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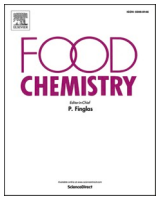

Short communication

A preliminary approach to increase oxidative stability in wines: the addition of sacrificial amino acids naturally occurring in wine to reduce Strecker aldehydes formation

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ABSTRACT

Strecker aldehydes (SA) are oxidation-related odorants, a menace to wine's ageing capacity and aromatic quality. To date, no universal solution exists to drastically reduce their formation beyond a meticulous oxygen management, which is difficult to control during commercialisation. These aldehydes mainly form via reaction of their corresponding Strecker amino acids with α-dicarbonyls. Therefore, this study aims to decrease their production by the addition of naturally occurring amino acids in wine, that might reduce the availability of α-dicarbonyls. Different accelerated oxidation procedures are performed on model wine and wine matrixes with sacrificial amino acids and SA are quantified and compared against their control. The additions of 4 mM of L-Tyrosine (Tyr) and L-Aspartic acid (Asp) reduce production rates up to 15 % in spiked wines or 7–8 % in rosé for 3-methylbutanal, methional and phenylacetaldehyde. This study sheds light on a promising technique for reducing SA in wine and potentially increasing its longevity.

1. Introduction

Among all the molecules identified as responsible for several wine oxidative faults, the Strecker aldehydes (SA) emerge as the main group of odorants with presumably parallel formations in terms of molecular reactions. These aldehydes have been identified as the causative agents of several aromatic deviations inducing "cooked vegetables" odours in the case of methional (Escudero et al., 2000), and "honey-like" for phenylacetaldehyde (Silva Ferreira et al., 2003). In summary, these aldehydes have been proven to induce a decline in terms of quality (Culleré et al., 2007; Marrufo-Curtido et al., 2021; San-Juan et al., 2011). Recent studies have reported that up to 75 % of commercially available wines contain levels of these odorants that are of concern (Marrufo-Curtido et al., 2021). The global impact of SA has recently been examined through a systematic oxidation of various red wines with varying grape variety, region, oak-ageing time and market price. It has been demonstrated that all of these factors are capable of exerting a significant influence on the quality of the wine (Aragón-Capone et al., 2025).

In the context of wine, three distinct production pathways have been demonstrated: fermentation via the Ehrlich route (Kłosowski et al., 2015), direct oxidation of their precursor alcohols (Escudero et al., 2000), or the reaction of Strecker amino acids (aaS) (valine, isoleucine, leucine, methionine, and phenylalanine) with α-dicarbonyls. The final reaction has been shown to exhibit significantly reduced reaction rates in comparison to other nucleophiles (Nikolantonaki & Waterhouse, 2012). Nevertheless, it has been demonstrated to be the primary formation mechanism for SA (Bueno et al., 2018; Grant-Preece et al., 2013). These α-dicarbonyls are formed by the oxidation of various phenolic compounds to form quinones (Monforte et al., 2020; Rizzi, 2006). Currently, a recently published work reports the notorious formation of SA in anoxic conditions (Denat et al., 2022), suggesting the potential role of α-dicarbonyls already present in the absence of wine oxidation, as previously indicated for Bueno et al. (Bueno et al., 2018).

The relevance of SA is such that numerous published works have addressed the impact of specific parameters, including pH (Marrufo-Curtido et al., 2022; Monforte et al., 2018), temperature (Denat et al., 2022; Monforte et al., 2018), metals (Monforte et al., 2018, 2019), and

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the kind of o-quinone on their production (Bueno-Aventín et al., 2021; Delgado et al., 2015; Escudero et al., 2025; Monforte et al., 2020; Oliveira et al., 2017). In relation to the nature of quinone-precursors, Bueno-Aventín, Escudero, and collaborators reported that different quinone precursors exhibited varying contributions to aldehyde production. On the one hand, dihydroxylated polyphenols produced high amounts of SA. On the other hand, delphinidin-3-glucoside and coumaric acid have been shown to impede the accumulation of SA. The negative correlation between delphinidin-3-glucoside and prodelphinidins with SA production could be a consequence of their higher electrophilic activity (Imran et al., 2021; Mouls & Fulcrand, 2015), which can cause their quinones to react with different nucleophiles rather than being involved in the Strecker degradation of amino acids (Bueno-Aventín et al., 2021; Escudero et al., 2025).

The primary concern associated with SA is that they form odourless adducts with SO_2 (de Azevedo et al., 2007). Consequently, the potential threat to wine may be already present even if it is not perceptible during the bottling process. However, as the ageing process progresses and SO_2 is consumed, these adducts are reversed to the aldehyde free forms (Bueno et al., 2016), which are critical for wine aroma (Marrufo-Curtido et al., 2021). This phenomenon provokes the consumer's disappointment of a product which is completely different than the one it was once bottled by the producer.

The detrimental impact of SA on wine quality and aroma has prompted the development of several approaches to address this issue during different stages of the winemaking process. Balboa-Lagunero et al., propose a selection of yeasts that have the capacity to reduce the availability of amino acids. They also indicate that the production of SA varies depending on the yeast, and consequently this results in different aromatic profiles. Despite the absence of a definitive solution as the strain with the lowest SA content was observed to present one of the highest scores in the oxidation degree (Balboa-Lagunero et al., 2013). Regarding direct applications on wine, Marrufo-Curtido et al. achieve the elimination of SA through the use of anion exchange resins but with side-effects on the colour (Marrufo-Curtido et al., 2021). Meanwhile, alternative strategies have been executed to directly reduce their production yields by using yeast derivatives selected based on their nucleophilic activity (Nikolantonaki & Schneider, 2024).

Despite their pioneering nature, these studies still report significant levels of aldehydes after the treatments. Given this, further research is needed, taking into account both the aromatic quality and market preferences that are focused on minimal intervention in the final product. With regard to Strecker reaction, a potential approach could be the addition of amino acids (Aa) other than leucine, isoleucine, valine, methionine and phenylalanine (aaS) to undergo Strecker reaction and produce odourless aldehydes. This would reduce the availability of α-dicarbonyls in wine to generate oxidation-related compounds from aaS.

2. Materials & methods

2.1. Standards & reagents

Strecker aldehydes analysis: Standards; 2-methylpropanal (≥99 %), 2-methylbutanal (≥95 %), 3-methylbutanal (≥95 %), methional (≥98 %), phenylacetaldehyde (≥95 %), and 2-methylpentanal (≥98 %) were from Merck (Darmstad, Germany). The stable isotopes used as internal standards were from Eptes (Vevey, Switzerland): 3-methylbutanal-d_2 (≥90 %), methional-d_3 (≥90 %) and phenylacetaldehyde-d_5 (≥95 %). Solvents and reactives: methanol (99.8 %), dichloromethane (99.8 %) Distol Pesticide quality and n-hexane for Organic Trace Analysis (≥95 %) were from Fisher Scientific (Madrid, Spain). PFBHA (≥98 %) for derivatisation was from Merck, and sodium hydrogencarbonate (≥99 %) was from PanReac (Barcelona, Spain).

Amino acids: Strecker amino acids (aaS); L-Valine (Val) ≥ 99 %, L-Isoleucine (Ile) ≥ 98 %, L- Leucine (Leu) ≥ 99 %, L- Methionine (Met) ≥ 99 %, and L-Phenylalanine (Phe) ≥ 98 % were from Sigma-Aldrich (Madrid, Spain). Sacrificial amino acids: L-alanine (Ala) ≥ 98 %, L-Tyrosine (Tyr) ≥ 98 %, L-Aspartic acid (Asp) ≥ 99 %, L-Glutamic acid (Glu) ≥ 99 %, L-Serine (Ser) ≥ 99 %, L-Glycine (Gly) ≥ 99 %, and L-Threonine (Thr) ≥ 98 % were from Sigma-Aldrich.

Metals: $FeCl_2{\cdot}4H_2O$ (99 %), $CuSO_4{\cdot}5H_2O$ (98 %), and $MnCl_2{\cdot}4H_2O$ (98 %) were from PanReac AppliChem.

Reactants for Strecker reaction: 4-methylcatechol (95 %) was from Sigma-Aldrich.

Model wine: Water was purified using a Milli-Q® system from Millipore (Bedford, Germany). Tartaric acid (≥ 99 %), sodium hydroxide pellets (≥98 %) were from PanReac AppliChem. Absolute ethanol (≥99.8 %) was from ITW Reagents (Barcelona, Spain).

Total SO_2 analysis: NaOH 0.01 M, mixed indicator 4.4 (methyl red – methylene blue), ortho-phosphoric acid at 85 % and hydrogen peroxide at 3 % *w/v* (10 vol.) were from PanReac AppliChem.

2.2. Total strecker aldehydes analysis by derivatisation with PFBHA

Total Strecker aldehydes were analysed using the methodology developed by Castejón-Musulén et al. (Castejón-Musulén et al., 2022). This method derivatises aldehydes with o-(2,3,4,5,6-pentafluorobencyl) hydroxylamine (PFBHA) to form their oximes. SA are analysed by gas chromatography–mass spectrometry (GC–MS) after a solid phase extraction (SPE).

2.3. Total SO_2 determination

In those cases in which real wine was the matrix to study, total SO_2 levels were determined to control the oxidative stimuli. For this purpose, the aspiration-titration method proposed by Rankine (Rankine & Pocock, 1970), and recommended by the International Organization of Vine and Wine (OIV) (OIV, 2009) was performed.

2.4. Oxidation treatment and O_2 consumption monitoring

The accelerated oxidation procedure performed was the one described by Marrufo-Curtido et al. (Marrufo-Curtido et al., 2018). In this procedure, the wine is exposed to a controlled dose of O_2 which is calculated based on the atmospheric O_2 levels (21 % *v/v*) and the headspace volume of the recipient. In order to execute this control, it is necessary to make other characterisations, such as the container's volume or the wine density and therefore, the weight needed for the desired headspace volume. During the accelerated oxidation process, the oxidation rate was controlled by monitoring the dissolved O_2 with Pst3 sensors placed in the vials. These vials were subjected to horizontal shaking at 100 r.p.m. and stored in the dark at 35 °C until the end of the treatment.

2.5. Addition of sacrificial amino acids to reduce reactive α-dicarbonyls availability

2.5.1. Sacrificial amino acids performance on model wine

The model wine used for the first experience was a hydroalcoholic solution (12 % ethanol) with 5 g L^{-1} of tartaric acid and an adjusted pH of 3.5 with NaOH (Oliveira et al., 2017). This model wine was exposed to 20 mg L^{-1} of O_2 and the following compounds were added: metals (5 mg L^{-1} of Fe^{2+}, 0.2 mg L^{-1} of Cu^{2+}, and 0.2 mg L^{-1} of Mn^{2+} – as used in other studies (Bueno-Aventín et al., 2021; Marrufo-Curtido et al., 2022)); polyphenols (4-methylcatechol commonly used as model phenol (Danilewicz, 2013; Elias & Waterhouse, 2010)at 2 mM); aaS at 0.2 mM each, and one sacrificial amino acid each time (L-Alanine (Ala), L-Tyrosine (Tyr), L-Aspartic acid (Asp), L-Glutamic acid (Glu), L-Serine (Ser), L-Glycine (Gly), and L-Threonine (Thr) were added at 2 mM).

In this experience as in the following ones, controls were prepared with the same composition but without the addition of sacrificial amino

acids.

2.5.2. Application red wine conditions

For this experience, the same quantities than in previous ones (section 2.5.1) were used for metals, O_2 exposure, Gly, Tyr, Thr, Asp, and aaS. This time, since the matrix was a real wine, a young red from D. O. Campo de Borja made from Garnacha (14.5 % ethanol), no 4-methylcatechol was needed.

2.5.3. Sacrificial amino acids concentration impact on the effectiveness

In this third experience, varying concentrations of Tyr and Asp (1, 2 and 4 mM) were added individually to the same red wine as well as metals and aaS. This time the O_2 exposure increased up to 35 mg L^{-1} over the stoichiometric to consume total SO_2.

2.5.4. Applicability to red, rosé and white wines

Eventually, 1 and 4 mM of Tyr and Asp were added to three different wines: one red, one young rosé and one white wine. The rosé was made from Garnacha (12.5 % ethanol) and the white was made from Garnacha Blanca (12.5 % ethanol), both from D.O. Cariñena. The red wine was the same as in section 2.5.2. Although the exposure to O_2 was the same than in section 2.5.3, this time neither metals nor aaS were added.

2.6. Data treatment

Data treatment approaches the identification of differences between several conditions and their control. For this purpose, ANOVAs were performed, and if significant ($p < 0.05$), post-hoc test of Fisher's Least Significant Difference (LSD) was performed to spot those differences. These analyses were performed by the XLSTAT 2024 software by Addinsoft (Paris, France).

3. Results and discussion

3.1. Screening of multiple amino acids in model wine

The first experience was designed to identify the most promising sacrificial amino acids for further analysis based on both produced aldehydes or their formation ratios. For this purpose, Ala, Asp, Glu, Gly, Ser, Thr and Tyr capacity to inhibit Strecker aldehydes formation was evaluated in model wine. The addition of Asp, Gly and Tyr significantly ($p < 0.05$) reduced the phenylacetaldehyde formation ratio up to 35 %. However, it is noteworthy that these amino acids did not have a significant effect on absolute concentrations, which is explained by their higher O_2 consumption rates. In fact, it is worth to mention that although Asp increased both concentrations and formation ratios in the other aldehydes; it was selected for further trials since phenylacetaldehyde has been reported as one of the most relevant aldehydes in wine aroma (Culleré et al., 2007).

Another amino acid worth considering for further reduction trials was Thr, since it reduced the formation of 2-methylpropanal and 2-methylbutanal by approximately 12 and 15 % respectively. The other sacrificial amino acids did not result in significant decreases in SA against the control, and in some cases, they even led to increases (Table 1**).**

3.2. Effectiveness on red wine matrix

Based on the aforementioned results, the effectiveness of Gly, Tyr, Thr, and Asp in reducing the formation of Strecker aldehydes was investigated in red wine spiked with aaS and metals. It was only Asp and Tyr that were capable of achieving a statistically significant ($p < 0.05$) reduction in both the total amounts and ratios of 2-methylpropanal. In addition, Tyr also reduced the ratios of 2-methylbutanal and phenylacetaldehyde. Altogether, these findings suggest that, despite their effectiveness in model wine, Gly and Thr would not be advantageous in a red wine matrix (Table 1). Consequently, they were excluded from subsequent experiments.

3.3. Addressing the dose effect of Tyr and asp in red wine

In this experience, the dose-dependent effects (1, 2, and 4 mM) of Tyr and Asp in the same young red wine enriched with aaS and metals were studied. Two-way ANOVAs for each aldehyde (dose and amino acid) revealed significant diminutions ($p < 0.05$) in absolute level (Table 2) and formation ratios (**Table S.1 in Supplementary Material**) for 3-methylbutanal, methional and phenylacetaldehyde. However, the findings also indicated a lack of significance ($p > 0.05$) in terms of the applied dose, the amino acid, and their interaction. This suggests that the effect would be independent of the dose and the application of either Asp or Tyr. Lower accumulations yields were observed for 3-methylbutanal ($p = 0.103$), methional ($p = 0.075$) and phenylacetaldehyde ($p = 0.045$), regardless the dose and the sacrificial amino acid added (**see** Table 2). The maximum reduction rates observed were 10.8, 13.7 and 15.3 % respectively.

3.4. Treatment applicability to red, white and rosé wines

As the dose did not have a significant impact on the SA production, the final experiment applied the maximum and minimum concentrations (1 and 4 mM) for Asp and Tyr in young white, red and rosé wines, without spiking them with metals or aaS. It is evident that rosé manifests the greatest sensitivity to this treatment, reporting maximum reduction rates of 8.1 %. Consequently, asignificant decrease in total amounts (Table 2) and formation ratios in 3-methylbutanal, methional and phenylacetaldehyde (**Table S.1**) is demonstrated. However, the interaction between the dose and amino acid factors is significant ($p < 0.05$), which means that an increase in dose does not affect Tyr effectiviness, but it does for the Asp.

In the case of red wine, the results do not align with the previous experience since no aaS or metals were added this time. In general, it could be stated that those aldehydes whose accumulation is significantly modified ($p < 0.05$) by the addition of Asp and Tyr are 3-methylbutanal, methional and phenylacetaldehyde (Table 2 **and Table S.1**). It is noteworthy that these three SA are predicted to be the most problematic, as indicated by their concentration range and their odour thresholds (Culleré et al., 2007).

The sensory impact these reductions might have can be estimated by Steven's perception equation (Eq.1), where k is a constant, C is the concentration, and n is the coefficient coefficient (Stevens, 1957); which ranges from 0.1 to 0.9 (Chastrette et al., 1998).

$$Intensity = k \times C^n \quad (1)$$

In fact, Chastrette et al. demonstrated that this equation yields acceptable results when near the threshold in a logarithmic scale of the concentration. Given that concentration obtained range in ±1 logarithmic order around the thresholds (Culleré et al., 2007), and for the highest SA reductions observed, intensity changes range from 0.7 % to 7.2 % depending on the n value (**Table S.2 in Supporting Information**). However, deeper sensory research needs to be made considering feasible synergic effects among these odorants (Ferreira et al., 2022).

3.4.1. Comparison with other alternative treatments

These results can be compared with those of other studies. Firstly, Nikolantonaki and Schneider indicate that the addition of a selected yeast derivative at 30 g hL^{-1}, can reduce the sum of total Strecker aldehydes formed by up to 28.3 % after three months in Chardonnay at winery scale (Nikolantonaki & Schneider, 2024). However, low effectiveness is observed for methional and phenylacetaldehyde, which are the most problematic as mentioned above.

In the meanwhile, the yeast selection proposed by Balboa-Lagunero et al. The selection criteria were based on the consumption capacities of

Table 1
Strecker aldehydes produced, consumed oxygen and aldehyde formation ratio of each amino acid in experiences in model and red wine. Results are expressed as the average ± standard deviation ($n = 2$). For each column and experience, statistical differences based on Fisher's LSD ($p < 0.1$) are expressed with superscript letters. In bold, those presenting significant differences in ANOVA ($p < 0.1$), and in green those with a significant decrease in the produced aldehyde or formation ratio if compared with the control. If no statistical difference is observed, no superscript letters are shown.

Matrix	Sacrificial amino acid	Produced aldehyde (μg L^{-1})					O_2 consumed (mg L^{-1})	Aldehyde formation ratio (μg aldehyde/mg O_2)				
		2-methylpropanal	2-methylbutanal	3-methylbutanal	Methional	Phenylacetaldehyde		2-methylpropanal	2-methylbutanal	3-methylbutanal	Methional	Phenylacetaldehyde
Model wine	Control	98.7 ± 2.5^{C}	143.8 ± 7.2^{C}	214 ± 11^{C}	338 ± 17^{C}	406 ± 20	11.88 ± 0.69	8.31 ± 0.69^{B}	12.1 ± 1.3^{B}	18.1 ± 1.9^{B}	28.4 ± 3.1^{B}	34.2 ± 3.7 ^{A}
	Ala	100.9 ± 6.3^{BC}	141.14 ± 0.54^{C}	209.8 ± 5.0^{C}	328.4 ± 3.7^{C}	348 ± 27	11.47 ± 0.80	8.82 ± 0.75^{B}	12.26 ± 0.82^{B}	18.26 ± 0.86^{B}	28.7 ± 1.7^{B}	30.5 ± 4.5 ^{AB}
	Asp	196 ± 21 ^{A}	273 ± 20 ^{A}	331.2 ± 4.9 ^{A}	529.3 ± 6.2 ^{A}	390 ± 33	13.76 ± 0.40	14.2 ± 1.9 ^{A}	19.8 ± 2.0 ^{A}	23.9 ± 1.0 ^{A}	38.2 ± 1.5 ^{A}	28.2 ± 3.1^{B}
	Glu	102 ± 17^{BC}	134 ± 10^{C}	196 ± 13^{C}	309 ± 24^{C}	363 ± 33	11.88 ± 0.64	8.6 ± 1.8^{BC}	11.3 ± 1.4^{BC}	16.5 ± 1.9^{BC}	26.0 ± 3.4^{BC}	30.5 ± 1.2^{AB}
	Gly	108.1 ± 5.4^{BC}	145.0 ± 7.2^{C}	199 ± 10^{C}	315 ± 16^{C}	348 ± 17	12.07 ± 0.24	8.89 ± 0.59^{B}	11.87 ± 0.80^{B}	16.4 ± 1.1^{BC}	26.0 ± 1.7^{BC}	28.7 ± 1.9^{B}
	Ser	98.6 ± 2.0^{C}	138.9 ± 2.6^{C}	198.1 ± 2.2^{C}	316.1 ± 4.1^{C}	386 ± 37	11.23 ± 0.24	8.79 ± 0.35^{B}	12.36 ± 0.50^{B}	17.63 ± 0.54^{B}	28.22 ± 0.91^{B}	34.4 ± 2.7 ^{A}
	Thr	86.79 ± 0.11^{D}	125.03 ± 0.46^{D}	196 ± 0.40^{CD}	301.6 ± 1.2^{CD}	388 ± 64	11.47 ± 0.73	7.57 ± 0.47^{BC}	10.94 ± 0.68^{BC}	17.1 ± 1.1^{BC}	26.4 ± 1.5^{BC}	33.7 ± 3.5 ^{A}
	Tyr	133 ± 31^{B}	203 ± 35^{B}	257 ± 30^{B}	400 ± 52^{B}	338 ± 47	15.10 ± 0.59	8.8 ± 1.7^{BC}	13.4 ± 1.7^{B}	16.9 ± 1.3^{BC}	26.4 ± 2.4^{BC}	22.3 ± 2.2^{C}
Red wine	Control	24.42 ± 0.31 ^{A}	12.31 ± 0.24^{AB}	33.84 ± 0.80	29.14 ± 0.30	192.4 ± 3.1	18.01 ± 0.23	1.351 ± 0.046 ^{A}	(768 ± 39) × 10^{-3A}	1.874 ± 0.044	1.611 ± 0.047^{B}	10.69 ± 0.10^{B}
	Asp	20.61 ± 0.42^{B}	11.82 ± 0.50^{AB}	35.1 ± 1.5	32.01 ± 0.70	198.6 ± 2.2	18.18 ± 0.45	1.130 ± 0.048^{B}	(765 ± 49) × 10^{-3} ^{AB}	1.928 ± 0.095	1.762 ± 0.041 ^{A}	10.92 ± 0.12 ^{AB}
	Gly	24.39 ± 0.61 ^{A}	13.0 ± 1.1 ^{A}	34.5 ± 3.3	29.7 ± 2.4	196 ± 25	18.03 ± 0.34	1.349 ± 0.039 ^{A}	(722 ± 42) × 10^{-3A}	1.91 ± 0.18	1.65 ± 0.98^{AB}	10.8 ± 1.2^{ABC}
	Thr	23.4 ± 1.5 ^{A}	12.88 ± 0.70^{AB}	34.6 ± 1.1	31.4 ± 1.4	199.7 ± 9.8	18.04 ± 0.74	1.302 ± 0.044 ^{A}	(714 ± 45) × 10^{-3A}	1.916 ± 0.040	1.743 ± 0.040 ^{A}	11.13 ± 0.14 ^{A}
	Tyr	19.81 ± 0.22^{B}	11.09 ± 0.80^{B}	35.0 ± 1.0	30.7 ± 1.7	193 ± 11	18.57 ± 0.74	1.074 ± 0.084^{B}	(660 ± 33) × 10^{-3B}	1.884 ± 0.038	1.661 ± 0.039 ^{AB}	10.37 ± 0.21^{C}

Table 2
Strecker aldehydes produced and consumed oxygen of varying concentrations of Asp and Tyr in different wine matrices: red wine enriched with metals and aaS and not enriched red, rosé and white wine. Results are expressed as the average ± mean standard deviation (n = 2). For each column and wine, statistical differences based on Fisher's LSD ($p < 0.1$) are expressed with superscript letters. In green those with a significant decrease in the produced aldehyde if compared with the control and in bold those groups with significant changes ($p < 0.1$). If no statistical difference is observed, no superscript letters are shown.

Wine	Sacrificial amino acid	Dose (mM)	Produced aldehyde (μg L^{-1})					O_2 consumed (mg L^{-1})
			2-methylpropanal	2-methylbutanal	3-methylbutanal	Methional	Phenylacetaldehyde	
Red (enriched with metals and aaS)	Control	–	63.7 ± 1.4^{AB}	61.4 ± 1.6	101 ± 1.9 ^{A}	101 ± 2.1 ^{A}	163.1 ± 3.9 ^{A}	42.37 ± 0.10
	Asp	1	66.5 ± 2.3 ^{AB}	58.8 ± 1.0	92.4 ± 1.1^{B}	89.60 ± 0.31^{B}	146.61 ± 0.73^{B}	41.89 ± 0.031
		2	68.7 ± 1.3 ^{A}	61.4 ± 2.1	92.2 ± 3.1^{B}	91.0 ± 3.9^{B}	146.8 ± 4.9^{B}	42.84 ± 0.41
		4	65.8 ± 1.4^{AB}	59.0 ± 1.2	91.6 ± 1.7^{B}	90.9 ± 1.9^{B}	144.5 ± 3.5^{B}	42.56 ± 0.17
	Tyr	1	62.77 ± 0.83^{B}	58.33 ± 0.73	92.6 ± 0.53^{B}	91.07 ± 0.62^{B}	147.76 ± 0.30^{B}	40.99 ± 0.20
		2	64.5 ± 1.8^{AB}	58.74 ± 0.48	91.04 ± 0.78^{B}	90.09 ± 0.82^{B}	143.7 ± 1.6^{B}	41.488 ± 0.038
		4	63.33 ± 0.32^{AB}	57.24 ± 0.69	90.1 ± 1.7^{B}	87.14 ± 1.73^{B}	138.3 ± 2.7^{B}	41.371 ± 0.094
Red	Control	–	36.93 ± 0.82	15.83 ± 0.25	35.80 ± 0.17	4.620 ± 0.071	19.4 ± 0.17^{B}	45.4
	Asp	1	37.11 ± 0.41	15.89 ± 0.10	36.03 ± 0.38	4.697 ± 0.098	19.1 ± 0.33^{B}	45.2
		4	36.73 ± 0.33	15.804 ± 0.064	36.07 ± 0.32	4.584 ± 0.073	18.3 ± 0.49^{B}	45.4
	Tyr	1	38.0 ± 1.2	15.73 ± 0.39	36.57 ± 0.55	4.62 ± 0.12	23.7 ± 1.7 ^{A}	45.2
		4	37.94 ± 0.50	15.96 ± 0.44	36.66 ± 0.30	4.54 ± 0.10	20.7 ± 0.42^{AB}	45.1
Rosé	Control	–	57.9 ± 2.8	24.04 ± 0.76	54.04 ± 0.18 ^{A}	9.411 ± 0.040 ^{A}	27.82 ± 0.12 ^{A}	20.8
	Asp	1	54.14 ± 0.76	22.10 ± 0.084	53.18 ± 0.20^{B}	9.183 ± 0.025 ^{A}	27.63 ± 0.53 ^{A}	20.3
		4	59.66 ± 0.33	22.7 ± 1.9	50.12 ± 0.18^{C}	8.702 ± 0.084^{B}	25.55 ± 0.62^{B}	20.1
	Tyr	1	52.54 ± 0.39	20.94 ± 0.10	50.48 ± 0.29^{C}	8.708 ± 0.029^{B}	25.89 ± 0.27^{AB}	20.1
		4	61.2 ± 5.0	23.27 ± 0.77	50.50 ± 0.12^{C}	8.664 ± 0.077^{B}	26.64 ± 0.41^{AB}	19.8
White	Control	–	33.0 ± 1.8	9.39 ± 0.50	55.41 ± 0.28	6.863 ± 0.042	20.7 ± 3.7	26.0
	Asp	1	29.1 ± 2.0	8.46 ± 0.38	55.39 ± 0.40	6.966 ± 0.062	18.24 ± 0.26	27.5
		4	29.12 ± 0.32	8.433 ± 0.073	55.48 ± 0.85	6.92 ± 0.27	18.3 ± 1.5	27.7
	Tyr	1	31.56 ± 0.29	9.09 ± 0.14	54.32 ± 0.31	6.890 ± 0.054	18.34 ± 0.86	26.5
		4	29.4 ± 2.1	8.41 ± 0.42	55.24 ± 0.29	6.794 ± 0.098	18.8 ± 1.0	27.4

amino acids precursors of oxidation notes (valine, methionine, and phenylalanine). This study led to significant variations between strains, with a reduction rate of up to 43.6, 53.5, and 57.3 % between the highest and the lowest productions for 2-methylpropanal, 2-methylbutanal and 3-methylbutanal respectively. However, for the most promising strain according to isoaldehydes results, phenylacetaldehyde levels do not vary significantly and even methional is remarkably produced (Balboa-Lagunero et al., 2013).

Another strategy worth to mention is the one used by Marrufo-Curtido et al. This work is based on the use of different type of resins. In fact, very promising results were obtained for the mixed model resin Strata X-A with highly remarkable reductions ranging from 11 % for 2-methylpropanal to 86 % for phenylacetaldehyde. Although being the best results among all the mentioned, its implementation on an industrial scale is challenging due to the quantity of resin used (10 g L^{-1}) and critical changes in pH, total acidity, and colour in wines (Marrufo-Curtido et al., 2021).

At last, the compatibility of all these treatments, including the addition of sacrificial amino acids, seems promising, given that they act in different processes (yeast selection, direct removal, and by decreasing the accumulation of quinones or the availability of reacting α-dicarbonyls once they are formed). This implies that further research needs to be made to address two key areas: firstly, the impact of combining these treatments on SA accumulation, and secondly, the applicability of these treatments at winery scale.

4. Conclusion

The addition of several amino acids naturally occurring in wine has been explored as a tool to diminish the formation of SA by reducing the availability of α-dicarbonyls reacting with aaS. Tyr and Asp have been identified as the most effective ones, and their significant effect has been identified in red and rosé wine matrixes for 3-methylbutanal, methional and phenylacetaldehyde. Despite the attainment of significant reductions of up to 15 % in enriched red wine with aaS and 8.1 % in non-spiked wine, further research needs to be made towards the sensory impact of these reductions as well as the combination with other SA reduction techniques.

CRediT authorship contribution statement

Ángel Manuel Aragón-Capone: Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Mónica Bueno:** Writing – review & editing, Writing – original draft, Supervision, Investigation. **David Marzo-Méndez:** Software, Investigation, Formal analysis, Data curation. **Ana Escudero:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Vicente Ferreira:** Writing – review

& editing, Resources, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2025.146461.

Data availability

No data was used for the research described in the article.

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