Chapter

Main Operating Conditions That Can Influence the Evolution of Wines during Long-Term Storage

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Abstract

Nowadays, among all the possible wine packaging materials, an increasing use of polyethylene terephthalate (PET), multilayer Tetra Brik, and Bag-in-Box containers can be observed. Due to the fact that oxygen is counted among the primary factors which act on wine aging and degradation, a tight control of oxygen is critical during wine making and conservation. Wine protection from external conditions is strictly linked to packaging, which has the basic role to preserve the quality of wine during its evolution and aging. In this chapter the time evolution of different wines will be analyzed according to the storage conditions used. In particular, the following specific cases of study will be discussed: Case of study 1a, 1b, and 1c: influence of storage conditions (storage temperature, packaging material and volume of packaging) on the time evolution of red wine over a storage period of 12 months. Case of study 2: evolution of glass bottled rosé wine as a function of closure (cork stopper with or without aluminum capsule), storage position and brightness regime over a period 12 months.

Keywords: red wine, rosé wine, storage conditions, packaging, bottle position, capsule, antioxidant capacity, kinetic characterization

1. Introduction

1.1 Food packaging, shelf life, and quality decay rate

According to [1], it is possible to highlight four basic functions for traditional food packaging. The most basic function of packaging is *containment*, as food products must be contained before they can be moved from one place to another. Furthermore, for many food products, the *protection* afforded by the package is an essential part of the preservation process. At this regard, packaging protects its contents from the outside environmental effects of water, water vapor, gases, odors, microorganisms, dust, shocks, vibrations, compressive forces, and so on. Packaging allows also primary packages to be assembled into secondary (e.g., cardboard boxes) and tertiary packages (e.g., stretch-wrapped pallets), thus improving the *convenience* throughout the supply chain. In this way, the handling of the material is made more functional because a reduced number of containers and loading operations must be handled or carried out, respectively. Finally, packaging can provide the *communication* necessary for food sailing: as consumers can make purchasing decisions using the numerous clues provided by the graphics and the distinctive shapes of the packaging, there is an old saying that "a package must protect what it sells and sell what it protects."

Overall, packaging is an essential element in food manufacture since it facilitates food management, increases food shelf life, and makes it more acceptable to consumers.

According to [2], "shelf life" can be defined as a finite length of time after production (in some cases after maturation or aging) and packaging during which the food product retains a required level of quality under well-defined storage conditions. In other words, taking for granted the consumer's safety, for any kind of food product, there should be a defined quality level (defined as "acceptability limit") discriminating products that are still acceptable for consumption from those no longer acceptable. Once defined the storage conditions to be used, for each food product, "shelf life" represents the time needed to reach the acceptability limit which is directly influenced by the "quality decay rate" of the stored food.

1.2 Packaging material for wine storage

Nowadays, glass containers are still preferred for wine bottling [3] being them readily recyclable and characterized by a high impermeability to gases and vapors, stability over time, and transparency [4]. On the other hand, because of some objective limitations for the extensive use of glass containers in food industry (i.e., heavy weight, fragility to internal pressure, impact and thermal shock, etc.) [5], there is a worldwide growing demand for alternative solutions to glass also for wine bottling [6]. This with the aim to propose inexpensive packaging resources, practical to use and often marketed as "eco-friendly," particularly in relation to their contributions to waste prevention [3, 7, 8].

For the above reasons, starting from the past two decades, among all the possible packaging materials, an increased utilization of polymeric materials also for wine packaging, including polyethylene terephthalate (PET) bottles, multilayer Tetra Brik®, and Bag-in-Box (BiB)-type containers, has been observed [1, 9]. Some of the main advantages and disadvantages of typical materials used in wine packaging are reported in **Table 1**.

1.3 Main storage conditions affecting the quality decay rate of wines

According to [15], wine aging can be defined as the time that goes from the end of winemaking (during which wine is subjected to different operations depending on both the vine and usual winery methodology) to its final consumption. In bottles, the proper aging of wine is linked to the presence of reduced conditions that lead to color changes and to the establishment of desired sensory (olfactory and tasteful) characteristics. During evolution and aging, the contact of wine with oxygen should be limited to the minimum. The time needed to develop such transformation differs among wines and is a function of both starting chemical composition and storage conditions.

Among all the operating conditions that can be selected during long-term wine storage, the main ones involved in the quality decay rate of wines are described below.

Material	Brief description	Advantages	Disadvantages
Glass [10, 11]	Soda-lime glass, composed of about 75% silicon dioxide (SiO_2), calcium oxide (CaO), sodium oxide (Na_2O), and several minor additives	Impermeable to gases and vapors Odorless and chemically inert Useful for heat sterilization Good insulation Produced in different shapes Variations in glass color can protect light-sensitive contents Transparent Reusable and recyclable	Brittleness Fragility to internal pressure, impact, and thermal shock Needs a separate closure Limitation in thin glass Heavyweight Transportation costs
PET [12]	Polyethylene terephthalate (PET) is combined with terephthalic acid and ethylene glycol	Fluid and moldable Produced in different shapes Flexible Variations in PET color can protect light-sensitive contents Transparent Inexpensive Lightweight Wide range of physical and optical properties Easy to print Integrated into production processes where the package is formed, filled, and sealed in the same production line Easy handling by consumers Needs a separate closure	Variable permeability to light Limited reuse Poor barrier to gases and vapors Not suitable to protect wine for long periods of time Migration of chemicals from PET to food
Tetra Brik® [13]	Tetra Brik® packaging is made up of three raw materials: duplex paper (about 75%), aluminum (about 5%), and low-density polyethylene (about 20%)	Good barrier properties to light Integrated into production processes where the package is formed, filled, and sealed in the same production line Lightweight Recyclable Efficient, low-cost protection Easy handling by consumers	Impacts the organoleptic quality Poor barrier to gases and vapors Not suitable to protect wine for long periods of time When used as primary packaging, it is coated or laminated to improve functional and protective properties Migration of chemicals from internal coating to the content Hard to recycle
Bag-in-Box® (BiB) [14]	The product is sealed in a bag comprising one or more plies of high barrier flexible films, mechanically supported by an external paperboard carton. A valve fitment is attached to the bag through which the product is filled and dispensed	Good barrier properties to light Integrated into production processes where the package is formed, filled, and sealed in the same production line Lightweight Improved distribution efficiency Enhanced end-use convenience Increased cost-effectiveness Easy handling by consumers	Impacts the organoleptic quality Poor barrier to light, gases and vapors Easily sorbs aroma compounds, particularly if hydrophobic Incomplete air tightness of the valve Not suitable to protect wine for long periods of time

Table 1.
Advantages and disadvantages of typical materials used in wine packaging.

1.3.1 pO_2 in storage atmosphere

During wine storage, spontaneous clearing, color stabilization, and reactions that lead to the formation of more complex compounds are observed [16]. In red and rosé wines, reactions of copigmentation and polymerization of anthocyanins (Ant) take place as the storage time in bottle increases [17]. These reactions cause the formation of more stable compounds responsible for the change from the bluish-red hues of young wines to the orange-red ones characteristic of aged wines [18].

As oxygen is one of the main factors affecting wine evolution as well as its deterioration [3, 19–22], changes occurring after fermentation are partly driven by chemical oxidations deriving from winemaking and storage [23].

During storage in glass bottle, the only barrier against the external atmosphere is represented by the closure system, and the evolution of phenolic compounds in the development of wine color and mouthfeel mainly depends on the transfer of oxygen through the bottle stopper [24]. In this condition, oxygen diffusion into the bottled wine is strongly dependent on the effective sealing of the closure [25, 26]. Indeed, oxygen permeability may greatly change from cap to cap, and this heterogeneity is one of the main factors affecting variation among bottles [23].

Furthermore, as recently reported by [27, 28], the combination of aluminum capsule with cork stopper as well as the storage position used during bottle aging can deeply influence the oxygen intake through the closure system and then the quality decay rate of the stored wine.

1.3.2 Storage temperature

Arrhenius equation describes the relationship between the kinetic constant of a reaction and temperature [29]:

$$k = A \bullet e^{-\frac{E_a}{R \times T}} \tag{1}$$

where k, kinetic constant; A, pre-exponential factor, constant for temperature variations not too high, the value of which depends on the frequency of collisions and the steric factor; E_a, activation energy, also constant for temperature variations not too high; R, gas constant 8.3144 J/(mol K); T, absolute temperature (K).

Based on this equation, it can be assumed that, as the temperature rises, there is an increase in the rate of occurring reactions.

In this context, the reaction mechanisms involved in wine aging as well as their activation energy are very sensitive to temperature, and increasing storage temperature involves an acceleration of the aging process of wine thus influencing its shelf life. In particular, high temperature is a particularly unfavorable condition during storage as the rate of quinone formation enhances with the increase in temperature, although the kinetics of this reaction is temperature independent [30–34].

Besides affecting the kinetics of degradative reactions and particularly the oxidative ones [35–37], temperature also influences the amount of oxygen dissolved in wine. At temperatures of 5–35°C, the amount of O_2 needed for the saturated wine ranged from 10.5 to 5.6 mg/L, the lowest concentration being dissolved at the highest temperature [38]. Furthermore, temperature influences the oxygen permeability of thermoplastic polymers [1, 34, 39, 40].

Other parameters affected by temperature are some physical features of wines, such as viscosity and density: Košmerl and Abramovič [41] characterized 40 samples of bottled Slovenian wines by standard chemical analyses, in order to analyze the effect of temperature (from 20 to 50°C) on their density and viscosity. They concluded that wine behaved as Newtonian fluids so that their density and viscosity were dependent on temperature and decreased nonlinearly with increasing temperature. In particular, they observed a very strong effect of temperature on the viscosity of wines in samples with a high reducing sugar concentration. Yanniotis et al. [42] measured the viscosity of commercial red, white, and sweet wines as well as of model aqueous ethanol and glycerol solutions; they observed that the viscosity decreased with the increase in temperature, and this trend could be fully described by the Arrhenius equation. It was also observed that alcohol and dry extract were the two main factors influencing the viscosity of wines [42].

1.3.3 Brightness level

Exposure of bottled wine to light tends to occur in retail outlets or in domestic situations where artificial (including fluorescent) lighting generates short wavelength (low visible and ultraviolet) radiations. As widely reported in the literature and, in particular, by Dias and coworkers [43], both off-odor production and pigmentation enhancement occur following light exposure.

Most of transparent glass bottles do not guarantee an adequate protection from long-wave radiations, thus exposing wine (mainly white and rosé) to the negative effects of photooxidation. Such reaction is often supported and potentiated by high temperatures [43] which are often detected on the shelves of some supermarkets.

1.4 Main parameters useful to describe the quality decay of wine over storage time

1.4.1 Chemical evolution of stored wine: Kinetics of SO_2 and anthocyanin degradation

As SO_2 plays an important protective role against oxidation in wine, the chemical degradation of this compound during storage may represent a good index of the oxidative processes occurring in the product as a function of the packaging used [39, 44].

Generally, in wine, SO_2 can exist in many interconvertible forms represented by a variety of “free” (FSO_2) and “bound” (BSO_2) forms. The actual protective concentration of SO_2 during wine evolution and aging depends on many factors (i.e., pH, level and type of binding compounds, oxygen concentration, and so on). Thus, the total SO_2 concentration ($TSO_2 = FSO_2 + BSO_2$) can be considered an index of the oxidative damage caused by storage conditions. Indeed, FSO_2 is an intermediate product which concentration is influenced by various chemical reactions different from the oxidative ones.

As reported in [26], the time evolution of TSO_2 concentration could be described by a first-order kinetic equation:

$$-d[TSO_2]_{t=t}/dt = kTSO_2 \bullet [TSO_2]_{t=t} \tag{2}$$

where k_{TSO2} is the kinetic constant related to TSO_2 degradation and $[TSO_2]_{t=t}$ is the concentration of total SO_2 at the generic reaction time t = t.

After integration, the following equation can be obtained:

$$[TSO_2]_{t=t} = [TSO_2]_{t=0} \bullet e^{-kTSO2 \bullet t} \tag{3}$$

where the two functional parameters k and $[TSO_2]_{t=0}$ may be considered a valid measure of the effect induced by oxidation during wine storage as a function of the packaging and storage temperature used.

Color is one of the most important organoleptic characteristics of red wines and affects the quality evaluation of the product [45]. Anthocyanins (Ant) are the most important molecules responsible of the young red wines' color. The color change from red-purple to brick-red hues is strongly related to the concentration of oxygen present in the stored wine [46].

The same experimental approach reported above to describe TSO_2 time evolution can be also followed to describe the time evolution of total anthocyanin concentration (TAnt) that may represent a second index of oxidative degradation of the product as a function of packaging.

1.4.2 Chemical evolution of stored wine: Antioxidant capacity

As polyphenols are widely known to play a protective action on the organism against cardiovascular and degenerative diseases [47], the moderate consumption of wine, especially red and rosé ones, has been associated with the reduction of mortality caused by many chronic diseases, a phenomenon that is commonly known as the "French paradox" [48]. In this context, the health properties of wines have been mainly interpreted on the basis of the antioxidant properties of the flavonoid fraction, which are related to both free radical scavenging and transition metal chelating mechanisms [49].

1.4.3 Sensorial evolution of stored wine

In the field of sensory science, sensory analysis was initially adopted as a tool for quality control [50]. Since then, it has evolved in one of the most diffused and sophisticated toolkits, allowing to achieve an exhaustive description of the characteristics of the products [51]. According to Stone et al. [52], "Sensory evaluation is a scientific discipline used to evoke, measure, analyze and interpret reactions referable to those characteristics of products as they are perceived by the senses of sight, smell, taste, touch, and hearing" [50].

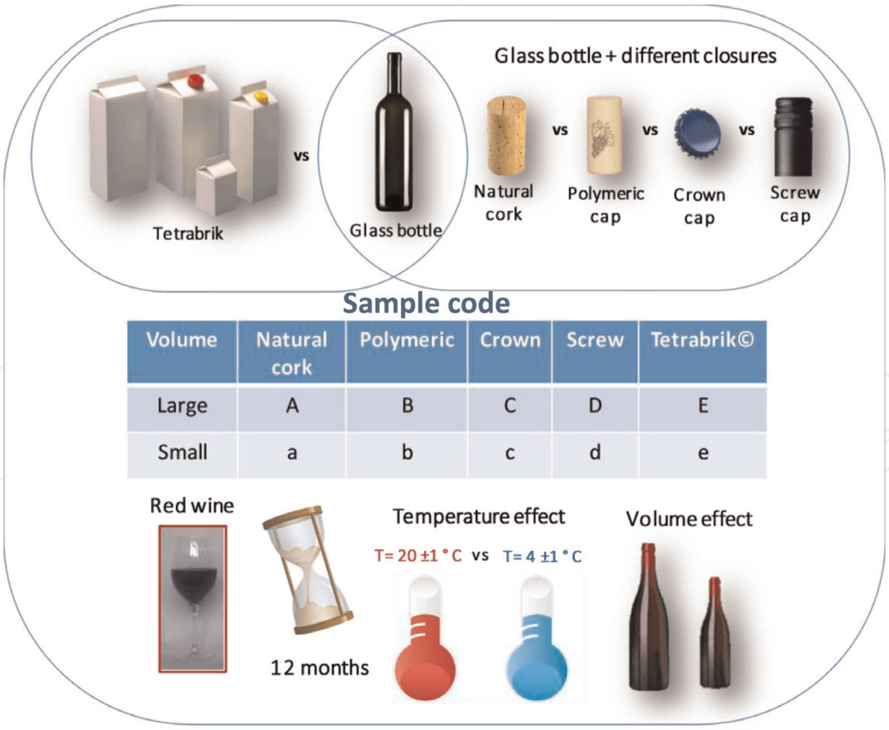
In this context, it is possible to introduce the "sensory shelf life" concept of a product [53]. This can be defined as the storage time at which overall quality, or the intensity of a specific sensory attribute, reaches a predetermined value or "failure criterion," assuming that once the product has reached this point, it is no longer saleable [54].

As a function of specific characters, sensory analysis should also be performed in parallel with microbiological and/or chemical-physical shelf life analysis to monitor the sensory profile of the product for potential deleterious sensory attribute changes [53]. Thus, sensory variables used during sensory shelf life testing could include the monitoring of specific sensory attributes related to visual, aroma, and taste attributes which can be used as indices of sensory quality.

As reported by Jackson [55], most sensory changes that negatively affect wine shelf life are those associated with oxidation and hydrolysis of esters. Such changes are involved in reduction, polymerization, structural rearrangement, and volatility modifications; their relative importance depends on wine style, production techniques, varietal origin, storage conditions, and consumer expectation [55].

2. Experimental evidences

With the aim to better understand the time evolution of wines during bottle aging as a function of storage conditions, among the literature available on the topic, we selected and discussed two real case reports recently developed by our group (**Figure 1**; **Table 2**).



Volume	Natural cork	Polymeric	Crown	Screw	Tetrabrik©
Large	A	B	C	D	E
Small	a	b	c	d	e

Figure 1.
Cases of study 1a, 1b, and 1c: graphical abstract—Experimental setup.

2.1 Case of study 1a, 1b, and 1c: Influence of storage conditions (temperature, packaging material, and volume of packaging) on the time evolution of a red wine over a storage period of 12 months

The red wine (**Table 2**) was packed in different packaging materials at the same time in a commercial winery bottling line using a fully automated bottling/filling station, as described in **Figure 1**.

Parameter	Mean value ± c.i.*
Alcohol (%v/v)	11.46 ± 0.06
pH	3.62 ± 0.01
Titratable acidity (g/L as tartaric acid)	4.82 ± 0.70
Net volatile acidity (g/L as acetic acid)	0.550 ± 0.003
Total SO_2 (TSO_2) (g/L)	0.106 ± 0.001
Total phenols (g/L as gallic acid)	2.140 ± 0.064
Total anthocyanins (g/L as malvin)	0.470 ± 0.006

**c.i., confidence interval = $P < 0.05$.*

Table 2.
Initial chemical composition of the red wine.

2.1.1 Case of study 1a: Influence of storage temperature

As reported in **Table 3**, after 12 months of storage, it can be observed that the aging of red wine was significantly delayed at the lowest temperature, regardless of the packaging solution adopted. The only exception was represented by the wine stored in glass bottles closed by natural corks [56].

Sample	**k_{TSO2} (months^{-1})**	**$[TSO_2]_{t=0}$ (mg L^{-1})**	**r^2**
A (T = 20 ± 1°C)	0.056^{a*}	106.8	0.95
A (T = 4 ± 1°C)	0.052^{a}	106.8	0.96
B (T = 20 ± 1°C)	0.060^{a}	105.7	0.97
B (T = 4 ± 1°C)	0.054^{b}	105.7	0.82
C (T = 20 ± 1°C)	0.053^{a}	105.3	0.96
C (T = 4 ± 1°C)	0.045^{b}	105.3	0.81
D (T = 20 ± 1°C)	0.061^{a}	106.2	0.93
D (T = 4 ± 1 °C)	0.052^{b}	106.2	0.82
E (T = 20 ± 1 °C)	0.070^{a}	105.5	0.96
E (T = 4 ± 1 °C)	0.043^{b}	105.5	0.70

**Within the same sample, values with different letters are significantly different ($P < 0.05$).*

Table 3.
*TSO_2 degradation constant (k_{TSO_2}) and initial total SO_2 concentration $[TSO_2]_{t=0}$ as a function of storage temperature (time = 12 months). Each sample was identified by code letter ranging from A/a to E/e as described in **Figure 1**.*

2.1.2 Case of study 1b: Influence of volume (two volumes for each packaging) on the chemical evolution of stored wine

As shown in **Table 4**, after 12 months of storage, it can be observed that the TSO_2 degradation rate significantly increased when the volume of the container decreased, regardless of the packaging solution used. In this case, the only exception was represented by the wine stored in glass bottles closed with screw caps.

Sample	**k_{TSO2} (months^{-1})**	**$[TSO_2]_{t=0}$ (mg L^{-1})**	**r^2**
A	0.056^{b*}	106.8	0.95
a	0.073^{a}	106.8	0.97
B	0.060^{b}	105.7	0.97
b	0.068^{a}	105.7	0.95
C	0.053^{b}	105.3	0.96
c	0.069^{a}	105.3	0.93
D	0.061^{a}	106.2	0.93
d	0.059^{a}	106.2	0.98
E	0.070^{b}	105.5	0.96
e	0.082^{a}	105.5	0.98

**Within the same sample, values with different letters are significantly different ($P < 0.05$). Samples represented with upper case letters refer to samples stored in packages with larger volume.*

Table 4.
*TSO_2 degradation constant (k_{TSO_2}) and initial total SO_2 concentration $[TSO_2]_{t=0}$ as a function of package volume (T = 20 ± 1°C, storage time = 12 months). Each sample was identified by code letter ranging from A/a to E/e as described in **Figure 1**.*

2.1.3 Case of study 1c: Influence of the packaging material (glass bottles provided with different closures, bag-in-box containers and Tetra Brik®) on the chemical and sensorial evolution of stored wine

As evidenced in **Tables 3** and **4**, the effects of packaging on both SO_2 degradation (**Table 5**) and sensorial characteristics (**Table 6**) were investigated during time

Sample	k_{TSO2} (months^{-1})	$[TSO_2]_{t=0}$ (mg L^{-1})	r^2
a	0.073^{b*}	106.8^{a*}	0.97
b	0.068^{c}	105.7^{a}	0.95
c	0.069^{c}	105.3^{a}	0.93
d	0.059^{d}	106.2^{a}	0.98
e	0.082^{a}	105.5^{a}	0.98

**In each column, the values labeled with different superscript letters show statistically significant differences ($P< 0.05$).*

Table 5.
Kinetic parameters describing the time evolution of TSO_2 concentration as a function of the packaging used during storage (small volume packages, T = 20°C, storage time = 12 months). Each sample was identified by code letter ranging from A/a to E/e as described in ***Figure 1****.*

in wines stored at room temperature (T = 20 ± 1°C) and in small containers. Among all the parameters evaluated, the concomitance of these two conditions together led to a faster degradation.

As reported in **Table 5**, the oxidative degradation occurring in the red wine stored in containers at room temperature (T = 20 ± 1°C) for 12 months was strongly dependent on the packaging, being the TSO_2 degradation rate statistically significant.

In particular, in the wine stored in Tetra Brik®, the reduction of TSO_2 concentration occurred at a faster rate compared to the wine in glass bottles, independently of the closure. This result may be explained with the fact that glass protected wine from oxidative reactions better than the multilayer material. As regards the closures, the lowest TSO_2 degradation rate was observed with screw caps.

Table 6 shows the main sensorial parameters evaluated in the red wines contained in various packages during storage in order to follow the development during time of the organoleptic characteristics. Apart from the closure, after 12 months the wine stored in glass bottles presented high values for the positive sensorial attributes "frankness," "harmony of odor," and "overall pleasantness." On the contrary, the wine stored in Tetra Brik® showed a worsening of the organoleptic characteristics, with high values for "degree of oxidation" and "aftertaste."

2.1.4 Conclusions related to case of study 1a, 1b, and 1c

The results show how the characteristics of packaging affect wine bouquet and flavor as a function of the storage conditions, suggesting that their rational

Sample	Degree of oxidation	Frankness	Harmony of odor	Aftertaste	Overall pleasantness
Wine at starting time	0.7^{b*}	6.0^{a}	4.7^{ab}	2.2^{b}	3.8^{a}
a	4.8^{a}	3.7^{ab}	4.2^{ab}	3.3^{ab}	4.8^{a}
b	4.3^{ab}	4.5^{ab}	5.3^{a}	3.7^{ab}	4.5^{a}
c	3.7^{ab}	4.8^{ab}	5.3^{a}	2.3^{b}	4.5^{a}
d	3.8^{ab}	4.5^{ab}	4.8^{ab}	4.2^{ab}	4.8^{a}
e	4.8^{a}	1.8^{b}	2.0^{b}	6.3^{a}	1.0^{b}

**In each column, the values labeled with different superscript letters show differences statistically significant ($P < 0.05$).*

Table 6.
Sensorial evolution of red wine as a function of the packaging used during storage (small volume packages, T = 20 ± 1°C, storage time = 12 months). Each sample was identified by code letter ranging from A/a to E/e as described in ***Figure 1****.*

optimization, based on experimental data, could improve the shelf life of wine and enhance the consumer's enjoyment during tasting.

Among all the experimental conditions, the rate of wine aging was higher when the volume of the containers decreased and storage temperature increased. Furthermore, after 12 months of storage, glass bottles generally better preserved wine from oxidation than multilayer materials, regardless of the closure characteristics.

To highlight the fact that the rate of TSO_2 degradation may represent a chemical index of the aging degree of the red wine during storage, the TSO_2 degradation kinetic constant (**Table 5**) was correlated for all packaging conditions with the sensory attributes (see **Table 6**). The correlation coefficients are reported in **Table 7**.

Parameter	k_{TSO2}
Frankness	**−0.84**
Harmony of odor	**−0.80**
Aftertaste	0.53
Degree of oxidation	**0.75**
Overall pleasantness	**−0.80**

Note: The correlation coefficients that indicate a strong correlation (≥0.6) are reported in boldface.

Table 7.
Correlation matrix relating the kinetic constant describing TSO_2 degradation to wine attributes (storage time = 12 months; T = 20°C; small volume packages).

According to Paula and Conti-Silva [57], a correlation coefficient of about 0.70 indicates a fairly strong correlation. Thus, data reported for this case of study evidenced that the TSO_2 degradation rate (k_{TSO2}) is strongly inversely correlated to positive sensorial attributes such as "frankness" and "harmony of odor" as well as the hedonic parameter "overall pleasantness," whereas the negative attribute "degree of oxidation" is directly correlated with k_{TSO2}.

Based on the above observations, an integrated approach deriving from the merging of both chemical and sensorial data can be used to identify the best packaging and storage conditions necessary to extend the shelf life of red wines. In this context, k_{TSO2} represents a useful index to describe the chemical evolution of red wines in combination with the main sensorial attributes generally associated with oxidative evolution.

The preliminary results obtained after 12 months of storage indicate that wine evolution during storage could be greatly influenced by the packaging characteristics (i.e., materials and volumes). Furthermore, also temperature imposed during the storage period seems to play a key role in the evolution of wine, since it can directly influence the oxygen permeability of the system "wine + package."

2.2 Case of study 2: Evolution of glass bottled rosé wine as a function of closure (cork stopper with or without aluminum capsule), storage position, and brightness regime over a period of 12 months

The samples reported in **Figure 2** are identified by code letters composed of a capital letter, which represents the closure type (C = with capsule) and the storage position (H = horizontal; V = vertical) and of a small letter, which indicates the light conditions. In particular, the letter "d" indicates that wines were stored in the dark, while "l" means that wines were stored under a cool fluorescent lamp (645 lux), considered as the common lighting of most supermarkets (**Table 8**) [28].

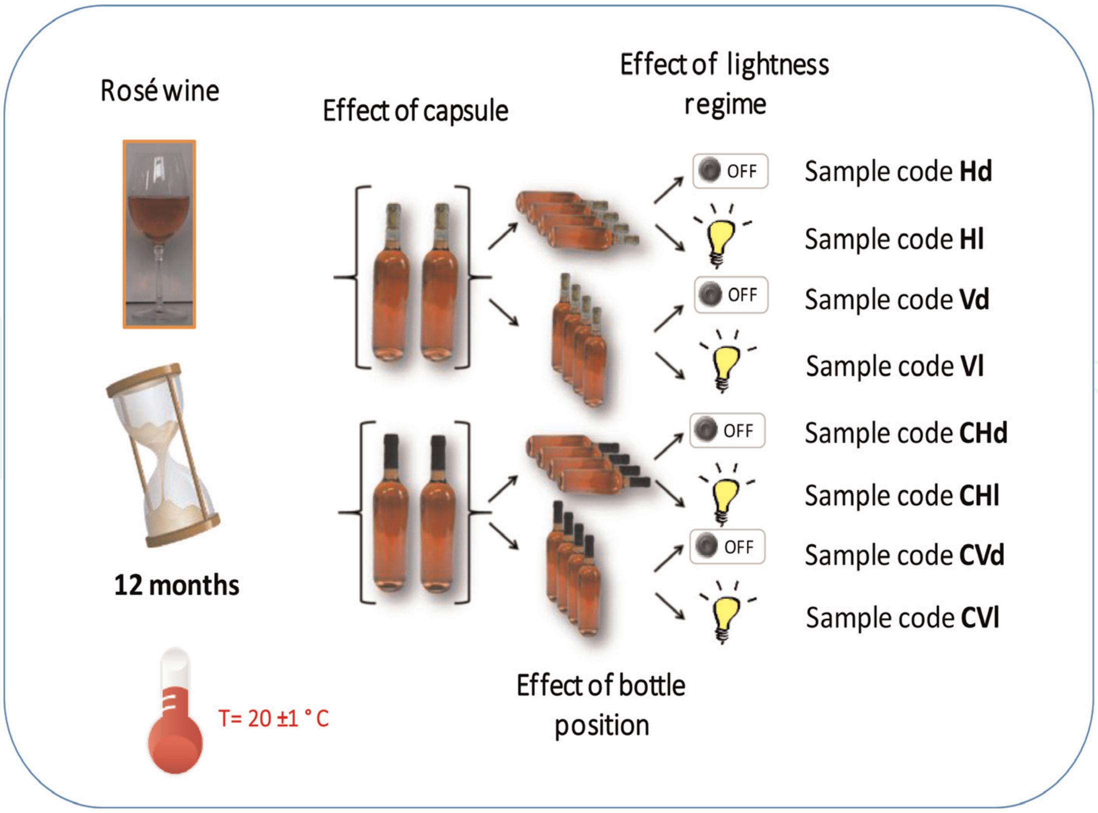


Figure 2.
Case of study 2: graphical abstract—Experimental setup.

Parameter	Mean value ± C.I. ($p < 0.05$)
Alcohol (%v/v)	11.33 ± 0.06
pH	3.32 ± 0.01
Titratable acidity (g/L as tartaric acid)	4.92 ± 0.01
Net volatile acidity (g/L as acetic acid)	0.33 ± 0.01
Total SO_2 (g/L)	0.133 ± 0.009
Total phenols (g/L as gallic acid)	0.332 ± 0.004
Not flavonoid phenols (g/L as gallic acid)	0.219 ± 0.009
Total anthocyanins (g/L as malvin)	0.087 ± 0.002

Table 8.
Chemical composition of the rosé wine utilized for the experimental runs ($t = 0$).

2.2.1 Influence of storage conditions on antioxidant capacity of stored wine

To highlight the influence of storage conditions on the time evolution of the rosé wine, the antioxidant capacity of all the stored samples was determined after 6 and 12 months from bottling by the ABTS assay according to Sgherri et al. [58]. As shown in **Figure 3**, following the first observation period (6 months after bottling), only small changes in the antioxidant capacity of wines were observed, whereas after 12 months of storage, conditions significantly affected this parameter.

In particular, the antioxidant capacity of wine was better preserved when the bottles were closed with capsules and stored in the dark in a horizontal position. Furthermore, the storage in the dark delayed the decrease of the antioxidant capacity of wine regardless of the other parameters. The influence exerted by the light exposure reached its maximum when the bottles were closed with cork stoppers and stored in a vertical position.

2.2.2 Influence of storage conditions on kinetics of TSO_2 and TAnt degradation

To better evidence the possible effects of the closure system (with or without capsule) and of the storage position (horizontal versus vertical) on the chemical deterioration of wine, the values of the kinetic constants k_{TSO2} and k_{TAnt} (**Table 9**) were carried out for bottles stored in brightness conditions. This is because changes in the antioxidant capacity of wine were faster when it was stored under a cool fluorescent lamp (see **Figure 3**).

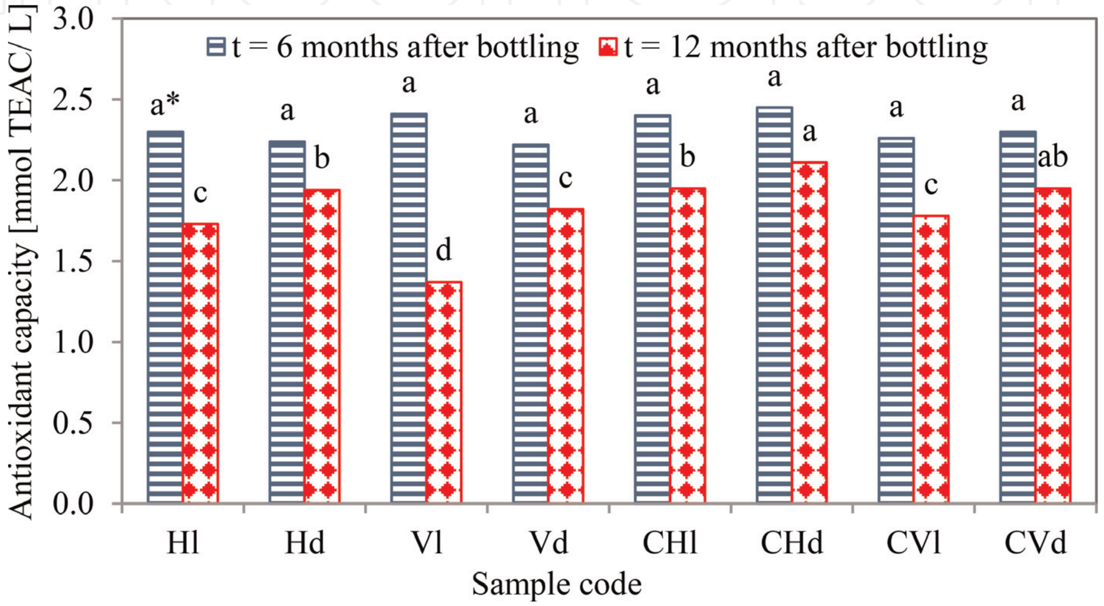


Figure 3.
*Evolution of antioxidant capacity during storage. *In each couple of data, the values labeled with different superscript letters show statistically significant differences ($P < 0.05$).*

As reported in **Table 9**, after 12 months from bottling the differences induced by both the closure system and the storage position on the degradation rate of TSO_2 as well as TAnt were statistically significant, evidencing that these storage conditions were among those that affect the oxidation rate of the rosé wine. In particular, wine degradation rate was the highest when the rosé wine was stored in glass bottles closed with natural corks without the application of a capsule, regardless of the position (vertical or horizontal) used during storage. Furthermore, independently

Sample*	k_{TSO2} ± c.i. (months^{-1}) × 10^2	$[TSO_2]_{t=0}$ ± c.i. (mg/L)	r^2	k_{Tant} (months^{-1}) × 10^2	$[TAnt]_{t=0}$ ± c.i. (mg/L)	r^2
Al	2.54 ± 0.06	133.8 ± 0.4	0.98	2.99 ± 0.07	87.3 ± 0.01	0.81
Bl	2.66 ± 0.06	135.7 ± 0.4	0.94	3.31 ± 0.07	87.0 ± 0.01	0.91
Cl	2.03 ± 0.06	132.5 ± 0.4	0.65	2.39 ± 0.07	87.5 ± 0.01	0.85
Dl	2.44 ± 0.06	130.0 ± 0.4	0.88	2.62 ± 0.07	86.5 ± 0.01	0.85

**Al = glass + natural cork without capsule, horizontal storage position, fluorescent lamp. Bl = glass + natural cork without capsule, vertical storage position, fluorescent lamp. Cl = glass + natural cork + capsule, horizontal storage position, fluorescent lamp. Dl = glass + natural cork + capsule, vertical storage position, fluorescent lamp.*

Table 9.
Kinetic parameters describing the time evolution of TSO_2 and TAnt concentration as a function of the storage conditions.

from the closure system, the time evolution of the rosé wine during storage was delayed when bottles were stored in the horizontal position.

2.2.3 Conclusions related to case of study 2

To confirm the convenience in using the rates of TSO_2 and total anthocyanin degradation as parameters effectively describing the oxidative evolution during storage of a rosé wine, the kinetic constants k_{TSO2} and k_{Ant} (**Table 9**) as well as their combination (k_{TSO2} + k_{Ant}) were correlated with the wine antioxidant capacity. This was performed over time and for all storage conditions. The Pearson's correlation coefficients are reported in **Table 10**.

Kinetic constant (months^{-1})	**TEAC (L^{-1})**
k_{TSO2}	**−0.86**
k_{Ant}	**−0.94**
k_{TSO2} + k_{Ant}	**−0.93**

Note: The correlation coefficients that indicate a strong correlation (≥0.6) are reported in boldface.

Table 10.
Correlation matrix relating the kinetic constant describing TSO_2 (k_{TSO2}), total anthocyanins (k_{Ant}), degradation, and a combination of them (k_{TSO2} + k_{Ant}) to wine antioxidant capacity (storage time = 12 months).

The results (**Table 10**) highlight that all the degradation kinetic constants were strictly inversely correlated with the antioxidant capacity of wine.

Notwithstanding k_{TAnt} did not result a good index for monitoring the chemical evolution of a red wine stored in the same conditions used in this research study [27], the correlation between k_{TAnt} and the antioxidant capacity showed by the rosé wine was higher than that determined when k_{TSO2} was considered.

Furthermore, k_{TSO2} confirmed to be a suitable index for the description of the oxidative evolution of different wines, regardless of the wine style (i.e., white, rosé, full-bodied red) and the operating conditions (i.e., packaging, storage or tasting conditions), according to what is reported in [59–61].

It can be concluded that also antioxidant capacity could be considered a useful index to describe the chemical evolution of the rosé wine under investigation, when correlated with the total anthocyanin decay rate constant (k_{TAnt}) and, at a lower extent, with the TSO_2 decay rate constant (k_{TSO2}).

3. Conclusions

Based on the analysis of recent papers available in international literature as well as on the experimental results discussed above, the main issues related to wine storage could be outlined in some main topics useful to better clarify the role played by both packaging and storage conditions on the evolution of the most diffused kinds of wines.

Firstly, packaging characteristics (i.e., material and volume) deeply influence wine evolution: glass bottles generally preserved wine better than multilayer materials; larger volumes slow down the wine deterioration rate over time regardless the kind of packaging selected.

Regardless the material utilized for packaging, the storage temperature plays a key role in the evolution of wine, since it can directly influence the oxygen permeability of the system "wine + package": lower temperature allows to improve the shelf life.

When the wine is stored in glass bottle, its quality decay rate appears significantly influenced by the kind of stopper, closure system, and storage position. In particular, when traditional cork stopper is utilized, the longer shelf life can be allowed by the combination of stopper with the extra-closure provided by an aluminum capsule. Moreover, the storage in glass bottles maintained in the dark and or in horizontal position further slows down the wine degradation, regardless the closure applied to the glass bottle.

Depending on the wine chemical composition, TSO_2 and TAnt decay rate constants (k_{TSO2}, k_{Ant}) together with antioxidant capacity can be considered the main chemical indexes to describe the wine evolution.

In conclusion, a new "integrated approach" deriving from the merging of chemical, kinetic, and sensorial data can be applied in order to identify the best storage conditions to preserve the quality of wines, improve their shelf life, and enhance the consumer's enjoyment during tasting.

Conflict of interest

Authors have no conflict of interest to declare.

Funding

This research was funded by the University of Pisa, project SALI (*Strumenti di sostenibilità delle produzioni alimentari*, Sustainability tools for food production) code PRA_2017_34.

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