.7 and 5.3). These studies and their practical implications deserve much more attention than they presently do. Further work in this field should try to assess the relative proportions of oxygen-dependent and non-oxidative reactions in the overall rate of typical aging.

2.1.2. Oxidative aging

Traditionally, oxygen pickup has been poorly controlled in the wine industry. As a consequence, typical aging is closely associated with oxidation. The sensory characteristics of oxidative aging are widespread and have always been observed by any winemaker. They include aroma descriptors such as cooked vegetables, boiled potatoes, black tea, damp garden soil, nuts, honey, and hay. Frequently, an increase in astringency as well as a color increase toward a darker yellow or even brown can also be noted. These sensory changes are also dependent on the flavonoid phenol content (Section 2.2.2).

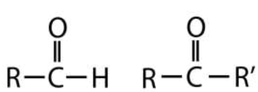
For a long time, there was only limited knowledge about the chemical reactions and reaction products responsible for oxidative spoilage. Only after the wider dissemination of more sophisticated analytical tools over the last quarter of a century, knowledge about typical aging has become more extensive.

The role of malodorous carbonyls produced upon oxidation

Carbonyl compounds[4] play a central role in the flavor of oxidative aging. Under storage conditions allowing for oxygen uptake, the coupled oxidation of vicinal dihydroxy-phenols leads to the formation of acetaldehyde and higher aldehydes, which substantially contribute to the aroma of Sherry wines (Wildenradt and Singleton 1974) and, at lower concentrations, also to that of other wines. Whilst the enzymatic generation of acetaldehyde during alcoholic fermentation is common to all wines, its non-enzymatic formation by oxidation can severely compromise the quality of white wines under certain conditions (Baro and Quiros Carrasco 1977). In the further course of this section, it will be shown that these conditions only exist when no free sulfur dioxide is present. Finally, for Riesling wines, it has already been shown a long time ago that under conditions of aerobic

---

[4] Carbonyls are organic molecules that carry a carbonyl group. This group is composed of a carbon atom (C) double-bonded to an oxygen atom (O) and written as -C=O. According to their molecular structure, carbonyl compounds are comprised of aldehydes and ketones. In aldehydes, the carbonyl carbon is connected to a carbon-based alkyl group (R) on one side and a hydrogen (H) atom on the other. Thus, their carbonyl group always occurs at the end of the molecule. In contrast, the ketones do not have the hydrogen that the aldehydes have, but two carbon-based alkyl groups connected to both sides of the carbonyl carbon. Hence, their carbonyl group always occurs in the middle of the molecule.



aldehyde ketone

storage a large array of compounds is produced that is not observed when storage takes place under anoxic conditions. These odor-active compounds include benzaldehyde, furfural, and acetaldehyde (Simpson 1978).

When wine was stored in wooden barrels allowing for oxygen uptake, an increase of saturated and unsaturated carbonyl compounds as well as methyl ketones was observed. Under these conditions, the typical smell of the oxidized wine was tentatively ascribed to 2-nonanon and 2-undecanone (Ferreira and Bertrand 1996).

In another study on white wines undergoing barrel-aging, 2,5-furandicarbaldehyde, furyl hydroxymethyl ketone, and hydroxymaltol have been identified as further chemical markers of oxidative aging, especially of the honey descriptor resulting therefrom. However, it is not known to which extent these compounds are derived from wood. Their concentration decreases by post-fermentation yeast lees stirring (Lavigne-Cruège et al. 2000). It is not clear whether the latter effect is due to adsorption of these compounds by yeast lees or to consumption of dissolved oxygen by post-fermentation yeast cells (Section 2.5.6).

Under conditions of accelerated aging, 22 new odor-active compounds were identified for the first time after oxidation of six different white wines. Four of them were present in all wines and 14 in more than half of them. Several of these compounds displayed a repulsive, oxidized smell. Using methods of sensory profiling analysis and multivariate statistics, 15 of the discriminated odor attributes proved to be affected by oxidation, whereby the overall aroma pattern changed by 60%. There was a sensory oxidation pattern common to all oxidized wines (Escudero et al. 2000 a).

The aroma profile of oxidized or 'evolved' white wines is ascribed to higher aldehydes[5] such as methional. It is produced by oxidation of coupled oxidation of methionol with ethanol, or via Strecker degradation of the amino acid methionine mediated by ortho-quinones[6] formed during wine oxidation (Escudero et al. 2000 b, Ferreira 2003 a).

Both alcohols and amino acids act as precursors of malodorous carbonyls

In simple terms, the Strecker degradation of amino acids involves their interaction with dicarbonyl[7] compounds. In the presence of α-dicarbonyl compounds,

[5] Higher aldehydes have more than one carbonyl (-C=O) group or a branched hydrocarbon chain, in contrast to simple aldehydes with only one carbonyl group and a linear hydrocarbon chain.

[6] As will be outlined in section 2.2.1, quinones are the oxidation products of phenols.

[7] Dicarbonyls = molecules with two carbonyl (–C=O) groups.

the amino acid is decarboxylated[8] and deaminated[9], thus forming an aldehyde with one carbon atom less than the original amino acid and known as "Strecker aldehyde". According to this pathway, 3-methylbutanal (malty aroma), phenylacetaldehyde (honey aroma) and methional (cooked vegetable aroma) are formed from the corresponding amino acids leucine, phenylalanine and methionine, respectively (Hofmann and Schieberle 2000).

In a wider sense, many other dicarbonyl compounds including ortho-quinones can be used. Indeed, in wine conditions, Strecker degradation was shown to occur to a greater extent via the reaction of ortho-quinones with the amino acids when metal ions are present as in any wine (Monforte et al. 2018). As already stated, these quinones are generated by oxidation of phenols, which act as primary oxygen acceptors in wine (Section 2.2.1.). Under comparable oxidation conditions, catechin, a flavonoid phenol, yielded more phenylacetaldehyde from phenylalanine than nonflavonoid phenols (Oliveira et al. 2017).

After the sensory role of the Strecker aldehydes was revealed, subsequent studies showed that the intensity of the cooked vegetables odor also correlates positively with the concentrations of 2-nonenal, benzaldehyde, furfural, and eugenol, while acetaldehyde levels are not significantly influenced by oxidation (Escudero et al. 2002). Further research confirmed the importance of methional as a key compound in the aroma pattern of oxidized white wines, altogether with phenylacetaldehyde, 3-(methylthio)-propionaldehyde, and sotolon (4,5-dimethyl-3-dihydroxy-2(5H)-furanone) (Ferreira et al. 2002, 2003 a, 2003 b, Ferreira 2007), benzaldehyde, furfural, and other higher aldehydes resulting from oxidation of unsaturated fatty acids[10] (Ferreira et al. 1997, Culleré et al 2007) or amino acids (Bueno et al. 2016).

As a summary of compositional data, it can be stated that the typical aroma of oxidative aging is caused by a large variety of carbonyls, among which higher aldehydes are the most important compounds, and sotolon as a volatile lactone[11]. For simplifying the analytical quantification of that kind of aroma, 2-phenylacetaldehyde, methional, sotolon, and 3-methylbutanal can be used as chemical markers (Pons et al. 2015, Mayr et al. 2015).

It is not yet clearly established whether the main pathway of the formation of all these aldehydes is the Strecker degradation of their corresponding amino acids

---

[8] Decarboxylation = removal of a carboxyl (-COOH) group typical for carboxylic acids.

[9] Diamination = removal of an amino (-NH2) typical for amino acids.

[10] Fatty acids are carboxylic acids with at least one carboxylic (-COOH) group and an aliphatic (composed solely of carbon and hydrogen) chain. They are unsaturated when they have one or more C=C double bonds in their chain.

[11] Lactones are cyclic carboxylic esters containing a -C(=O)-O- structure formed by intramolecular esterification of carboxylic acids.

or direct oxidation of their corresponding alcohols. However, from a practical point of view, the conditions of their generation and their sensory impact are much more important: Their concentration strongly correlates with oxygen uptake, temperature, and the intensity of odor descriptors referred to as boiled potatoes, farm-feed, hay, straw, wood, honey, etc.

Microbiological approach to reduce aging-relevant amino acids

Based on the assumption that the higher aldehydes involved in the smell of oxidative aging are primarily formed by the Strecker reaction of their corresponding amino acids, first attempts have been made to reduce the concentration of these amino acids by microbiological means. Specifically, Saccharomyces cerevisiae yeast strains were selected on the basis of their high consumption of amino acids such as phenylalanine, methionine and leucine.

Following fermentations of real must with these yeasts, chemical and sensory analyses were performed after one and three months of an aging process under periodic aeration at room temperature. Some of the yeast strains left behind lower residual concentrations of pro-oxidative amino acids after fermentation. Thus, they allowed production of less 'evolved' wines with lower mounts of higher aldehydes and lower sensory scores for oxidation-related aroma descriptors (Balboa-Lagunero et al. 2013).

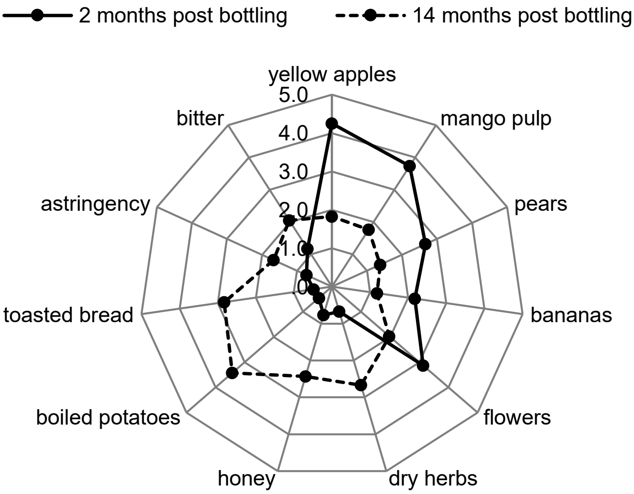
It would make sense to continue such trials on a pilot scale and bring them to technical maturity in view of the current trend to reduce SO_2 additions. They would open the way to new perspectives in research on yeast, which generally focuses on other topics such as fermentation kinetics or the production of fruity aromas.

Variable acceptance threshold of oxidative aging

As already stated, under comparable oxidation and storage conditions, the relative concentrations of oxidation-related higher aldehydes depend on the respective kinds and amounts of precursors and further intrinsic factors of each wine. They are determined by viticultural conditions, fruit ripeness, vinification and even yeast strain. This explains why oxidative aging displays somewhat variable aroma profiles. It might explain furthermore why some tasters perceive oxidative aging as less repulsive in wines made from very ripe fruit than in wines made from less ripe grapes. Fruit quality, consumers' expectations, traditions, and cultural environment determine to what extent the flavor of typical aging is accepted.

Figure 1 gives an extreme example of typical aging in an unoaked white wine intended to be fruity. The aroma profile changed completely during the first year of bottle storage. As a side effect, astringency and bitter ratings also increased. The reason for this is explained in section 2.2.1.

Figure 1: Typical aging of an unoaked Chardonnay during 12 months of bottle storage with cork at 18° C (65 F).



Limited effect of sulfur dioxide on higher aldehydes

The formation rates of the oxidation-derived higher aldehydes such as methional and phenylacetaldehyde are strongly dependent on the individual wine for a given amount of oxygen consumed. Most of them display a formation rate that correlates positively with the concentration of their corresponding amino acids, but not with their corresponding alcohols. Indeed, they are to a large extent complexed as bisulfite adducts at the free SO_2 levels usually found in wines. Cleavage of the bound forms occurs during the first steps of oxidation as a consequence of equilibrium shifts caused by SO_2 depletion. As the free SO_2 level decreases, the concentration of the free odor-active fraction increases. At low levels of free SO_2, *de novo* formation can also be observed with amino acids as the most important precursors (Grant-Preece et al. 2013, Ferreira et al. 2015, Bueno et al. 2016).

The entirety of research results show that higher aldehydes responsible for the smell of oxidative aging are ultimately generated by several pathways altogether:

- oxidation of higher alcohols,
- Strecker degradation of amino acids,
- release from SO_2-bound forms.