

1 **Light-struck taste in white wine: reaction mechanisms, preventive strategies and**
2 **future perspectives to preserve wine quality**

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11 **Abstract**

12 *Background*

13 The light-dependent reactions involving riboflavin (RF) and methionine (Met) as substrates
14 are responsible for the light-struck taste (LST). This fault is associated to cabbage-like odors
15 due to the formation of methanethiol and dimethyl disulfide impacting negatively on the
16 sensory properties of white wine. The reaction can occur for a relatively short period of white
17 wine bottled in clear glass under both natural and artificial lights.

18 *Scope and Approach*

19 This review aimed to point out the aspects related to the mechanisms of light-dependent
20 reactions and the oenological strategies applicable to counteract the appearance of this
21 detrimental fault.

22 *Key Findings and Conclusions*

23 LST can be prevented through the proper choice of the fermenting yeast, the addition of
24 certain adjuvants being able to remove RF, and additives with a protective effect, such as
25 hydrolysable tannins. As the use of these oenological tools plays an important role in limiting
26 the detrimental change, they represent the strategies applicable in productive approaches.
27 In this context, the more recent findings are summarized also to update the knowledge about
28 the complex reaction mechanisms allowing to overcome the formation of this fault and
29 supporting the wine industry.

30 **Keywords:** light exposure; riboflavin; methionine; sulfur compounds; off-flavors; storage.

31

32 1. Introduction

33 The quality maintenance of wine during its storage is a fundamental aspect for both wine
34 producers and consumers. This purpose can be achieved controlling certain environmental
35 factors, such as light exposure and temperature, which increase can be responsible for
36 faster oxidative reactions and quicker aroma decay. Nowadays, more attention has been
37 given to the light exposure that can cause detrimental changes in wine where the light-
38 induced off-flavours are associated to the light-struck taste (LST) or “*Goût de Lumière*”
39 (Dozon & Noble, 1989). This fault is mainly due to photochemical oxidation processes in
40 which riboflavin (RF), a highly photosensitive vitamin, plays an important role. The
41 photosensitisation process of RF proceeds with photo-oxidative degradation of methionine
42 (Met) generating methanethiol (MeSH) and dimethyl disulphide (DMDS) (Maujean & Seguin,
43 1983a). Both volatile sulfur compounds (VOCs) give unpleasant cabbage and onion-like
44 odours that make wine undrinkable.

45 The prevention of LST appearance is crucial for the winemakers as the wine quality needs
46 to be ensured and maintained. In order to understand the impact of LST, a national survey
47 was carried out (<https://www.surveio.com/survey/d/K6Y3T0W6C5S5Z1G2J>) and 231
48 responses from Italian wineries were collected. The results showed that LST occurred 1011
49 times which makes 4.4 incidents per winery, and the wine was recalled from the market in
50 15 wineries (6.5%), with consequent loss of income. Many producers utilized flint bottles for
51 their white and rosé wines (even 80% of the total production). Moreover, we asked the
52 technological procedures and treatments the winemakers usually apply to prevent LST.
53 Most of the winemakers (50%) use bentonite as a prevention tool; other treatments include
54 the addition of polyvinylpolypyrrolidone (PVPP) which is ineffective in RF removal as a
55 recent research showed (Fracassetti et al., 2017).

56 Beside white wine, the light exposure also affects the sensory characteristics of other foods,
57 such as milk (Patton, 1954) and beer. Particularly in the latter, the formation of 3-methyl-2-
58 butene-1-thiol induces a unique “skunky” odour and taste (Cardoso et al., 2012). Riboflavin
59 is the photosensitizer that causes the photolysis of iso- α -acids leading to the beer spoilage
60 in the presence of sulfur-containing amino acids (Gunst & Verzele, 1978; Cardoso et al.,
61 2012).

62 In order to clarify and point out LST-related aspects, this review focuses on (i) the reaction
63 mechanisms responsible for the defect formation, (ii) the light-induced faults in wine and (iii)
64 the other light-dependant effects. The (iv) oenological strategies are also examined
65 considering both microbiological and technological approaches.

66

67 **2. Reaction mechanisms involved in light-dependent changes**

68 LST is a wine fault recognizable as a distinctive, unpleasant sulfide-like aroma resembling
69 onion and cooked cabbage; it appears after light exposure with emission spectra within UV-
70 Vis, particularly between 370 and 450 nm. The photodegradative reactions may occur within
71 minutes or days. This spoilage concerns white wines, both still and sparkling, usually bottled
72 in flint glass which is ineffective in shielding the harmful wavelengths. Since 1970, the new
73 marketing approaches have led to an increased use of clear bottles to show the wine colour
74 to the customers, because it is considered as an important feature of wine quality (i.e., its
75 oxidative status). Moreover, wine has begun to be increasingly available at the large-scale
76 retail trade or grocery stores where the protection against the light exposure could hardly be
77 ensured (Dozon & Noble, 1989).

78 RF, or vitamin B₂, is characterized by a bright, yellow colour and it is sensitive to UV-Vis
79 light radiation. Chemically it is composed of tricyclic heterocycle isoalloxazine, involved in
80 redox reactions, and ribitol, an alcohol responsible for protein binding. RF is a constituent of

81 prosthetic groups, flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD),
82 which play essential roles in oxidoreductase enzymes like dehydrogenases, oxidases, or
83 electron transferase (Choe et al., 2005). They take part in redox reactions due to their ability
84 to transfer single electrons and hydrogen atoms.

85 RF shows the highest light absorption at 225, 275, 370 and 450 nm at pH 7 (Drössler et al.,
86 2003; Abbas & Sibirny, 2011). Once RF is exposed to blue or UV-A light, it acts as a
87 photosensitizer. A photosensitizer is a species that reaches a high energy state when
88 exposed to light at specific wavelengths inducing chemical reactions or physical changes in
89 a target substrate. Specifically, when RF is exposed to light, it reaches the excited triplet
90 state, a bi-radical with powerful oxidant effect ($E^0 \sim +1,7 \text{ V}$) inducing the direct oxidation of
91 many biomolecules (Cardoso et al., 2012). Photo-oxidation can occur in two possible
92 pathways. In Type I mechanism, the triplet sensitizer reacts directly with compounds able to
93 donate electrons, such as phenols and amino acids (Figure 1). In this pathway, RF acts as
94 electron or hydrogen acceptor, leading to produce either free radicals or free radical ions.
95 The reaction between triplet RF and a substrate can occur through three different
96 mechanisms: electron transfer (ET), hydrogen atom transfer (HAT) and proton-coupled
97 electron transfer (PCET) (Cardoso et al., 2012). The proceeding of reaction depends on the
98 thermodynamic properties of both excited triplet RF and substrates. For ET, one-electron
99 oxidation potential below 1.8 V for the reducing substrate is the limiting thermodynamic
100 property, whereas for HAT mechanism, bond dissociation energy is the limiting factor, which
101 should be of less than 300 kJ. PCET is an intermediate mechanism depending on both
102 electron oxidation potential and dissociation energy. The formation of free radicals initiates
103 free-radical chain reactions by attracting hydrogen or electrons from other compounds. As
104 a consequence, oxygen may be reduced to peroxy radical which generates hydrogen
105 peroxide and therefore hydroxyl radical (Min & Boff, 2002; Cardoso et al., 2012) triggering
106 the possible further oxidation processes in wine. In direct reaction between excited triplet

107 RF and various substrates, reduced RF radical or anionic RF radical are formed (Figure 1).
108 These RF radicals can be oxidized by oxygen, regenerating ground state RF, and forming
109 superoxide anion radical. The latter may then form hydrogen peroxide, a strong oxidising
110 species, by dismutation that causes depletion of antioxidants present in wine, including
111 sulfur dioxide and polyphenols. Furthermore, the reaction between hydrogen peroxide and
112 superoxide anion (Haber-Weiss reaction) may occur, leading to hydroxyl radical formation
113 (Choe et al., 2005). Moreover, hydrogen peroxide may undergo Fenton reaction catalysed
114 by iron (II) ions, leading to hydroxyl radical formation as well. Hydroxyl radical with a
115 reduction potential of + 2.3 V is one of the strongest oxidizing species, that may induce the
116 oxidation of wine and the appearance of sensory fault. It has been demonstrated that in
117 Type I pathway the excited triplet RF may also react directly with triplet oxygen, transferring
118 an electron to form superoxide anion. However, only less than 1% of the reaction of triplet
119 sensitizer and triplet oxygen produces superoxide anion (Kepka & Grosswiener, 1972).
120 Such reaction causes the conversion of triplet oxygen to singlet oxygen ($^1\text{O}_2$) and ground
121 state RF (Type II pathway) (Figure 1). Singlet oxygen directly and rapidly gives rise to non-
122 radical reactions with electron rich compounds (e.g., with double bonds) that result oxidised
123 (Min & Boff, 2002).

124 Singlet oxygen can find different substrates in wine, such as amino acids or phenolic
125 compounds (Thomas & Foote, 1978; DeRosa & Crutchley, 2002). Regarding amino acids,
126 singlet oxygen primarily reacts with tryptophan, histidine, tyrosine, Met and cysteine at
127 significant rates, forming peroxides (Min & Boff, 2002; Huvaere & Skibsted, 2015).
128 Tryptophan, histidine and tyrosine contain double bonds in their structure, which make them
129 promptly attacked by singlet oxygen. Methionine and cysteine contain a sulfur atom with
130 four nonbonding electrons which are rapidly attracted by electrophilic singlet oxygen.
131 Remucal and McNeill (2011) demonstrated that in aqueous solution at pH 7.4 tyrosine,
132 tryptophan, Met and histidine react with singlet oxygen at similar rates, but the amount of

133 amino acid degradation which can be attributed to single oxygen reaction varies from 10%
134 for tyrosine and tryptophan up to 100% for histidine. In the presence of RF, singlet oxygen
135 is responsible for about 33% of Met degradation (Remucal & McNeill, 2011). One of known
136 compounds arising from the reaction between Met and singlet oxygen is methionine
137 sulfoxide (Fracassetti et al., 2020), a stable compound which does not undergo further
138 oxidation or degradation processes (Barata-Vallejo et al., 2010).

139 Singlet oxygen can react with certain di-phenols (e.g., catechol) firstly generating
140 hydroquinones as well as benzoquinones as secondary oxidation product (Briviba et al.,
141 1993).

142 Flavonoids present in wine can interact with singlet oxygen through both chemical and
143 physical processes. The latter pathway prevails with increasing abundance of phenolic
144 functions as well as, with the presence of catechol and pyrogallol rings (Huvaere & Skibsted,
145 2015). Chemical quenching leads to the transfer of energy from a molecule in high-energy
146 state to another molecule, the latter can be oxidized or its spin is modified. When chemical
147 quenching occurs, the generated quinones can trigger oxidation chain reactions.
148 Consequently, quinones can bind to other phenols producing brown dimers or polymers
149 which may precipitate when high molecular weight is reached (Ribéreau-Gayon et al., 2006).

150 Furthermore, xanthylum derivatives can be produced thus inducing the browning of white
151 wine (Li et al., 2008).

152 The occurrence of the two photo-oxidative mechanisms depends on the concentration of
153 oxygen in the reaction environment. In anoxic conditions only Type I occurs, whereas in the
154 presence of oxygen, both mechanisms may take place to a different extent (Min & Boff,
155 2002; Grant-Preece et al., 2017b). Compounds that are easily oxidised, like certain
156 phenolics or amino acids, promote Type I pathway, while species not prone to oxidising like
157 alkenes, favour Type II. In any case, the factor mainly influencing the reaction mechanism
158 is the presence or absence of oxygen, as some compounds degraded via Type I at low

159 oxygen concentrations may be degraded via Type II when the oxygen concentration
160 increases (Min & Boff, 2002).

161

162 **3. The light-induced faults in wine**

163 RF and Met are the two factors mainly affecting LST formation. RF concentration in grape
164 and must seldom exceeds a few tens micrograms per liter (Riberau-Gayon et al., 2006), but
165 its content can rise to 110-250 µg/L during alcoholic fermentation (Mattivi et al., 2000;
166 Fracassetti et al., 2017), due to the activity of *Saccharomyces cerevisiae*. RF amount can
167 be further increased to 160-318 µg/L when wine remains in contact with yeast lees once the
168 alcoholic fermentation is completed (Andrés-Lacueva et al., 1998). A concentration of RF
169 lower than 50-80 µg/L greatly decreases the risk of developing the LST (Pichler, 1996;
170 Mattivi et al., 2000; Fracassetti et al., 2019a). Therefore, the measurement of RF
171 concentration in finished wine may be a suitable chemical marker for the susceptibility of
172 wine to develop LST (Andrés-Lacueva et al., 1998; Mattivi et al., 2000). In the study carried
173 out by Mattivi et al. (2000), sensory evaluation of 85 white wines from Italy, Slovenia and
174 Spain was performed. Each wine was prepared in double, with and without the addition of
175 RF (1 mg/L), then both samples were exposed to light for 48 h. After that, trained panelists
176 rated the intensity of the off-flavour aroma. Results showed that the intensity of the defect
177 was significantly higher in the samples with the RF added, confirming that RF is a crucial
178 factor for the appearance of this off-flavour. RF concentration in wine and sensory values of
179 the LST were positively correlated, but the low correlation coefficient ($r = 0.3544$) indicated
180 that RF concentration did not allow to predict the intensity of the off-flavour formed.
181 Noteworthy, there were also some samples with a high concentration of RF which did not
182 develop the off-flavour, as well as some wines that did get spoiled despite their low
183 concentration of RF. These results evidenced that there are some other wine features that

184 can affect the stability to light and that the occurrence of LST is due to complex mechanisms
185 that cannot be fully explained only considering the presence of RF. In fact, other factors can
186 affect the light stability of wine including the transition metals, as they are involved in redox
187 reactions, polyphenols, precursors of the off-flavour, sulfur-containing amino acids, sulfur
188 dioxide (Mattivi et al., 2000). The latter plays an important role on the rate of light-induced
189 radical reaction chains (Fracassetti et al., 2020).

190 LST in wine was first described by Maujean et al. (1978), who focused their study on the
191 effect of light on Champagne. They found that the molecules responsible for the fault
192 formation were sulfur-containing amino acids, as Met and cysteine, and RF as a
193 photosensitizer. According to these authors, the addition of RF, Met and cysteine to
194 Champagne, increased the off-flavour formation after exposure to light in anoxic conditions.
195 The proposed mechanism of the light-dependent reaction concerns the formation of triplet
196 state RF (Maujean & Seguin, 1983a). This species is characterized by having high energy,
197 unstable electronic distribution, weaker bonds and high capacity to accept electrons making
198 triplet state RF more reactive compared to its equivalent ground state (Wardle, 2009). Met
199 is among the wine components able to donate electrons. Met is firstly decarboxylated and it
200 loses a hydrogen atom generating an imine. In this way, RF is fully reduced by acquiring
201 two electron-equivalents and two hydrogen atoms (Figure 2). The imine is not stable and
202 easily hydrolyses to methional. The latter is also chemically unstable, photosensitive and,
203 through a retro Michael reaction, decomposes to MeSH and acrolein. Two molecules of
204 MeSH can yield dimethyl disulfide (DMDS) (Maujean & Seguin, 1983a). Both these sulfur
205 compounds are highly volatile and have a low perception threshold, as 0,3 µg/L in model
206 solution and 2-10 µg/L in wine for MeSH and 20-45 µg/L in wine for DMDS (Mestres et al.,
207 2000; Pripis-Nicolau et al., 2004; Fracassetti & Vigentini, 2018). MeSH is characterized by
208 rotten egg or cabbage-like olfactory notes, whereas DMDS gives cooked cabbage and
209 onion-like odour. These two molecules are responsible for the LST.

210 Met concentration also affects LST formation. Fracassetti et al. (2019a) found that in model
211 wine solution with a constant concentration of Met (3 mg/L) and increasing concentration of
212 RF (0-300 µg/L), the amount of degraded Met rose in parallel after light exposure. On the
213 other hand, when RF concentration was constant (200 µg/L) and Met concentration
214 increased (0–13 mg/L), Met degraded to a much greater extent. The average content of Met
215 in wine is about 3-5 mg/L (Amerine & Ough, 1980; Riberau-Gayon et al., 2006; Grant-Preece
216 et al., 2017; Sartor et al., 2021), nonetheless it can vary depending on different factors such
217 as grape cultivar, vineyard treatments, winemaking conditions, yeast performing the
218 alcoholic fermentation and its autolysis, and it can reach about 15 mg/L (Soufleros et al.,
219 2003; Fiechter & Mayer, 2011). The molar ratio of degraded Met/degraded RF ranged
220 between 2 and 35, which disagrees with the 1:1 ratio previously thought to occur between
221 these two substrates (Maujean & Seguin, 1983b). This could be explained by the formation
222 of other products originating from Met in photo-degradative reactions (Barata-Vallejo et al.,
223 2010). Additionally, the concentrations of DMDS and dimethyl trisulfide (DMTS), product of
224 the reaction between MeSH and DMDS, were about ten times higher in the samples where
225 Met concentration increased, compared to samples where RF concentration increased.
226 These results are in agreement with the sensory evaluation performed by the expert
227 panelists who perceived cooked cabbage odour with higher intensity in the set of samples
228 with increasing Met concentration. This study clearly shows that LST formation in terms of
229 concentration of VOCs and perception of this defect, linearly increased as Met concentration
230 grew indicating that this amino acid can be more detrimental than RF. Therefore, besides
231 RF, the level of Met in white wine needs to be considered for preventing LST.

232 The mechanism of LST formation is very complex and certain aspects of the reactions
233 occurring in wine matrix need further clarification. Recently, a new possible pathway of
234 MeSH formation was described by using the proton-transfer-reaction mass spectrometry
235 (PTR-MS) technique (Asaduzzaman et al., 2020). In the experimental conditions adopted

236 (Met 75 mg/L, RF 1.7 mg/L pH 8.0, light exposure at wavelengths 405-640 nm with
237 maximum at 430, 550 and 640 nm for six hours), MeSH was the first compound appearing
238 just after only 2.3 min under light, and it rapidly increased. DMDS was found, after 3.5 min
239 of light exposure. These results confirm that two molecules of MeSH yield to DMDS. The
240 third detected compound was methional (at 5.30 min) that is surprising and disagrees to the
241 light-dependent mechanism previously proposed by Maujean and Seguin (1983a). Other
242 coproducts of MeSH formation *via* methional, such as formic acid and 2-propenal, occurred
243 only after 29 and 22.5 min of light exposure, respectively. A further proof that MeSH can be
244 directly formed from Met under light exposure conditions was obtained when an aldehyde
245 group blocker (sodium cyanoborohydride) was added prior to light exposure. In this case
246 MeSH increased rapidly, similarly to the previous conditions without aldehyde blocker
247 (Asaduzzaman et al., 2020). According to Asaduzzaman et al. (2020), during the early steps
248 of photo-oxidation, MeSH can be generated by an alternative and fast pathway that does
249 not include methional and involves a direct cleavage of Met side chain. However, no data
250 related the occurrence of sulfur compounds in model wine or wine was reported which acidic
251 pH can influence RF behaviour under light (Sheraz et al., 2014). Besides Met, Maujean and
252 Seguin (1983a) investigated also another sulfur amino acid, cysteine, which may also take
253 part in the off-flavour development. Hydrogen sulfide may also have a role in unpleasant
254 odour perception (Haye et al., 1977; Maujean et al., 1978; Maujean & Seguin 1983a).
255 As previously stated, the photodegradation reactions of RF can occur in two possible
256 pathways depending mainly on the oxygen concentration. In bottled wine, the concentration
257 of oxygen ranges between 1 mg/L and 9 mg/L (Ugliano et al., 2013). The oxygen-free
258 environment is rapidly obtained in bottled wines especially if the bottling is carried out using
259 inert gases and the wine is added with SO₂. That is why in wine Type I mechanism is
260 favoured, where excited triplet RF reacts with electron rich compounds like Met, leading to
261 unpleasant sulfur compounds formation. Besides Met, RF can also react with other electron-

262 rich amino acids like tyrosine, tryptophan, histidine or cysteine (Choe et al., 2005; Huvaere
263 & Skibsted, 2015). RF quenching leads to the formation of substrate radicals, which fate in
264 wine is not fully understood yet (Cardoso et al., 2012).

265 Among wine components phenolic compounds are also efficient quenchers of triplet RF
266 (Huvaere & Skibsted, 2015). The reaction between phenols and flavins is a chemical type
267 of quenching, resulting in oxidative degradation of phenols (Cardoso et al., 2012). In
268 particular, flavonoids with a catechol-like B ring have high quenching rates, probably due to
269 the stabilisation of *o*-hydroxy phenoxyl radical anion. Deactivation of excited triplet RF by
270 flavonoids results in their consumption with generation of dimeric compounds and other
271 oxidised species. These may affect the colour and antioxidant capacity of wines.

272

273 **3.1 Other consequences of light exposure of wine**

274 After light exposure modifications of wines composition other than the sulfur compounds-
275 related off-flavours can occur. Dozon and Noble (1989) conducted a sensory analysis of still
276 and sparkling white wines, exposed to 40-watt fluorescent light bulbs with spectrum similar
277 to that of sunlight. The results of descriptive analysis of wines kept under light for 24 and 72
278 hours showed that after longer light exposure, not only the perception of cooked cabbage
279 and wet dog odours increased, but also citrus and honey aroma perception was significantly
280 lower. This could be due to either the masking effect of LST appearance or the chemical
281 changes in the composition of other aroma, such as esters or terpenes, undergoing to
282 degradation or hydrolysis (Benítez et al., 2003; D'Auria et al., 2009). Indeed, the exposure
283 to UV light of Champagne for 24 hours completely changed the esters profile. The content
284 of certain esters decreased, like ethyl acetate, ethyl butanoate, 3-methyl-1-butanol acetate,
285 ethyl hexanoate, or disappeared like ethyl decanoate. In order to clarify the possible
286 influence of RF on depletion of these molecules, ethyl hexanoate (14 mg) was irradiated in

287 the presence of RF (2 mg) for one hour. At the end of illumination, the concentration of the
288 ester was measured, and it showed a decrease up to 9%. This observation proved that the
289 photo-oxidation of RF can induce changes in concentrations of other aromas, including
290 esters (D'Auria et al., 2003). Since the sensory analysis was not carried out, we cannot state
291 if such a difference had a relevant impact on the overall flavour perception.

292 Light exposure can also induce the formation of other undesirable aroma compounds such
293 as acetaldehyde, which is considered one of the main markers of oxidative reactions
294 (Danilewicz, 2003; Han et al., 2019). Dias and co-authors (2013) found that the dominating
295 descriptor identified in Chardonnay wine stored under light for 18 days was acetaldehyde
296 which increase was significant after 10 days of exposure. This compound was also present
297 in model wine samples left outdoor during Australian summer. On the contrary,
298 acetaldehyde was not detected in the samples kept in the dark neither at room temperature
299 nor at 45°C (Clark et al., 2007). The light exposure was crucial for the formation of
300 acetaldehyde and it had a greater affect than temperature. Similarly, in different Spanish
301 white wines saturated with oxygen and left one week in the dark, there was not a significant
302 change in acetaldehyde concentration (Escudero et al., 2002). These results highlight the
303 light exposure is required for the formation of acetaldehyde at least in terms of triggering the
304 oxidation processes in short periods of time. As the light exposure promotes also the
305 formation of radicals, other wine compounds, e.g. tartaric acid, amino acids other than Met,
306 phenolics, can be also oxidized.

307 Tartaric acid (TA) is among the most abundant compounds of wine (Clark et al., 2007;
308 Riberau-Gayon et al., 2006). Its oxidation leads first to the formation of dihydroxyfumaric
309 acid. By its further oxidation and decarboxylation, glyoxal and glyoxylic acid (GA) are formed
310 (Clark, 2008). Both these molecules can bind two flavanol units such as (+)-catechin or (-)-
311 epicatechin, forming a dimer with the units bound through a carboxymethine bridge.
312 Afterwards, the dimer undergoes a dehydration and an oxidation leading to a formation of

313 yellow pigments, known as xanthylum ions (Li et al., 2008). These compounds contribute
314 to the oxidative browning spoilage of wine. The oxidative degradation of TA is favoured in
315 the presence of iron ions. Iron (III) forms complexes with α -hydroxy carboxylic acids, such
316 as TA, which are relatively stable when stored in darkness, but are photodegraded once
317 exposed to light (Grant-Preece et al., 2017a; Grant-Preece et al., 2017b). The mechanism
318 of photochemical degradation of α -hydroxy acids includes their oxidative decarboxylation in
319 the presence of iron (III) acting as catalyzer of oxidation (Balzani & Carassiti, 1970).
320 According to this pathway, TA degrades to 2-hydroxy-3-oxo-propanoic acid and its possible
321 tautomers, 2,3-dihydroxypropenoic acid and hydroxypyruvic acid. These compounds can
322 react with hydrogen peroxide present in the solution due to Fenton reaction, leading to GA
323 formation among other degradation compounds (Figure 3). Moreover, in the irradiated TA
324 solution, the dissolved oxygen consumption accelerates (Grant-Preece et al., 2017a). This
325 is because transition metal ions in their reduced forms can reduce oxygen to radical species.
326 The superoxide radical anion in acidic condition forms hydroperoxyl radical, which in turn
327 yields hydrogen peroxide. The latter can be further reduced by iron (II) generating hydroxyl
328 radical that is a very powerful oxidant and even at low concentrations can readily oxidise
329 TA. In this pathway, known as Fenton reaction, TA forms a radical which is then oxidised by
330 molecular oxygen or iron (III) to dihydroxymaleic acid which is in equilibrium with its
331 tautomers, hydroxyoxaloacetic acid and dihydroxyfumaric acid (Clark & Scollary, 2003).
332 These compounds can be further oxidised and decarboxylated to glyoxylic and other acids.
333 The light exposure may increase the browning potential of white wines. The oxidation of TA
334 probably proceeds through both photodegradation of iron (III) tartrate and Fenton reaction.
335 GA formation requires the light exposure as well as the presence of oxygen and iron which
336 plays a major role as initiator of both photodegradation and Fenton reaction (Clark et al.,
337 2007). As for LST, the protection of wine against the light can prevent the oxidation of TA
338 and the consequent browning of wine. Nonetheless, a lower content of iron, being the

339 catalyser of Fenton reaction, can also limit the TA-related oxidative pathways. Iron can
340 derive from grape and it can be introduced in wine through the adsorption from winemaking
341 equipment as well as the treatment with fining agents, such as bentonite (Hopfer et al., 2015;
342 Bekker et al., 2019). It is among the metal ions that may change during winemaking as a
343 consequence of processes (e.g., filtering, pH adjustments, yeast hull addition and bentonite
344 fining) (Castineira Gomez et al., 2004; Nicolini et al., 2004). Some operations in winemaking
345 process including the treatment with polyvinylpyrrolidone or chelating resin (Loubser &
346 Sanderson, 1985), ion exchange technique (Benítez et al., 2002) as well as the use of
347 bentonite, the proper filtration system and the yeast lees (Bekker et al., 2019) can allow to
348 keep lower the concentration of iron and slow down the oxidative rate of Fenton reaction.

349 350 **4. Oenological strategies preventing the light-struck taste**

351 **4.1 Microbiological approaches: lowering riboflavin and methionine levels**

352 Microbiological strategies suitable for limiting the concentration of compounds involved in
353 LTS defect are not available, yet. Fracassetti and collaborators (2017) observed that some
354 commercial strains of *S. cerevisiae* released different amount of RF in wine, revealing that
355 is probably a strain-dependent character. This evidence paves the way for the development
356 of new approaches that exploit the natural biodiversity of the strains in terms of RF and Met
357 production. To this purpose, a better understanding of RF and Met pathways under
358 oenological conditions is advised. This section illustrates the metabolism of LTS-associated
359 molecules in *S. cerevisiae* with particular attention to the involved genes and enzymatic
360 reactions. Besides *S. cerevisiae*, non-*Saccharomyces* yeasts are gaining interest due to
361 their positive impact on aromatic profiles of certain wines. For this reason, sequential
362 inoculum or co-inoculum schemes can be carried out. A focus on non-*Saccharomyces*

363 yeasts is presented as well as the possible role of lactic acid bacteria on RF and Met
364 production and release.

365

366 4.1.1 Riboflavin

367 RF is one of the essential vitamins for the growth of animals, being involved as a coenzyme
368 in a great variety of metabolic reactions. In particular, FAD and FMN, the two RF active
369 forms, act as cofactors for oxidoreductases and as prosthetic groups for enzymes in the β -
370 oxidation pathway (Massey, 2000). Since mammals have lost the ability to produce RF, it
371 assumed a great commercial value; thus, lower organisms such as yeasts have been
372 exploited in the industrial processes to produce this vitamin (Garcia-Ramírez et al., 1995).
373 Some microorganisms and all animal cells are capable of uptake riboflavin, while riboflavin
374 overproducers have distinct systems for riboflavin excretion (Abbas et al., 2011). Partly for
375 this reason, yeast metabolism determines a significant contribution to RF concentration in
376 wine and to study if the RF production is dependent on the used yeast strain become
377 relevant in the LST occurrence (Fracassetti et al., 2017). RF biosynthetic pathway has been
378 widely studied in *S. cerevisiae* both for academic and biotechnological interests. RF
379 precursors are GTP and ribulose 5-phosphate and in the first step of the pathway, GTP is
380 converted by GTP cyclohydrolase II, (Rib1) to 2,5-diamino-6-(ribosylamino)-4-(3H)-
381 pyrimidinone 5'-phosphate (DRAP); then, it is reduced by Rib7p to 2,5-diamino-6-
382 (ribitylamino)-4-(3H)-pyrimidinone 5'-phosphate (Gudipati et al. 2014). Afterwards, a
383 deamination occurs to obtain the 5-amino-6-ribitylamino-2,4-(1H,3H)-pyrimidinedione-5'-
384 phosphate catalysed by Rib2p (Urban et al., 2003). The two following steps consist of a
385 dephosphorylation through an unidentified phosphatase and of a condensation with ribulose
386 5-phosphate, obtaining the 3,4-dihydroxy-2-butanone-4-phosphate (DHAB) by the DHBP
387 synthase (RIB3). The latter step is catalysed by lumazine synthase (RIB4) and provides the

388 formation of the 6,7-dimethyl-8-(1-D-ribityl) lumazine (Jin et al., 2003; García-Ramírez et al.,
389 1995). Finally, the last reaction uses two molecules of 6,7-dimethyl-8-(1-D-ribityl)-lumazine
390 and the riboflavin synthase (RIB5) catalyses the generation of one molecule of riboflavin
391 (Santos et al. 1995) (Figure 4). Hence, starting from RF, FMN and FAD are synthesized by
392 riboflavin kinase (Fmn1p) and FAD synthetase (Fad1p), respectively (Santos et al. 2000;
393 Wu et al. 1995). The characterization of the *S. cerevisiae* biosynthetic pathway was carried
394 out studying the deletion mutants for all the interesting genes: *RIB1*, *RIB2* and *RIB7*
395 (Oltmanns et al., 1972), *RIB3* (Bacher et al., 1977), *RIB4* (Garcia-Ramirez et al., 1995) and
396 *RIB5* (Santos et al., 1995). All the obtained mutants revealed an auxotrophic behaviour for
397 RF, suggesting that *S. cerevisiae* strains could be genetically modified to get strains not RF
398 producers. Since it is not currently acceptable to propose genetically modified organisms
399 (GMOs) in oenology, these mutants could be used to obtain yeast extracts suitable as
400 nutrients during the winemaking process or as an additive to prevent the anti-fermentative
401 activity of medium-chain fatty acids, as described in Ribéreau-Gayon et al. (2006). In 2017,
402 Fracassetti and collaborators evaluated the impact of several conventional oenological
403 nutrients derived from yeast, usually containing vitamins, on RF concentration during
404 vinification. Results revealed a higher RF level in wine samples added with the nutrients (76
405 and 72 µg/L, for yeast extract and yeast lysate, respectively) in comparison to the unfortified
406 ones (55 µg/L); in particular, RF increase of 21 µg/L detected in the presence of yeast extract
407 can be ascribed to the RF found in the tested additive (70 µg/g) (Fracassetti et al., 2017).
408 Spontaneous fermentations are characterized by a succession of several non-
409 *Saccharomyces* yeasts resulting from their natural presence on grapes as well as promoted
410 by oenological practices, technology and cellar hygiene (Jolly et al., 2014). Despite these
411 findings, non-*Saccharomyces* yeasts usually disappear during the early stages of
412 fermentation (Fleet et al., 1984; Henick-Kling et al., 1998) because of their slow growth and
413 inhibition due to SO₂, high ethanol and low oxygen concentrations (Jolly et al., 2014).

414 Though no evidence is reported in literature, it may be hypothesized that the lysis of non-
415 *Saccharomyces* cells can contribute to the release of RF, even during the early stage of the
416 fermentation process.

417 Concerning the wine-related lactic acid bacteria (LAB), the genera *Oenococcus* and
418 *Lactobacillus* were compared by Terrade and co-authors (2009) to determine their vitamins
419 requirements for growth conditions. The authors discovered that the tested *Lactobacillus*
420 strains were auxotroph for RF as opposed to the *O. oeni* strains, revealing the ability of the
421 latter species to synthesize vitamin B₂.

422

423 4.1.2 Methionine

424 In grape and must 28-39% of the total nitrogen is represented by free amino acids (Rapp &
425 Versini, 1991). Nitrogen content increases during grape maturation and at grapevine harvest
426 it corresponds to 70% of the organic nitrogen. Amino acids are the main part of nitrogen
427 source for yeasts during the alcoholic fermentation and for lactic bacteria in malolactic
428 fermentation. Moreover, they can be a source of undesirable compounds in wines, such as
429 ethyl carbamate, biogenic amines, and β -carbolines (Herraiz & Ough, 1993). In addition,
430 free amino acids are a source of assimilable sulfur, essential for yeast growth and relevant
431 in winemaking, since sulfur metabolism can generate unpleasant compounds, such as
432 hydrogen sulphide and mercaptans (Rauhut, 1993).

433 For all these reasons the free amino acids concentration must be taken into account,
434 especially at the end of the alcoholic fermentation since the autolysis of the yeast cells leads
435 to their discharge (Moreno-Arribas et al., 2009).

436 Particularly, Met, a sulfur-containing amino acid, plays several roles in yeast metabolism
437 (Henschke & Jiranek, 1991) and in wine off-flavour (Fracassetti et al., 2019). Its catabolism
438 in yeasts has been especially studied in *S. cerevisiae*. The enzyme 5-methyl-

439 tetrahydropteroyltriglutamate-homocysteine S-methyltransferase (Met6) catalyses the
440 transformation of a molecule of 5-methyltetrahydropteroyltri-L-glutamate and one of L-
441 homocysteine to Met and tetrahydropteroyltri-L-glutamate (Ugliano & Henschke, 2009). Met
442 catabolism proceeds by the conversion of methionine to a-keto-g-(methylthio)butyrate
443 (KMBA). KMBA is then decarboxylated to methional, that is subsequently reduced to
444 methionol (Perpète et al., 2006). Moreover, Met can be transformed to methanethiol by a
445 demethiolase and then esterified to methanethioacetate (Ugliano & Henschke, 2009).
446 Usually, around 3-4 mg/L of methionine is found in wine and it derives from yeast cells lysis
447 (Riberau-Gayon et al., 2006, Fracassetti et al., 2017). Met is stable in RF-free conditions,
448 while RF presence induces Met degradation to form MeSH and DMDS (Maujean et al., 1978;
449 Maujean and Seguin, 1983b; Andrés-Lacueva et al., 1998).

450 Also non-*Saccharomyces* yeasts could contribute to increase Met concentration in wine
451 during the winemaking process with similar release mechanisms, even though this aspect
452 was not previously described for non-*Saccharomyces* yeasts.

453 Specific attention has to be given to *O. oeni*, because this species contributes to wine
454 sensorial properties producing VOCs deriving from Met degradation in significant quantities,
455 such as methanethiol and dimethyl disulfide (Pripis-Nicolau et al., 2004; Vallet et al., 2007).
456 It is probable that also cell lysis of LAB could discharge significant amount of Met and its
457 derivatives at the end of the malolactic fermentation.

458

459 **4.2 Technological approaches**

460 The prevention of LST can be achieved by applying some oenological procedures in winery
461 once the alcoholic fermentation is completed. Several approaches have been investigated
462 with the aim either to reduce the RF concentration, or to add compounds that could act as
463 a triplet RF quencher and/or as a Met competitor for the reaction with the excited triplet RF,

464 thus reducing the formation of Met-derived spoilage molecules. In any case, the
465 technologies applied in wine production should not take part in the formation of LST and, in
466 general, in any wine fault. In this context, attention is required in case of using UV-C light.
467 UV radiation is widely used in food processing due to its antimicrobial effect (Bintsis et al.,
468 2000). Even if the treatment is not approved by the International Organization of Vine and
469 Wine (OIV), it was successfully applied for decreasing the microbial population in must
470 (Fredericks et al., 2011; Falguera et al., 2013; Fracassetti et al., 2019) and wine (Matias et
471 al., 2016; Mijowska et al., 2017). The UV radiation of wine containing RF can cause its
472 photo-degradation and the formation of VOCs leading to the detrimental change of the
473 sensory property.

474

475 4.2.1 *Riboflavin removal*

476 Because RF is one of triggering factor of LST formation, its depletion should reduce wine
477 defect. A level of RF lower than 80-100 $\mu\text{g/L}$ decrease the risk of LST appearance (Pichler,
478 1996; Mattivi et al., 2000). RF removal from wine can be attained by the use of fining agents,
479 such as bentonite. Bentonite is a montmorillonite clay that assumes negative charge at wine
480 pH and is commonly used in winemaking process as a clarifying agent. Its main task in
481 winemaking is the adsorption of wine proteins that are positively charged, in order to avoid
482 the formation of protein-related haziness. Its usual dosage ranges between 2 g/L and 8 g/L
483 that should be specifically calculated for each wine (Riberau-Gayon et al., 2006).

484 Bentonite shows the capacity to adsorb RF, but its action is not specific, thus the amount of
485 clay necessary for an adequate RF depletion is high (Pichler, 1996). In the study of Pichler
486 (1996), 2 g/L of bentonite were needed for the removal of 95 $\mu\text{g/L}$ of RF. However, such
487 bentonite dosage can lead to a significant depletion of wine aromas, thus the reduction of
488 its overall quality (Riberau-Gayon et al., 2006).

489 More recently Fracassetti et al. (2017) investigated the effectiveness of different fining
490 agents (bentonite, zeolite, polyvinylpolypyrrolidone [PVPP], kaolin, colloidal suspension of
491 pure silica, egg albumin charcoal) in terms of RF removal from model wine solution and
492 white wine. In a model wine solution RF was added up to 350 µg/L. The results pointed out
493 that the RF depletion was proportional to the increased concentrations of bentonite added
494 and at the highest concentration of bentonite (1 g/L), 35% of RF was removed. Another
495 effective adjuvant was zeolite even if its use is not approved by OIV. An addition of 1 g/L
496 zeolite decreased the RF concentration by 40%; this adjuvant was tested because it
497 represents a possible replacement of bentonite to improve protein and tartrate stability
498 (Mercurio et al., 2010). Large pore-sized charcoal was able to adsorb 70% and 94% of RF
499 at the concentration of 5 mg/L and 10 mg/L, respectively. Doses higher than 10 mg/L
500 completely removed RF in model solution. The small pore-sized charcoal was less active, it
501 removed 50% of RF. PVPP, silica, kaolin and egg white were not effective in RF depletion.
502 Bentonite, charcoal and zeolite were then evaluated in Chardonnay wine containing 350
503 µg/L of RF. Their capacity to remove RF resulted lower compared to that in a model wine
504 solution, with RF removed corresponding to 10% for zeolite, 25% for bentonite and 70% for
505 charcoal. This could be due to the role played by other wine components such as proteins,
506 phenols, lipids, polysaccharides that can be adsorbed by the clarifying agents which active
507 sites are less available to adsorb RF (Ribéreau-Gayon et al., 2006). The adsorption
508 mechanism is not RF-specific, that is why the compounds present at higher concentrations
509 in wine compete with RF for the active sites of charcoal, preventing the vitamin from being
510 adsorbed. Moreover, both charcoal and high doses of bentonite, can adsorb flavouring
511 compounds, thus making the wine poorer in terms of aroma complexity and sensory
512 characteristics. With the usually applied doses the amount of RF removed is not high enough
513 to ensure the total prevention of LST.

514

515 4.2.2 *The use of antioxidants in LST prevention*

516 Some antioxidants are present in wine, those originated from yeast metabolism, such as
517 glutathione (GSH), or added during the winemaking procedures, such as sulfur dioxide
518 (SO₂), and phenolics. Among the latter, flavan-3-ols showed the ability to inhibit the light-
519 induced fault. Specifically, the addition of (+)-catechin and (-)-epicatechin monomers and
520 dimers slowed down the formation of LST (Maujean & Seguin, 1983b). These authors
521 suggested that flavan-3-ols and maybe the condensed tannins, which building blocks are
522 represented by flavan-3-ols, can shield RF from light. Additionally, phenolic compounds
523 demonstrate the capacity to quench triplet RF in model beer solutions (Grant-Preece et al.,
524 2017). The use of phenols, both condensed and hydrolysable tannins, is a promising way
525 to limit the appearance of LST thanks to their antioxidant properties as well as to their ability
526 in quenching the singlet oxygen (Briviba et al., 1993; DeRosa & Crutchley, 2002).
527 Nevertheless, the phenolics need to be adequately chosen because of their bitter taste and
528 astringency, and also woody texture in case of hydrolysable tannins (Vivas et al., 2003).
529 Therefore, their addition to white wine should be thoroughly evaluated in order not to alter
530 the sensory properties of wine.

531 The hydrolysable tannins are commonly used in winemaking in order to improve wine
532 stability and sensory characteristics (Vivas et al., 2003; Pascual et al., 2017; Vignault et al.,
533 2018). Hydrolysable tannins have also been assessed as a potential effective measure to
534 prevent LST, as proved by Fracassetti et al. (2019a) who investigated the influence of the
535 addition of chestnut, oak and nut gall tannins in model wine solution. Their capacity to
536 prevent LST was investigated at the concentration of 40 mg/L, since this amount of tannins
537 added to wine does not influence the astringency or bitterness perception (Robichaud &
538 Noble, 1990). The experiments were carried out both in oxic and anoxic conditions. In the
539 presence of oxygen, nut gall tannin was able to decrease Met degradation (11% of degraded

540 Met), compared to either the tannin-free conditions (18% of degraded Met) or samples
541 added with chestnut or oak tannins (18.1 and 21.5%, respectively). The major Met protection
542 with nut gall tannin compared to other tannins, could be due to its two-fold higher total phenol
543 index (TPI) and high concentration of gallic acid. This phenolic acid is a singlet oxygen
544 quencher (Lagunes & Trigos, 2015), therefore, it can reduce singlet oxygen thus preventing
545 Met degradation. In anoxic conditions, Met degradation increased in all samples, but once
546 again nut gall tannin showed a major protective effect (20.2% of degraded Met in solution
547 with nut gall tannin, compared to 28.5% degraded in control sample). In air-free conditions,
548 Type I mechanism occurs, where triplet excited RF reacts directly with Met. The authors
549 suggested that nut gall tannin can compete with Met for the reaction with RF, thus limiting
550 its degradation. In terms of VSCs formation, both MeSH and DMTS concentrations were
551 six-folds higher in anoxic conditions compared to oxic ones. DMDS concentration was even
552 eighty-four folds higher. These results are in agreement with the theoretical LST mechanism:
553 in the presence of oxygen, both Type I and II mechanisms can take place (Min & Boff, 2002;
554 Grant-Preece et al., 2017). Oxygen can quench triplet excited RF and can also react with
555 Met giving its stable oxidation products, including methionine sulfoxide (Fracassetti et al.,
556 2020). As a consequence, less VSC are formed in oxic conditions. In the presence of
557 oxygen, the addition of hydrolysable tannins hampered the DMTS formation, as this
558 compound was not found in the solution. DMDS production was significantly lower when
559 chestnut and oak tannins were added, while with nut gull tannin it was not detected at all.
560 The most significant differences in VSC formation were even more evident in anoxic
561 conditions, where lower concentrations of MeSH, DMDS and DMTS were found in the
562 presence of tannins in comparison to control sample. These differences were also
563 sensorially perceived and significantly lower scores were found in the presence of tannins,
564 accordingly to VSC content.

565 The possible mechanisms of LST prevention performed by tannins can be due to their ability
566 in RF quenching, thus protect Met from degradation, or they can react with singlet oxygen
567 forming quinones (DeRosa & Crutchley, 2002), electrophile molecules able to react with
568 amine group of Met or with free thiol group of MeSH protecting from DMDS and DMTS
569 formation.

570 As regard to the addition of tannins in white wine, the effectiveness of chestnut tannin was
571 investigated (Fracassetti et al., 2019b). A RF-enriched wine was exposed to light in
572 presence of chestnut tannin. After two hours of illumination and consequent twenty-four
573 months of storage in the dark the analysis showed that MeSH and DMDS were not detected
574 or found in concentrations lower than a perception threshold as the sensory analysis did not
575 reveal an olfactory defect.

576 Hydrolysable tannins showed to successfully limit both Met degradation and VSC formation.
577 They may not totally prevent LST, but their addition prior to bottling can limit the risk of the
578 formation of light-dependent spoilage. An important aspect to take into consideration when
579 applying this preventive method is the dosage of tannins in order not to affect the taste of
580 wine. It is noteworthy to mention that tannins at concentrations studied (50 mg/L) did not
581 lead to any colour alterations after light exposure (Fracassetti et al., 2019b; Fracassetti et
582 al., 2019c). Other antioxidants, including GSH and SO₂, were tested individually or in
583 combinations, together with chestnut tannin. In model wine, the most effective condition
584 preventing the appearance of LST was the addition of all three antioxidants together, as only
585 negligible amount of MeSH and DMTS were detected, while no DMDS was detected. On
586 the other hand, the results obtained in white wine slightly differed from the model solution.
587 In the presence of chestnut tannin and GSH alone or in combination with SO₂, MeSH and
588 DMDS were undetected or detected at concentrations below their perception threshold.
589 MeSH was present in concentrations over the perception threshold in samples of white wine
590 without any added antioxidant but with SO₂. These results suggest that SO₂ could not be

591 able to protect from LST during wine storage, contrarily to what was observed in model wine
592 solution. The formation of sulfonate compounds was showed in white wine where SO₂ was
593 added and in an environment where oxygen is present (Arapitsas et al., 2016). The
594 concentration of these compounds increased for higher amounts of oxygen dissolved on
595 bottling. We can assume SO₂ favoured the formation of VOCs in the experimental conditions
596 adopted even because a medium richer in radicals could be generated as a consequence
597 of the photo-degradation of RF. In fact, SO₂ showed to favour the oxidative pathways when
598 an acidic solution containing RF and Met is exposed to light (Figure 5). The photo-oxidation,
599 monitored by NMR, led to strong and fast increase of Met sulfoxide which formation was
600 limited when gallic acid was present instead of SO₂ (Fracassetti et al., 2020). This suggests
601 the ability of phenolics in the overall prevention of the light-dependent oxidations which have
602 a detrimental impact on desired sensory characteristics of wine.

603 To the best of our knowledge no data have been reported on RF and Met decay with regards
604 to the wood ageing and batonnage. Even if these winemaking practices are less common
605 for white wine than for red wine, the ageing in oak containers is becoming a common practice
606 in some winegrowing regions (González-Centeno et al., 2020) increasing and improving the
607 availability of white wines aged in wood in the market, adapting to the demands of the
608 international trade (Alañón et al., 2018). During the wood ageing, amino acids can undergo
609 through oxidative deamination generating higher alcohols (Câmara et al., 2006; Carpena et
610 al., 2020). However, no specific result was reported on Met and its susceptibility to oxidative
611 deamination in such winemaking condition.

612

613 **4.3 Packaging and storage approaches**

614 Glass bottle is a physical barrier shielding wine from light. Its choice is of crucial importance
615 when it comes to limiting the risk of LST. Consumers often prefer flint glass bottles because

616 the colour of wine, a marker of its oxidative status, is visible. Moreover, the production and
617 recycling costs are lower for clear bottles and they have a lower carbon footprint (Hartley,
618 2008). In a survey carried out among 231 Italian wineries
619 (<https://www.surveio.com/survey/d/K6Y3T0W6C5S5Z1G2J>), up to 80% of total white wine
620 production *per* winery is bottled in clear glass. The protection from UV/Vis light offered by
621 clear glass is significantly lower compared to other commonly used bottle colours, such as
622 amber or green. Flint glass allows to pass about 90% of the harmful light (under 500 nm),
623 whereas green and amber bottles allow to pass 50% and 10% of light, respectively (Clark
624 et al., 2011).

625 The importance of wine bottle colour in LST prevention is a well-known aspect needing a
626 further consideration. Dozon and Noble (1989) carried out a sensory study to evaluate the
627 effect of light on white wines, both sparkling and still, which were bottled in flint and green
628 bottles, and then exposed to light. Panel of trained judges determined the minimum time of
629 exposure necessary to produce a difference in aroma compared to a control kept in the dark.
630 The results showed that for samples in flint bottles, the time required to develop an off-odour
631 was significantly shorter than for samples kept in green bottles. For flint bottles it was 3.4
632 and 3.3 hours for still and sparkling wine, respectively. In green bottles, an off-odour
633 appeared after 18 and 31.1 hours for still and sparkling wine, respectively. Green bottles do
634 not provide a total protection against LST, but they definitely increase the time necessary
635 for the fault perception, which resulted six- and ten-fold longer for still and sparkling wines,
636 respectively. It is noteworthy to mention that in this study wine samples were kept 35 cm
637 from the light source, while in the commercial retail conditions, wines usually are placed
638 farther from the light source. In real life conditions, time of light exposure necessary to
639 produce the olfactory defect, probably would have to be longer.

640 Differences between flint and green bottles in preventing LST were also investigated by
641 Arapitsas et al. (2020). In their study, wines were kept in a specially arranged room

642 simulating supermarket conditions, with windows with curtains, shelves, air conditioning and
643 lamps kept on 12 hours/day. Sensory analysis managed by an expert panel, who evaluated
644 wines within fifty days of light exposure, showed that most of flint bottles developed LST
645 after four weeks. The more intense perception of the defect was observed for longer time of
646 light exposure, proving this factor to be mainly causative to LST occurrence. Moreover, all
647 the wines bottled in flint glass developed LST, whereas the wines bottled in green glass
648 never exceeded four out of 10 point-scale in sensory analysis, meaning that the spoilage
649 was not clearly developed. These results confirm the previous ones, regarding the capacity
650 of green bottles to protect wines from LST better than flint ones (Dozon & Noble,1989).
651 Moreover, wines in green bottles were resistant to LST development up to 50 days of light
652 exposure which confirms that in retailing conditions, due to further wine positioning from the
653 light source, LST needs more time to develop (Arapitsas et al., 2020).

654 Another interesting outcome from this work is that LST is irreversible; the sensory evaluation
655 conducted after one year of wine storage in the dark showed the same results as the
656 analysis performed immediately after the light exposure (Arapitsas et al., 2020). The light
657 can be both absorbed by the glass and partially reflected. As a consequence, the shape of
658 the bottle and the direction of the light can also affect the occurrence of LST in wine. It has
659 been proved that long neck bottles with a shallow angle on the bottle shoulder such as
660 Rhenish bottles, show a better protection from light compared to short neck or sharp
661 shoulder angle bottles (Hartley, 2008).

662 Nonetheless, even if dark bottles can shield the light and prevent the appearance of LST,
663 the light exposure of white wine bottled in dark glasses (Antique Green and French Green)
664 can have an impact on its characteristics. In this condition, highest concentration of
665 xanthylum ions causing a major browning was found indicating a more evidenced oxidation.
666 This occurred as a consequence of the increase of temperature due to the dark bottle (Maury
667 et al., 2010). For this reason, taking into account the overall quality of white wine, oenological

668 approaches built up by means of technology, chemistry and microbiology are crucial to
669 counteract the detrimental light-dependent faults.

670 Nowadays, in order to protect the wine bottles in flint bottles, plastic or paper films are used
671 to cover the bottles. These devices are able to absorb the wavelengths that cause LST, but
672 they increase the cost of wine production in terms of necessary material and labouring
673 hours, since each bottle has to be wrapped individually. Moreover, the bottle wine wrapping
674 is associated with the waste disposal problems and the increase of plastic material
675 production.

676

677 **5. Conclusions**

678 Several factors are involved into the light-dependent spoilage of wine. LST depends mainly
679 on the concentration of RF and Met, but also to the chemical composition of wine (i.e. iron,
680 copper, phenolic compounds, antioxidants added). The type of light source in terms of
681 wavelengths emitted by the lamps, the duration of the light exposure during wine storage,
682 the distance of the lamp as well as the bottle shape and color need to be taken into account.
683 As many aspects can affect the occurrence of wine faults, it is clear that the entire
684 winemaking process, from the must production and alcoholic fermentation up to the storage
685 and selling conditions, are important aspects that have to be considered in order to maintain
686 and ensure the quality of the wine till the bottle opening.

687 In an oenological perspective, technological aspects including the use of specific adjuvants
688 having the ability of bind sulfur-containing off-flavors and quench excited RF or oxidized Met
689 as well as removing RF represent a challenge to counteract this wine fault. As the same
690 time, the use of yeast able to release low amounts of RF and Met can carry out a protective
691 effect. In this scenario, investigation on oenological tannins of different origin will support
692 the wine industry with affective tool against the detrimental effect of LST. Contemporarily,

693 the selection of low RF and Met producing yeast strains can also open up new applications
694 to positively tackle this problem of current oenology and a further improvement of precision
695 oenology.

696

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701 **Figures' Captions**

702 **Figure 1:** Riboflavin photosensitization by Type I or Type II mechanisms (Cardoso et al.,
703 2012).

704 **Figure 2:** Reaction scheme of methional formation due to light exposure (Maujean & Seguin,
705 1983).

706 **Figure 3:** Scheme of the proposed tartaric acid degradation through the Fenton reaction
707 and under light exposure (Clark et al., 2007).

708 **Figure 4:** Riboflavin pathway in *Saccharomyces cerevisiae* (Gudipati et al. 2014).

709 **Figure 5:** Photo-catalytic cycle for the riboflavin-mediated oxidation of methionine in the
710 presence of gallic acid and sulfur dioxide through Type I and Type II mechanisms
711 (Fracassetti et al., 2020).

712

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