FUNGAL CHITOSAN vs BENTONITE IN 'SOLARIS' WHITE WINE UNDER REDUCED SO_2. PART 2: PHYSICOCHEMICAL STABILITY AND SENSORY QUALITY DURING STORAGE

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Abstract

This study evaluated the effects of fungal-derived chitosan (CHIT) and bentonite (BENT), applied under standard and reduced SO_2 regimes, on total copper and iron concentrations, protein stability, and the post-storage trained-panel sensory profile of 'Solaris' white wine across successive processing stages and after 60 days of storage. The experimental design included fining treatments, determination of Cu and Fe concentrations, assessment of protein stability, and sensory evaluation after storage. Chitosan provided the most consistent reduction in both Cu and Fe and was associated with a more favourable trained-panel sensory profile after storage, while also achieving protein stability under the applied heat-test criterion. Bentonite delivered the greatest safety margin for protein stabilisation and the lowest final turbidity; however, under reduced SO_2, it was associated with stronger panel-perceived oxidative character and aldehydic notes/browning after storage. Overall, the findings indicate that fining-agent selection is a key determinant of SO_2-reduction strategies for white wine production, although longer storage trials, combined with direct oxidative-marker analysis, are needed to confirm long-term oxidative and aroma stability.

Keywords: *colloidal stability, oxidation, browning, clarity, sensory evaluation*

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1. Introduction

Iron (Fe) and copper (Cu) are technologically relevant trace metals in white wines because, even at concentrations routinely encountered in oenological practice, they can modulate oxidation kinetics and increase the risk of physicochemical instability during storage. Copper is of particular concern not only due to its catalytic redox activity but also because its concentration is subject to regulatory control; the maximum acceptable level in wine is 1 mg/L [1]. As metal load increases, under matrix-dependent conditions such as oxygen availability, the presence of phenolic substrates and the degree of sulphur dioxide (SO_2) protection, the likelihood of metal-related hazes (iron/copper casse) and enhanced non-enzymatic oxidation rises. Mechanistically, Fe and Cu participate in redox cycling that promotes reactive oxygen species formation and accelerates pathways leading to browning, loss of aromatic "freshness", and the development of honey/nut-like notes [2, 3]. These considerations support viewing fining and clarification not merely as operations aimed at turbidity reduction, but also as interventions capable of shifting the metal balance and, indirectly, the oxidative stability of wines throughout subsequent stabilisation and storage.

In practical terms, the long-term quality of white wines reflects the interplay between protein/colloidal stability and oxidative stability. Under low-intervention approaches, including regimes with reduced SO_2, quality faults may become more readily expressed over time, and the technological margin for error narrows. Accordingly, Part 2 of the present study compares two fining agents-fungal chitosan (CHIT) and bentonite (BENT) using endpoints that are directly linked to shelf stability and sensory quality of 'Solaris' wine during storage, with emphasis on Fe/Cu profiles, oxidation-related colour development (A_{420} and CIE L*a*b* parameters), and sensory consequences. This approach is motivated by the increasing relevance of "low SO_2" strategies, in which the management and distribution of SO_2 across processing steps can materially influence aroma stability and perceived quality during storage [4].

Fungal chitosan is described as a multifunctional fining agent whose value derives from combined interactions with the colloidal matrix and the capacity to bind cationic species, including metal ions. Such binding may promote the removal of metals with the sediment fraction and thereby attenuate oxidative pressure during storage, particularly under limited SO_2 protection [5]. From the perspective of chitin chemistry, this functionality is rooted in the polycationic character of chitosan at wine pH, where protonated amino groups and residual hydroxyl functionalities enable coordination/chelation and electrostatic association with metal species, thereby providing a mechanistic basis for using chitosan and its derivatives as metal-binding materials in complex aqueous matrices [5, 6]. Recent work has further advanced the concept of "unconventional" fungal chitosan obtained from mushroom by-products as alternative clarifying/stabilising agents for white wines, reinforcing the applied relevance and timeliness of comparative studies in this field [7]. Across comparative investigations, chitosan often shows a marked ability to reduce Cu, whereas its effects on Fe tend to be more moderate and depend on dose, pH, initial metal load, and wine matrix characteristics [5, 8]. From a strictly oenological perspective, chitosan, including fungal sources, has also been proposed as a viable alternative to bentonite for protein stabilisation in white wines, although its performance remains strongly matrix-dependent and contingent on treatment conditions [9]. Consequently, rigorous interpretation requires that net changes in Fe and Cu be evaluated alongside the fining mechanism and tested for coherence with oxidation markers and sensory outcomes during storage.

Bentonite remains the reference material for protein stabilisation of white wines because it consistently and predictably removes haze-forming proteins, providing robust technological assurance against protein instability during distribution and storage [10]. The trade-off associated with this efficacy arises from non-selective adsorption. Simultaneously with protein adsorption, bentonite may co-remove compounds relevant to quality, including phenolics and/or volatile components, may increase volume losses, and alter colloidal properties; effects that can be particularly consequential in aromatic white wines and under low-intervention technological regimes [10]. Importantly, evidence indicates that bentonite's impact on wine composition may not be purely a sedimentation-driven process but may also involve, depending on clay characteristics and matrix conditions, ion-exchange phenomena and associated shifts in elemental composition, potentially leading to bidirectional changes in selected metal concentrations [11]. Therefore, comparative assessments should consider protein stability and clarity alongside Fe/Cu profiles and oxidation markers to avoid the oversimplified inference that "fining performance" is synonymous with "storage stability".

In white wines, absorbance at 420 nm (A_{420}), commonly referred to as the browning index, is widely used as an indicator of yellow-brown colour development during storage because it integrates the accumulation of phenolic oxidation products and oxidative pigments [12]. Mechanistically, the coupled action of oxygen, phenolic substrates and transition metals is central: Fe and Cu participate in redox cycles that generate hydrogen peroxide and other reactive oxygen species, promote the oxidation of phenolics to quinones, and drive subsequent reactions responsible for browning and aroma evolution [13]. Model studies further support the view that interactions between transition metals and SO_2 can significantly modulate browning kinetics, strengthening the interpretative axis linking "Fe/Cu - SO_2 - colour/oxidation" [14]. From a practical perspective, combining A_{420} with CIE L*a*b* parameters, such as changes in L* and shifts in b*, provides a coherent description of the direction and magnitude of colour change and can support interpretation of potential links between chromatic evolution and loss of sensory freshness.

Sensory assessment in technological studies of white wine relies on ISO-aligned panel methodologies and descriptive profiling, e.g. Qualitative Data Analysis (QDA), because such approaches translate chemical evolution, including oxidation, phenolic transformations, Fe/Cu balance, and SO_2 level/distribution, into quantifiable differences in aroma and taste attributes and in overall quality. For hybrid cultivars such as 'Solaris', sensory expression may be particularly sensitive to the antioxidant protection regime. Sulphite management during vinification has been shown to influence flavour stability and sensory properties over time, with direct relevance for quality perception during storage [4]. In the context of fining, it is also critical to resolve two overlapping effects: (i) oxidation-driven sensory changes manifested as increased honey/nut notes and reduced freshness and (ii) fining-related "aromatic shifts" arising from possible losses of quality-relevant components through non-selective adsorption, which may alter perceived fruitiness and aroma intensity independently of oxidation per standard error. This remains an active area of interest in light of recent findings highlighting the complex and sometimes divergent impacts of fining agents on colour, phenolics, aroma and sensory quality [15].

To improve clarity in the subsequent sections, we adopt a framework that explicitly links fining mechanisms to the observed quality markers during storage. Specifically, for fungal chitosan, we anticipate a potential reduction in oxidative pressure through combined metal binding, particularly Cu, and stabilisation of the colloidal system, which

could translate into slower browning development (A_{420}/CIE L*a*b*) and improved retention of freshness attributes. For bentonite, despite high protein stabilisation efficiency, potential quality costs associated with non-selective adsorption and possible shifts in metal balance, dependent on the bentonite preparation and matrix conditions, must be taken into account [11]. This framework allows chemical and physicochemical parameters to be coherently integrated with sensory outcomes in 'Solaris' wine during storage and supports a structured evaluation of fungal chitosan as a potential alternative to bentonite within contemporary technological strategies, including low-SO_2 variants.

The paper, being a second part of the research devoted to the effect of fining agents (fungal chitosan and bentonite) on the quality of wines under different SO_2-regime storage [16], aims to evaluate the effect of clarifying 'Solaris' wine on stability and sensory quality during storage by analysing: (i) changes in Fe and Cu profiles, (ii) oxidation-related colour development, and (iii) changes in sensory attributes and overall quality, considering variants differing in the level of SO_2 protection.

2. Materials and Methods

The experimental setup, including the plant material, wine preparation, treatment conditions (fining procedure, SO_2 adjustment, storage), experimental design, and sampling schedule, was described in detail in Part 1 [16]. Four time points were defined in the experiment:

- T0 (baseline): wine after completion of alcoholic fermentation (after the first racking off the lees), prior to fining treatment and before adjustment of SO_2 to the target levels.
- T1 (post-fining): wine after 7 days of contact with the fining agent (bentonite (BENT) or chitosan (CHIT)) or after 7 days of natural settling (NF/CTRL), followed by racking off the sediment. At this stage, analyses included colour, phenolic compounds, clarity, metals and microbiological parameters.
- T2 (post-cold stabilisation): wine after 30 days of storage at 12 ± 1 °C following SO_2 adjustment to SO_2_std or SO_2_low. This stage corresponded to wine "ready for bottling". At T2, a full set of physicochemical, microbiological and metal analyses was performed, together with sensory assessment.
- T3 (post-storage under near-commercial conditions): wine after an additional 60 days of storage at 16–18 °C in 0.75 L glass bottles, stored horizontally in darkness, with low ullage (approximately 2 cm). T3 enabled assessment of long-term stability, particularly in variants produced with reduced SO_2.

Accordingly, only the analytical procedures specific to the parameters investigated in the present study are described.

2.1. Determination of Iron and Copper

Iron (Fe) and copper (Cu) concentrations were determined by flame atomic absorption spectrometry (FAAS), in accordance with OIV methods OIV-MA-AS322-05A (Fe) and OIV-MA-AS322-06 (Cu) [17]. Measurements were performed using a Thermo Scientific iCE 3000 Series spectrometer equipped with an air-acetylene flame (9:6 L/min). Prior to analysis, wine samples (5 mL) were diluted to 50 mL with 1.5% HNO_3 (Suprapur, Merck). Copper was quantified using the standard additions approach (0, 0.5 and 1.0 mg/L), whereas iron was quantified using external calibration (0.5–10 mg/L). Ethanol was removed prior to analysis by gentle rotary evaporation (40 °C, 15 min).

2.2. Turbidity and Protein Stability

Turbidity and protein stability were assessed using a nephelometric turbidity measurement and a heat-induced protein instability test. Turbidity was measured nephelometrically. Prior to measurement, samples were equilibrated to room temperature (20 ± 1 °C) and gently homogenised by inversion to ensure representativeness while avoiding foam formation. Readings were taken in clean optical cuvettes according to the instrument manufacturer's instructions.

Protein stability was evaluated using a standard heat test based on accelerated protein haze formation. Aliquots of wine were transferred to sealed glass tubes and incubated at 80 °C for 30 min, then cooled to room temperature (20 ± 1 °C). Turbidity was measured immediately before and after heating, and the heat-induced turbidity increase was calculated as ΔTurbidity = Turbidity_post − Turbidity_pre. Lower ΔTurbidity values indicated greater protein stability, whereas higher ΔTurbidity values reflected a higher propensity for heat-induced protein haze.

2.3. Sensory Evaluation

To determine the effects of fining agents and differentiated SO_2 regimes on sensory quality, the aroma profile, taste attributes, overall quality, and the intensity of undesirable sensory notes were evaluated in wine samples after 60 days of bottle storage (T3). The evaluations were performed in accordance with OIV guidelines [18].

The sensory panel consisted of 10 experienced and trained assessors (6 women and 4 men), aged 21–55 years, with previous experience in wine evaluation and regular participation in sensory panels. Inclusion criteria were:

- no allergy to alcoholic products;
- normal olfactory and gustatory function, verified using a three-alternative forced-choice aroma recognition test;
- absence of upper respiratory tract infection;
- avoidance of coffee, chewing gum, spicy foods and perfume for at least 1 h prior to the session.

Assessors were trained to recognise key aroma and taste attributes characteristic of 'Solaris' wines and to apply the scale consistently. Before the formal QDA evaluation, a calibration session was conducted to standardise the interpretation of descriptors, scoring criteria and use of the intensity scale. Although formal panel-performance indices, such as assessor agreement coefficients or reproducibility statistics, were not calculated as a separate objective of this study, sensory consistency was supported by the use of experienced assessors, a calibration session, standardised descriptor definitions, coded samples, randomised serving order and a unified sensory evaluation sheet.

Assessments were carried out in a dedicated sensory laboratory under controlled conditions:

- odour-neutral environment and absence of acoustic disturbances;
- room temperature: 20 ± 1 °C;
- neutral white light (5500–6500 K);
- individual tasting booths separated by partitions;
- serving temperature of 'Solaris' wines: 10 ± 1 °C.

Samples were served in ISO-standard wine glasses, with 30 mL poured into each glass. Each wine was coded with random three-digit numbers, and the serving order was randomised for each assessor using a Williams design.

Quantitative Descriptive Analysis (QDA) was used to characterise the sensory properties of the wines.

During a calibration session, the panel established a consensus list of attributes for 'Solaris' wines, covering aroma, taste, mouthfeel and undesirable sensory attributes, i.e. citrus aroma (lemon, lime), tropical fruit aroma (passion fruit, pineapple), floral aroma, overall fruity intensity, aromatic freshness, bitterness, perceived acidity, taste balance, overall quality, oxidative character, reductive character, aldehydic notes/browning.

Each attribute was rated on a 10-point linear intensity scale (0 - absent/very weak; 10 - very intense), except for undesirable attributes, which were evaluated on a 0–5 scale, where 0 indicated absence of the attribute, and 5 indicated high intensity.

Each assessor: (i) evaluated no more than 12 samples per session to minimise sensory fatigue, (ii) used still water and unsalted crackers as palate cleansers between samples, (iii) worked individually in silence, without interaction with other assessors.

For each attribute, mean scores and standard deviations were calculated. The QDA profiles were visualised using radar charts. Differences among wine variants within each sensory descriptor were assessed using one-way ANOVA followed by Tukey's HSD test at $\alpha = 0.05$. Homogeneous-group letters were added to the figures to indicate statistically significant differences among variants.

The sensory study was conducted in accordance with the Declaration of Helsinki and the principles of research ethics involving human participants. Assessors participated voluntarily and provided informed consent. Tasting volumes were limited to ensure that alcohol intake remained within safe limits.

2.4. Statistical Analysis

All statistical analyses were performed using Statistica 12.5 (StatSoft Polska, Kraków, Poland). For each response variable, the effects of technological variant (NF/CTRL–SO_2_std, NF/CTRL–SO_2_low, BENT–SO_2_std, BENT–SO_2_low, CHIT–SO_2_std, CHIT–SO_2_low), time point (T0-T3), and their interaction were assessed using two-way analysis of variance (ANOVA). Where significant main effects and/or interactions were detected, means were compared using Tukey's HSD post hoc test. Differences were considered statistically significant at $p < 0.05$. Uppercase letters (e.g. A, B, C) indicate statistically significant differences attributable to main effects (comparisons of marginal means for a single factor, irrespective of the other factor). Lowercase letters (e.g. a, b, c) indicate statistically significant differences within the variant × time point interaction (cell means).

3. Results and Discussion

3.1. Copper Concentration

At T0, the copper (Cu) concentration in the analysed wine was 1.30 mg/L and served as a common reference point for all variants, confirming the comparability of the starting material (Table 1). Overall, Cu concentration decreased markedly during processing and storage, with the dominant decrease after the first technological step (T1), whereas subsequent changes at T2 and T3 were smaller. On average, Cu declined from 1.30 mg/L at T0 to 0.88 mg/L at T1, and then decreased only slightly to 0.84 mg/L at T2 and 0.81 mg/L at T3. This indicates that the main Cu-lowering effect was associated with the initial fining/settling stage, while later storage resulted only in minor additional changes rather than further intensive removal. Since T0 represented the same base wine before the application of the technological treatments, the interpretation of treatment effects should focus primarily on the post-treatment time points T1-T3.

Table 1. Changes in copper and iron concentrations during processing and storage of 'Solaris' white wine subjected to BENT or CHIT fining under various SO_2 regimes.

Variant / time point	T0	T1	T2	T3	Mean
Cu concentration [mg/L]					
NF/CTRL–SO_2_std	1.30 ± 0.031^{a}	1.20 ± 0.028^{ab}	1.15 ± 0.024^{ab}	1.10 ± 0.022^{b}	1.19^{C}
NF/CTRL–SO_2_low	1.30 ± 0.031^{a}	1.21 ± 0.025^{ab}	1.17 ± 0.023^{ab}	1.12 ± 0.024^{b}	1.20^{C}
BENT–SO_2_std	1.30 ± 0.031^{a}	0.85 ± 0.021^{c}	0.80 ± 0.019^{c}	0.78 ± 0.020^{c}	0.93^{B}
BENT–SO_2_low	1.30 ± 0.031^{a}	0.87 ± 0.019^{c}	0.83 ± 0.020^{c}	0.81 ± 0.018^{c}	0.95^{B}
CHIT–SO_2_std	1.30 ± 0.031^{a}	0.55 ± 0.016^{d}	0.52 ± 0.012^{d}	0.50 ± 0.014^{d}	0.72^{A}
CHIT–SO_2_low	1.30 ± 0.031^{a}	0.57 ± 0.013^{d}	0.55 ± 0.014^{d}	0.53 ± 0.011^{d}	0.74^{A}
mean	1.30^{B}	0.88^{A}	0.84^{A}	0.81^{A}	
variant $\mathbf{p = 2.01 \cdot 10^{-4}}$, time point $\mathbf{p = 1.33 \cdot 10^{-5}}$, interaction $\mathbf{p = 1.47 \cdot 10^{-3}}$					
Fe concentration [mg/L]					
NF/CTRL–SO_2_std	6.90 ± 0.23^{ab}	6.70 ± 0.21^{bc}	6.60 ± 0.23^{c}	6.55 ± 0.21^{c}	6.69^{B}
NF/CTRL–SO_2_low	6.90 ± 0.23^{ab}	6.72 ± 0.20^{bc}	6.65 ± 0.24^{bc}	6.60 ± 0.20^{c}	6.72^{B}
BENT–SO_2_std	6.90 ± 0.23^{ab}	7.10 ± 0.26^{a}	7.05 ± 0.21^{a}	7.00 ± 0.19^{ab}	7.01^{A}
BENT–SO_2_low	6.90 ± 0.23^{ab}	7.15 ± 0.20^{a}	7.10 ± 0.19^{a}	7.05 ± 0.22^{a}	7.05^{A}
CHIT–SO_2_std	6.90 ± 0.23^{ab}	4.80 ± 0.15^{de}	4.70 ± 0.12^{de}	4.65 ± 0.13^{e}	5.26^{C}
CHIT–SO_2_low	6.90 ± 0.23^{ab}	4.95 ± 0.13^{d}	4.85 ± 0.14^{de}	4.80 ± 0.11^{de}	5.38^{C}
mean	6.90^{A}	6.24^{B}	6.16^{B}	6.11^{B}	
variant $\mathbf{p = 9.74 \cdot 10^{-9}}$, time point $\mathbf{p = 2.18 \cdot 10^{-6}}$, interaction $\mathbf{p = 1.95 \cdot 10^{-4}}$					

Note. ANOVA p-values are given for the technological variant, the time point, and their interaction. Different letters indicate statistically significant differences according to Tukey's HSD test at $p < 0.05$.

From T1 onwards, the highest Cu values were observed in the control variant (NF/CTRL). In this treatment, the decrease was limited and gradual, from 1.20–1.21 mg/L of Cu concentration at T1 to 1.10–1.12 mg/L at T3, with mean values of 1.19–1.20 mg/L across T0-T3. This pattern suggests that, in the absence of a fining agent, Cu reduction occurred mainly through natural sedimentation and gradual incorporation of Cu-associated fractions into the sediment. However, these spontaneous processes were not sufficient to achieve the Cu levels observed in the fined variants. Even after 60 days of storage, Cu in NF/CTRL remained at approximately 1.1 mg/L, indicating a relatively high residual metal load compared with BENT and CHIT-treated wines. From a technological perspective, such residual Cu may represent a potential pro-oxidative factor, although the present study did not directly quantify oxidation-derived aroma markers such as acetaldehyde or/and other aldehydes. Therefore, the presented Cu data should be interpreted as an indicator of potential oxidative susceptibility, rather than as direct evidence of aroma degradation [2, 3, 13].

The application of bentonite (BENT) substantially increased the efficiency of Cu reduction already at T1, where Cu decreased to 0.85 mg/l in BENT–SO_2_std and 0.87 mg/l in BENT–SO_2_low. At T2-T3, Cu remained within a narrow range of 0.78–0.83 mg/L. The mean Cu concentration across the full T0-T3 sequence was 0.93–0.95 mg/L, with this value partly reflecting the inclusion of the common initial T0 concentration. These results indicate that, under the present experimental conditions, the key effect of bentonite was a rapid reduction in the Cu fraction, most likely co-removed with colloidal particles and sediment during clarification, whereas later stages resulted in only minor additional decreases. Nevertheless, the interpretation of BENT-related effects should take into account that bentonite is primarily a protein-stabilising fining agent. Its influence on metal

concentrations is therefore likely to be indirect and dependent on the characteristics of the preparation and matrix conditions. The literature also indicates that ion-exchange processes and associated shifts in elemental composition of wine may occur, with the direction and magnitude varying with bentonite type [10, 11, 19]. In the present experiment, the net effect of BENT was clearly reductive, particularly at T1, suggesting that co-removal with sediment predominated and that any potential ion-exchange phenomena did not offset the overall decrease in Cu.

The strongest Cu reduction was achieved with fungal chitosan. Cu concentration decreased abruptly to 0.55 mg/L in CHIT–SO_2_std and 0.57 mg/L in CHIT–SO_2_low already at T1, and subsequently remained low at T2-T3. The mean Cu concentration across T0-T3 was 0.72–0.74 mg/L. In relative terms, this corresponded to an approximately 56–58% reduction at T1 and a 59–62% reduction by T3 compared with T0.

In absolute terms, CHIT reduced Cu by approximately 0.73–0.75 mg/L at T1, whereas BENT reduced it by approximately 0.43–0.45 mg/L, while NF/CTRL by only approximately 0.09–0.10 mg/L. Thus, among the tested treatments, chitosan caused the most rapid and pronounced decrease in Cu concentration. This strong response may be related to the metal-binding and adsorptive properties of chitosan, as well as to its ability to promote aggregation and sedimentation of colloidal material. The observed decrease in Cu should thus be interpreted as the combined result of possible Cu complexation or coordination by chitosan functional groups, electrostatic interactions with colloidal particles, and the co-removal of Cu-associated fractions with the sediment. This interpretation is consistent with the known behaviour of chitosan as a fining and adsorptive material and with reports describing its efficiency in Cu adsorption under wine-like acidic conditions [5, 8, 20]. In practical terms, chitosan exhibited a more pronounced effect on Cu reduction than bentonite, whereas bentonite's effect appeared to be more indirectly associated with clarification and sedimentation processes [10, 11]. However, because the present study measured only total Cu, it cannot determine whether chitosan preferentially reduced the most reactive, or “labile,” Cu fraction. This should be regarded as a limitation of the present work and verified in future studies using speciation-oriented analytical approaches.

Differences in Cu concentration within individual variants between applied SO_2 levels (standard vs low) were small; typically 0.01–0.03 mg/L at a given time point, and did not alter the hierarchy of Cu-removal effectiveness: CHIT > BENT >> NF/CTRL. This indicates that within the studied range, the SO_2 dose was not a determining factor for the total Cu concentration. Nevertheless, a secondary influence of SO_2 on the speciation and reactivity of the remaining Cu pool cannot be excluded, e.g. through redox interactions or binding of oxidation intermediates, even in the absence of a measurable effect on total Cu. This interpretation is consistent with the current understanding that the primary role of SO_2 is to control oxidative processes rather than remove metals from the wine matrix [2, 13]. Model studies have shown that browning kinetics may depend on the combined action of ethanol, SO_2, and transition metals, and that the presence of metals can modulate colour evolution even at similar SO_2 levels [14]. Consequently, in the present experiment, the fining agent, rather than the SO_2 regime, determined the rate and magnitude of Cu reduction, with the strongest effect observed after CHIT application.

The significance of Cu reduction in white wines extends beyond the decrease in metal concentration itself and is linked to potential oxidative durability and sensory stability. Fe and Cu are involved in redox cycling and may participate in reactions that lead to the formation of reactive oxygen species, phenolic transformation, browning, and changes in aroma-related compounds [2, 13]. In this context, it is technologically favourable that

in the BENT and CHIT variants Cu reached concentrations below 1 mg/L already at T1 and remained lower than in NF/CTRL up to T3. As the present study did not include direct markers of oxidative aroma degradation, such as acetaldehyde, methional, phenylacetaldehyde, hexanal, or other selected aldehydes, the observed differences in Cu concentration should be discussed as a potential explanation for different oxidative trajectories, but not as direct proof of aroma degradation or protection against aldehyde formation. The analysis of these markers would provide a more complete assessment of the relationship between metal removal, SO_2 regime, and aroma stability.

Recent research increasingly focuses not only on total Cu, but also on more reactive or labile Cu fractions, which may better determine oxidation risk and quality changes over time. It has been suggested that assessing Cu forms may predict susceptibility to adverse storage transformations more effectively than total Cu alone [21]. In this context, Cu reduction by CHIT may suggest a potentially beneficial rapid decrease in the reactive species; however, this remains a hypothesis because Cu speciation was not directly measured in the present work. The literature reports that the presence and concentration of copper in the raw material/must can influence the progress of fermentation and the formation of oxidation-related products, including acetaldehyde, which is relevant to both the sensory profile and SO_2 reactivity [22]. Future studies should therefore combine total Cu determination with Cu speciation and direct quantification of oxidation-related aldehydes to verify whether the lower Cu concentrations observed after CHIT treatment translate into improved aroma stability.

A further limitation of the present study is the 60-day storage period. This period was sufficient to compare the short-term effects of fining treatments and SO_2 regimes on total Cu concentration, but it is relatively short for a full assessment of long-term oxidative stability, especially in wines produced with reduced SO_2. Therefore, the present results should be interpreted as evidence of short-term Cu reduction and metal stabilisation rather than as a definitive prediction of long-term oxidative behaviour. Extended bottle-storage trials, preferably combined with aldehyde profiling, colour monitoring, oxygen exposure control, and sensory evaluation, would be required to confirm whether the Cu reduction achieved by CHIT and BENT provides durable protection against oxidative aroma deterioration.

3.2. Iron Concentration

At T0, the iron (Fe) concentration in the analysed wine was 6.90 mg/L in all variants, providing a common reference point for evaluating changes during subsequent processing and storage stages (Table 1). Based on experiment-wide means, Fe concentration decreased from 6.90 mg/L at T0 to 6.24 mg/L at T1 and then remained at a comparable, slightly lower level at T2 and T3, reaching 6.16 and 6.11 mg/L, respectively, indicating that at the global level, the main decrease in Fe occurred after the first processing step. Because T0 represented the same base wine before treatment, the interpretation of technological effects should focus primarily on T1-T3. At the variant level, the averaged trend masked three contrasting responses: a strong reduction in Fe concentration after chitosan treatment, a moderate, gradual reduction in the control, and an increase in Fe concentration after bentonite treatment.

The most evident decrease was observed in the CHIT variants. Already at T1, Fe decreased sharply to 4.80 mg/L in CHIT–SO_2_std and 4.95 mg/L in CHIT–SO_2_low, and subsequently remained low at T2-T3, within 4.65–4.85 mg/L. This corresponded to a reduction of 28–30% relative to T0 at T1 and 30–33% by T3. In terms of mean values across T0-T3, CHIT reached 5.26–5.38 mg/L and formed the group with the lowest

Fe concentration among the tested variants. This indicates that chitosan produced the most effective and fastest Fe-lowering effect, with the dominant change occurring during the initial treatment/settling stage and only minor additional adjustment during later storage. Mechanistically, this effect may be associated with the adsorptive and coagulating properties of chitosan, including possible interactions with metal-associated colloidal fractions and their co-removal with sediment. This interpretation is consistent with the recognised use of fungal-derived chitosan to reduce metal content, including iron, and to limit the risk of iron haze or iron casse [5, 23, 24]. However, because only total Fe was evaluated, the present study cannot determine whether chitosan preferentially reduced the most reactive Fe fraction or mainly lowered the overall Fe.

In contrast, the control variant exhibited only a moderate, gradual decrease in Fe (Table 1), from 6.90 mg/L at T0 to 6.55–6.60 mg/L at T3, with mean values of 6.69–6.72 mg/L. This represents a reduction of only 4–5% by T3. The absence of a fining agent, therefore, limited Fe removal to spontaneous processes, most likely natural sedimentation and the gradual incorporation of Fe-associated fractions into the sediment during stabilisation and storage.

An opposite pattern was observed in the bentonite variants. In these wines, Fe increased at T1 to 7.10 mg/L in BENT–SO_2_std and 7.15 mg/L in BENT–SO_2_low, and remained elevated at T2-T3 (ca.7.00–7.05 mg/L at T3). Mean Fe concentration values across T0-T3 were the highest in BENT among all sample variants. This small but consistent increase of approximately 0.10–0.25 mg/L, relative to T0, indicates that the net Fe balance after bentonite treatment was not reductive. This profile is consistent with reports that bentonites, depending on their origin, activation, mineral composition, dose, contact time, and the wine matrix, may modify elemental composition through elemental transfer, sorption/desorption, or ion-exchange phenomena [11, 19, 25]. Nevertheless, this interpretation should be approached with caution because Fe was not quantified independently in the bentonite preparation, and Fe speciation in the wine was not determined. Therefore, the observed increase should be interpreted as a net outcome of bentonite-wine matrix interactions, rather than as definitive proof of direct Fe release from the fining agent.

The effect of SO_2 level on Fe concentration was secondary and did not change the overall interpretation. Differences between SO_2_std and SO_2_low within the same fining treatment were small and did not exceed 0.15 mg/L at individual time points, while the hierarchy of Fe concentration remained consistent: BENT showed the highest, NF/CTRL intermediate, and CHIT the lowest Fe values. This indicates that, within the analysed SO_2 range, the fining agent, rather than the SO_2 regime, was the primary factor determining Fe removal or enrichment. This is consistent with the role of SO_2 as a modulator of oxidative pathways rather than as an agent that directly removes transition metals from the wine matrix [2, 13, 14].

From a quality perspective, the observed Fe differences are relevant because Fe, similarly to Cu, can participate in redox cycling and may contribute to non-enzymatic oxidation, phenolic transformation, browning, and changes in aroma-related compounds [2, 13]. In this context, the decrease in Fe after CHIT treatment may be technologically beneficial, whereas the persistently higher Fe values in BENT variants indicate that bentonite, although effective for protein stabilisation, may also modify the mineral profile of wine. As the present study did not include direct markers of oxidative aroma degradation, Fe data should be interpreted as an indicator of potential oxidative susceptibility, rather than as direct evidence of aroma degradation or protection against aldehyde formation. Including such markers in future studies would allow a more

complete assessment of the relationship between metal profile, SO_2 regime, and aroma stability.

As with Cu, the 60-day storage period should be acknowledged as a limitation when evaluating changes in Fe, particularly with respect to long-term oxidative behaviour.

3.3. Protein Stability

The data on protein stability are presented in Table 2. ΔTurbidity reflects the amount of heat-reactive, haze-forming material remaining in the wine, whereas the absolute turbidity at T3 reflects the general clarification status of the wine before the heat test. Importantly, protein stability in this test is classified on the basis of the heat-induced increase in turbidity (ΔTurbidity), rather than the absolute turbidity measured before heating. In oenological practice and industry laboratories, ΔTurbidity < 2 NTU is widely used as an operational criterion for confirming protein stability, although some laboratories apply more conservative internal thresholds (< 0.5–1.0 NTU) as an additional safety margin depending on quality policy, commercial risk, and expected storage or transport conditions [26, 27].

Under the ΔTurbidity < 2 criterion, the control variants were unequivocally unstable. Despite their already high turbidity at T3, 97.2 ± 1.3 NTU in NF/CTRL–SO_2_std and 92.0 NTU in NF/CTRL–SO_2_low, a further substantial increase after heating was recorded, with ΔTurbidity values of 8.2 and 7.8 NTU, respectively. This indicates the presence of a considerable amount of heat-unstable proteins and colloidal material that can denature, aggregate, and form persistent haze under thermal stress. Such a strong response is typical of white wines lacking effective protein stabilisation and indicates a high risk of haze formation during bottle storage, transport, or exposure to elevated temperatures [27]. The similar ΔTurbidity values in both control variants also show that reducing the SO_2 level did not compensate for the absence of a protein-stabilising treatment.

Table 2. Wine turbidity, ΔTurbidity and protein stability at T3.

Variant / time point	Turbidity at T3 [NTU]	ΔTurbidity [NTU]	Stability classification
NF/CTRL–SO_2_std	97.2 ± 1.3^a	8.2	unstable
NF/CTRL–SO_2_low	92.0 ± 1.1^b	7.8	unstable
BENT–SO_2_std	2.1 ± 0.2^e	0.4	stable
BENT–SO_2_low	1.9 ± 0.2^e	0.5	stable
CHIT–SO_2_std	3.8 ± 0.2^c	1.6	stable
CHIT–SO_2_low	3.3 ± 0.1^d	1.2	stable

Note. ANOVA p-values are given for the technological variant. Different letters indicate statistically significant differences according to Tukey's HSD test at $p < 0.05$.

Bentonite provided the strongest stabilising and clarifying effect. In both BENT variants, turbidity at T3 was very low: 2.1 NTU in BENT–SO_2_std and 1.9 NTU in BENT–SO_2_low, while ΔTurbidity was minimal, at 0.4 and 0.5 NTU, respectively. These values indicate not only protein stability according to the ΔTurbidity < 2 criterion, but also a wide practical safety margin, close to or within the more conservative thresholds used by some laboratories. At the same time, the low absolute Turbidity values show that bentonite was also the most effective treatment in terms of final optical clarity. This is consistent with bentonite's established role as the reference fining agent for protein

stabilisation of white wines, based primarily on adsorption and removal of haze-forming proteins with the sediment [26].

The chitosan variants also met the protein-stability criterion, as indicated by the increase in heat-induced turbidity. In CHIT–SO_2_std and CHIT–SO_2_low, ΔTurbidity values were 1.6 and 1.2 NTU, respectively, and therefore remained below the accepted 2 NTU threshold. Accordingly, these wines can be classified as protein-stable under the applied heat-test criterion.

The presented classification (Table 2) should not be interpreted as full equivalence to bentonite in terms of final clarity or stabilisation margin. The absolute turbidity at T3 was higher in the CHIT variants; thus, although chitosan reduced the heat-reactive haze-forming fraction sufficiently to meet the ΔNTU < 2 stability criterion, it did not clarify the wine as strongly as bentonite. This distinction explains why CHIT-treated wines were classified as protein-stable despite Turbidity values at T3 above 2.0. The threshold of ΔTurbidity < 2 refers to the additional turbidity formed during the heat test, whereas the initial Turbidity at T3 describes the turbidity of the wine before heating. Therefore, the CHIT-treated variants were protein-stable because their post-heating turbidity increase was limited, but they remained less clarified than the BENT-treated variants. Compared with the unfined NF/CTRL controls, chitosan markedly reduced heat-induced haze formation, as shown by the much lower ΔTurbidity values (1.2–1.6 NTU for CHIT vs 7.8–8.2 NTU for NF/CTRL). Nevertheless, compared with bentonite, chitosan provided a narrower safety margin (1.2–1.6 NTU for CHIT vs 0.4–0.5 NTU for BENT). Therefore, chitosan-stabilised wines can be considered comparable to bentonite-treated wines only with respect to the ΔTurbidity criterion, but not in terms of stabilisation strength or optical clarification.

From a technological perspective, the turbidity results indicate that bentonite remains the more conservative option when both very low final turbidity and a wide protein-stability margin are required. In contrast, chitosan provided acceptable protein stability under the conditions of this experiment, but with higher residual turbidity and a smaller distance from the instability threshold. This suggests that chitosan may be useful as an alternative or complementary stabilising treatment, particularly in strategies aimed at reducing bentonite use, but its application should be interpreted in relation to the required clarity standard, expected storage conditions, and acceptable commercial risk. In wines intended for prolonged storage, long-distance distribution, or exposure to elevated temperatures, additional validation, such as extended storage trials, repeated heat tests, or combination strategies, should be justified.

Mechanistically, the improvement observed after chitosan treatment may be associated with electrostatic interactions and partial coagulation or sedimentation of the protein and colloidal fraction, thereby reducing the amount of material available to aggregate during heating. Previous studies have shown that alternative stabilisation methods can reduce the need for bentonite, which is associated with wine losses, waste generation, and changes in wine composition [28]. However, in the present study, although chitosan improved both clarification and protein stability, its effects were not identical to those of bentonite.

Differences between SO_2 levels were small and did not change the stability classification within a given treatment. The NF/CTRL variants remained unstable, whereas both BENT and CHIT variants were classified as stable. This confirms that protein stability was primarily affected by the fining/stabilisation treatment rather than by the SO_2 regime. This interpretation is consistent with the nature of the heat test, which primarily reflects the tendency of heat-unstable proteins and colloids to denature, aggregate, and form haze, rather than oxidative processes controlled by SO_2.

Overall, the results indicate that bentonite provided the most conservative stabilisation and the highest final clarity, while chitosan provided effective protein stability according to the accepted ΔTurbidity criterion, but with higher residual turbidity and a narrower safety margin [26–28].

3.4. Wines' Aromatic Profile at T3

The aromatic profile of 'Solaris' wines assessed at T3 indicates that the varietal aromatic "core" was driven primarily by citrus notes and descriptors associated with freshness and aromatic lightness, whereas tropical notes were secondary and moderate (Figure 1). This is consistent with literature data on 'Solaris' wines, which more commonly emphasise citrus, floral, and green-/fruit-related notes than unequivocally exotic pineapple-passion-fruit characters [29, 30]. Therefore, the comparatively lower scores for tropical notes should not be interpreted as reduced varietal typicality, but rather as a feature consistent with the sensory character of this cultivar and the applied processing conditions.

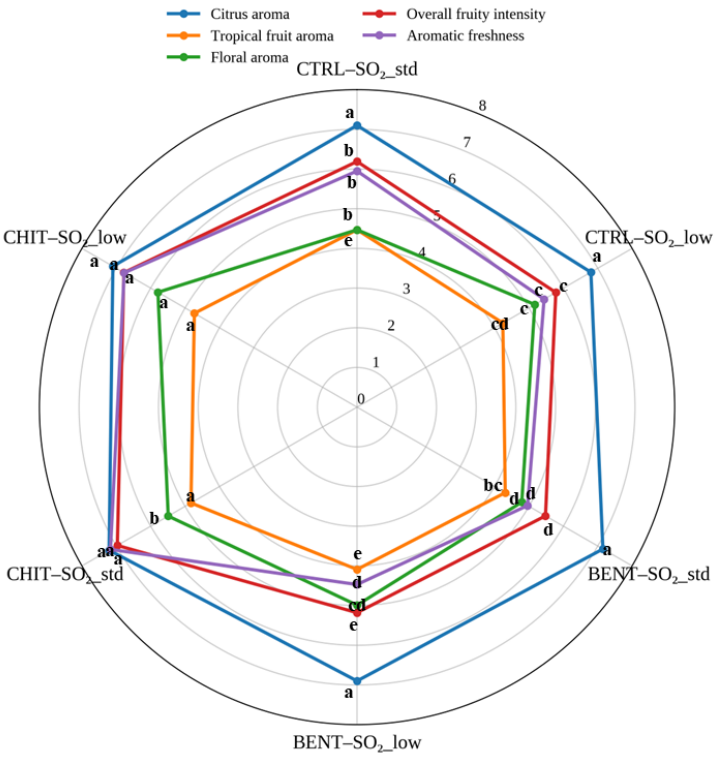

Figure 1. Radar chart showing the aromatic profile of the analysed 'Solaris' wine variants at T3. [*Note.* Different letters assigned to values within each sensory descriptor indicate statistically significant differences among variants according to Tukey's HSD test at α = 0.05]

Citrus aroma remained high and relatively uniform across technological variants, whereas aromatic freshness and overall fruit intensity appeared more sensitive to the applied treatment. One-way ANOVA showed a significant effect of treatment on tropical fruit aroma ($p = 1.49 \cdot 10^{-14}$), floral aroma ($p = 1.06 \cdot 10^{-9}$), overall fruity intensity ($p = 1.79 \cdot 10^{-9}$), and aromatic freshness ($p = 2.76 \cdot 10^{-15}$), whereas citrus aroma did not differ significantly

among variants ($p = 0.4923$). The practical sensory relevance of these differences should be interpreted cautiously. In the present study, formal sensory thresholds or minimum perceptible differences were not established for the individual descriptors. Therefore, the observed differences should be treated primarily as relative differences within the trained-panel assessment, rather than as direct evidence that all differences would necessarily be clearly perceptible or relevant to consumers. This distinction is important because descriptive sensory scores can indicate treatment-related tendencies, but their practical relevance depends on the magnitude and consistency of the differences, the descriptor considered, and the sensitivity of the sensory panel.

Bentonite-treated variants showed lower aromatic freshness and overall fruit intensity, particularly when combined with reduced SO_2, suggesting a less expressive aromatic profile at T3. This effect should be interpreted as a treatment-related sensory tendency rather than as definitive evidence of aroma loss exceeding a known sensory threshold. The literature indicates that clarification and stabilisation treatments can affect volatile compounds and aroma perception, depending on the fining agent type, dose, and the wine matrix [15]. For bentonite, non-selective adsorption and matrix modification have been reported to influence the aromatic fraction, which may be particularly relevant in wines with delicate aromatic profiles [31, 32]. In the present study, the lower scores observed in BENT variants are consistent with the literature, but the absence of direct analysis of volatile compounds precludes confirmation of the underlying mechanism.

Chitosan treatment was associated with higher scores of aromatic freshness and overall fruit intensity, together with a tendency towards better retention of floral and tropical attributes. As with bentonite, these differences should be interpreted as relative sensory differences within the experimental dataset, not as proof that chitosan caused changes exceeding established thresholds of practical sensory relevance. Nevertheless, the direction of the response is technologically interesting, especially under reduced SO_2 conditions, because the commercial value of 'Solaris' wines is strongly linked to freshness and a citrus-floral character. Reviews on chitosan applications in oenology indicate that chitosan may influence the colloidal system, reduce oxidative pressure, and modify quality parameters, thereby indirectly supporting aroma preservation [5, 7]. To fully confirm this effect, integration of sensory data with volatile-compound analysis and, in the context of oxidative aroma degradation, markers such as acetaldehyde or selected aldehydes is required.

The moderate intensity of tropical aromas may also reflect their greater sensitivity to clarification and storage conditions. Compounds contributing to perceived tropicality can be affected by fining, oxidation-prone conditions, and SO_2 management; therefore, their retention may depend on both the SO_2 regime and the choice of stabilising treatment [13, 15]. In the present study, however, this interpretation remains tentative because individual volatile compounds responsible for tropical notes were not quantified.

Overall, the T3 aromatic assessment suggests that the fining agent had a greater influence on freshness-related descriptors than the SO_2 regime alone. The results indicate a favourable sensory tendency for CHIT and a less expressive profile for BENT, especially under reduced SO_2, but the practical sensory relevance of these differences remains a limitation of the present study because no formal perceptibility thresholds were determined. Future work should therefore combine descriptive sensory analysis with volatile profiling, aldehyde determination, and longer storage trials to verify whether the observed differences translate into durable and practically relevant changes in wine aroma.

3.5. Taste Attributes at T3

At T3, 'Solaris' wines were characterised by high perceived acidity (6.8–7.3 points) and moderate bitterness (2.8–4.2 points) (Figure 2). Differences among technological variants were most clearly expressed in the integrative attributes: taste balance and overall quality (5.8–7.8 and 5.8–8.2 points, respectively). This is typical of descriptive analysis, in which global attributes integrate several concurrent taste stimuli and oral sensations [18]. However, formal thresholds of practical sensory relevance or minimum perceptible differences were not determined in this study. Therefore, the observed differences should be interpreted primarily as relative differences within the trained-panel assessment, rather than as direct evidence that all numerical differences would necessarily be equally relevant to consumers.

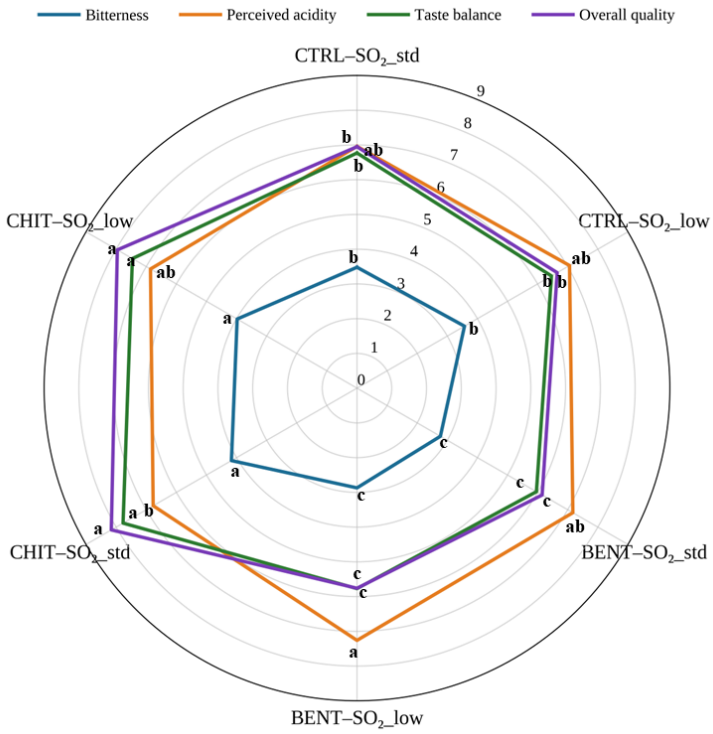

Figure 2. Radar chart showing the taste profile (bitterness, perceived acidity, taste balance, and overall quality) of the analysed 'Solaris' wine variants at T3. [*Note.* Different letters assigned to values within each sensory descriptor indicate statistically significant differences among variants according to Tukey's HSD test at $\alpha = 0.05$]

The lowest bitterness was recorded in the bentonite variants (2.8–2.9 points), intermediate values in the control wines (3.5–3.6 points), and the highest bitterness in the chitosan variants (4.0–4.2 points). This pattern is consistent with the relationship between bitterness perception and phenolic composition, particularly flavan-3-ols, as well as with the potential influence of fining treatments on the colloidal fraction and mouthfeel-related sensations [32–34]. Although CHIT wines showed the highest bitterness scores, the values remained within a moderate range and did not coincide with lower balance or quality

scores, suggesting that bitterness was not perceived as a dominant negative attribute in these variants.

Perceived acidity was high in all variants, which is consistent with the sensory character of 'Solaris' wines and with the general relationship between freshness, sourness, titratable acidity and pH [29, 35]. Between-variant differences in acidity were relatively small compared with those observed for balance and overall quality. Bentonite-treated wines tended to show slightly higher perceived acidity, whereas chitosan-treated wines showed slightly lower acidity scores. This may reflect cross-modal interactions, in which a stronger phenolic or mouthfeel component can reduce the perceptual dominance of acidity, even when acidity remains analytically high [34, 35]. Given the narrow numerical range of acidity scores, these differences should be interpreted with caution.

Taste balance showed clearer differentiation among treatments than acidity or bitterness alone. The highest balance scores were recorded for the chitosan variants (approximately 7.6–7.8 points), while the lowest were for the bentonite-treated samples. This indicates that the overall integration of acidity, bitterness and mouthfeel was most favourable in CHIT-treated wines, despite their moderately higher bitterness. In contrast, the lower balance scores in BENT wines suggest that reduced bitterness alone did not translate into a more harmonious taste profile. Because taste balance is an integrative attribute and showed larger between-treatment differences, it may have greater practical relevance than the small differences observed for acidity. This interpretation remains cautious because no formal minimum perceptible difference was established.

Overall quality followed a pattern similar to taste balance. The highest quality scores were obtained for the chitosan variants, moderate for the controls, and the lowest for bentonite-treated wines. This distribution suggests that, at T3, chitosan treatment was associated with the most favourable overall sensory impression, whereas bentonite, particularly under reduced SO_2, was associated with a less attractive taste profile. This may reflect treatment-related changes in the wine matrix and sensory integration, as reported for fining agents in white wines [5, 32]. As in the aroma assessment, these results should be interpreted as trained-panel evidence of relative treatment effects, not as a direct measure of consumer acceptance.

Overall, the taste assessment at T3 indicates that the fining agent had a stronger influence on integrative sensory attributes than the SO_2 regime. Chitosan-treated wines combined moderate bitterness with the highest taste balance and overall quality, whereas bentonite-treated wines showed the lowest bitterness but also the lowest balance and quality scores. Thus, the practical sensory relevance of the results appears strongest for taste balance and overall quality, where between-treatment differences were larger and consistent, while smaller differences in perceived acidity should be interpreted more cautiously. Future studies should include consumer testing or predefined sensory relevance thresholds to confirm whether the trained-panel differences observed here translate into commercially meaningful sensory differences.

3.6. Wine Faults at T3

In the T3 sensory assessment, three fault-related indicators, i.e., oxidative character, reductive character, and aldehydic notes/browning, showed clear differentiation across the technological variants and SO_2 regimes (Figure 3), confirmed by one-way ANOVA (significant effect of treatment on oxidative character ($p = 4.39 \cdot 10^{-8}$), reductive character ($p = 1.51 \cdot 10^{-14}$), and aldehydic notes/browning ($p = 1.11 \cdot 10^{-11}$)). Lower scores indicate lower fault intensity and, therefore, a more favourable sensory outcome. From an oenological perspective, these attributes are important for white-wine quality because

even moderate increases in oxidation or reduction notes can diminish the perceived freshness and cleanliness of the profile before unequivocal defects become dominant [36]. However, as in the previous sensory sections, formal thresholds for practical sensory relevance were not established; therefore, the results should be interpreted as evidence of relative treatment effects from a trained panel.

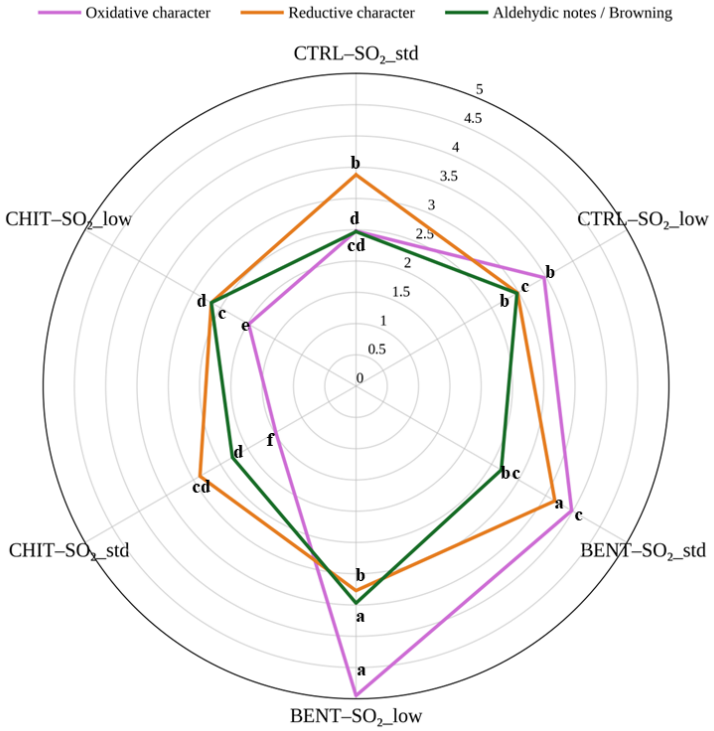

Figure 3. Radar chart showing the intensity of faulty and undesirable sensory attributes (oxidative character, reductive character, and aldehydic notes/browning) of the analysed 'Solaris' wine variants at T3. [*Note.* Different letters assigned to values within each sensory descriptor indicate statistically significant differences among variants according to Tukey's HSD test at $\alpha = 0.05$]

The highest oxidative character was recorded for BENT–SO_2_low (5.0), whereas the lowest values were observed for the chitosan variants: CHIT–SO_2_std (1.5) and CHIT–SO_2_low (2.0). The control variants also indicated an effect of SO_2 level, with NF/CTRL–SO_2_low (3.5) showing a higher oxidative score than NF/CTRL–SO_2_std (2.5). This pattern suggests that reduced SO_2 protection results in increased panel-perceived oxidative character, but the magnitude of this effect depended strongly on the fining treatment. The combination of bentonite with reduced SO_2 was the least favourable, whereas chitosan-treated wines showed the lowest oxidative scores. This may reflect differences in matrix modification, colloidal interactions, and protection against oxidation-related sensory changes; however, the mechanism should be interpreted cautiously because direct chemical markers of oxidation were not quantified [11, 32, 37].

Aldehydic notes/browning followed a trend broadly consistent with oxidative character. The highest intensity was observed for BENT–SO_2_low (3.5), followed by NF/CTRL–SO_2_low (3.0), whereas the lowest value was recorded for CHIT–SO_2_std (2.3). This supports the sensory interpretation that variants with higher oxidative character also tended to show stronger aldehydic/browning-related impressions. Nevertheless, this descriptor represents panel perception and should not be treated as a direct quantification of specific aldehydes or carbonyl compounds. As colour stability and retention of freshness in white wines depend on the balance between oxygen exposure, SO_2 availability, transition metals, phenolic composition, and matrix structure, the lower aldehydic/browning scores in CHIT variants may indicate a more favourable short-term sensory profile, but confirmation would require analytical aldehyde profiling, oxygen exposure control, and longer storage trials [38, 39].

Reductive character varied within a narrower range (2.7–3.7) than the oxidation-related indicators. The lowest scores were noted for the chitosan variants (CHIT–SO_2_low, 2.7; CHIT–SO_2_std, 2.9), whereas higher values were observed in the control and bentonite treatments, including NF/CTRL–SO_2_std (3.4) and BENT–SO_2_std (3.7).

Reductive faults are commonly associated with volatile sulphur compounds, such as H_2S and related species, which can mask fruit aromas and reduce sensory quality [36]. However, because volatile sulphur compounds were not measured analytically, the most cautious conclusion is that chitosan treatment was not associated with an increase in the panel-perceived intensity of reductive notes at T3. This is practically relevant because SO_2-reduction strategies should limit oxidation risk without simultaneously shifting the wine profile towards reductive defects.

Taken together, the three fault-related indicators suggest that the most favourable sensory profile at T3 was observed in the chitosan variants, particularly CHIT–SO2_std, which combined the lowest oxidative and reductive characters and the lowest aldehydic notes/browning score. The least favourable profile was observed for BENT–SO_2_low. These results suggest that the choice of fining agent was important for short-term sensory stability under the tested SO_2 regimes. Again, the interpretation should remain limited to the 60-day storage period and to sensory descriptors assessed by the trained panel.

Future studies should combine sensory evaluation with analytical determination of aldehydes, volatile sulphur compounds, oxygen exposure, and longer bottle storage to verify whether the observed trained-panel differences translate into long-term and practically relevant changes in wine quality [5, 8, 40].

4. Conclusions

The presented results allow to draw the following conclusions:

1. The fining agent was the primary factor differentiating the evolution of ‘Solaris’ wine quality parameters across successive processing stages and storage under the conditions of this experiment. The main technological effect was expressed immediately after fining, whereas subsequent stages largely consolidated the observed directions of change.
2. Fungal-derived chitosan showed the most consistent profile in reducing the wine’s transition-metal load (Fe and Cu), which is consistent with its ability to interact with metal-associated fractions and matrix components and to promote their co-removal with the sediment. However, the effect on specific reactive or labile metal fractions requires further confirmation.

3. Bentonite, despite its very high effectiveness in protein stabilisation and final clarification, exhibited a metal-response profile distinct from chitosan. This outcome should be interpreted as a net effect specific to the bentonite preparation used and the wine matrix.
4. The SO_2 regime had only a limited influence on Fe and Cu concentrations within a given technological variant; however, it was relevant to quality stability over time, particularly with respect to the development of oxidation-related sensory attributes during storage.
5. With respect to protein stability, bentonite provided the largest practical safety, while chitosan also achieved protein stability under the applied ΔTurbidity criterion. Both technologies can mitigate the risk of protein haze, although they differ in their broader impacts on the wine matrix.
6. Post-storage sensory evaluation indicated that chitosan variants were associated with a more favourable trained-panel sensory profile compared with bentonite, particularly under reduced SO_2.

Overall, the results confirm that evaluation of SO_2-reduction strategies should integrate physicochemical criteria, including protein stability and metal profiles, with post-storage sensory outcomes. Within this framework, chitosan may represent a supportive tool for maintaining 'Solaris' wine quality under reduced SO_2 in the short term and under the tested technological conditions, whereas the use of bentonite under low-SO_2 conditions may require careful management of oxidation-related sensory risk during processing operations and storage. Further and more comprehensive studies are needed to confirm the observed effect during longer-term bottle storage.

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6. Author Contributions

Conceptualisation, I.O. and M.K.-M.; methodology, I.O. and M.K.-M.; software, I.O.; validation, I.O. and M.K.-M.; formal analysis, I.O.; investigation, I.O. and M.K.-M.; resources, I.O. and M.K.-M.; data curation, I.O.; writing—original draft preparation, I.O.; writing—review and editing, I.O. and M.K.-M.; visualisation, I.O.; supervision, M.K.-M.; project administration, I.O.; funding acquisition, M.K.-M. All authors have read and agreed to the published version of the manuscript.

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