Review article
DOI: /10.5513/JCEA01/27.3.5182
Journal of Central European Agriculture, 2026, 27(3), p.809-823

The influence of yeasts on the sensory properties of sparkling wines

Utjecaj kvasaca na senzorna svojstva pjenušavih vina

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Received: January 14, 2026; accepted: June 16, 2026

ABSTRACT

Sparkling wine production relies heavily on the metabolic activity and technological performance of yeasts, which play a decisive role not only in primary and secondary fermentation but also in shaping the sensory properties of the final product. This review provides an overview of the influence of *Saccharomyces* and non-*Saccharomyces* yeasts on the chemical composition, aromatic complexity, foam characteristics, and overall sensory profile of sparkling wines. Special emphasis is placed on yeast autolysis—a key process during ageing on lees—which releases polysaccharides, mannoproteins, peptides, and aroma precursors that enhance mouthfeel, foam stability, and the development of tertiary aromas. The selection of yeast strains significantly affects fermentation kinetics, the formation of volatile compounds, and the stylistic attributes of both base wines and finished sparkling wines. Recent studies highlight the potential of hybrid yeast strains, sequential inoculation strategies, encapsulated yeasts, and the use of yeast-derived enological products to improve fermentation control, accelerate autolysis, and modulate sensory quality. Furthermore, non-*Saccharomyces* yeasts are increasingly recognised as valuable tools for enhancing aromatic diversity, reducing undesirable metabolites, and improving foam properties. Innovations in yeast technology, together with a deeper understanding of their biochemical contributions, offer new opportunities for tailoring sparkling wine styles while maintaining high product quality and consistency. Future research should focus on optimizing yeast selection for specific grape varieties, improving autolysis efficiency, and developing sustainable practices that support the production of high-quality sparkling wines with distinctive sensory identities.

Keywords: secondary fermentation, autolysis, volatile compounds, foam stability, aroma complexity, hybrid strains

SAŽETAK

Proizvodnja pjenušavih vina uvelike ovisi o metaboličkoj aktivnosti i tehnološkim svojstvima kvasaca, koji imaju ključnu ulogu ne samo u primarnoj i sekundarnoj fermentaciji, već i u oblikovanju senzorskih svojstava konačnog proizvoda. Ovaj pregledni rad daje uvid u utjecaj *Saccharomyces* i ne-*Saccharomyces* kvasaca na kemijski sastav, aromatsku kompleksnost, svojstva pjene i ukupni senzorski profil pjenušavih vina. Poseban naglasak stavljen je na autolizu kvasaca – ključni proces tijekom odležavanja na talogu – pri kojem dolazi do oslobađanja polisaharida, manoproteina, peptida i prekursora aroma koji poboljšavaju punoću okusa, stabilnost pjene i razvoj tercijarnih aroma. Odabir sojeva kvasaca značajno utječe na kinetiku fermentacije, stvaranje hlapljivih spojeva i stilske značajke baznih i gotovih pjenušavih vina. Nedavna istraživanja ističu potencijal hibridnih sojeva, sekvencijalne inokulacije, inkapsuliranih kvasaca te enoloških pripravaka na bazi kvasaca za poboljšanje kontrole fermentacije, ubrzavanje autolize i moduliranje senzorskih svojstava. Ne-*Saccharomyces* kvasci sve se više prepoznaju kao vrijedni alati za povećanje aromatske raznolikosti, smanjenje nepoželjnih metabolita i poboljšanje svojstava pjene. Inovacije u tehnologiji kvasaca, zajedno s boljim razumijevanjem njihovih biokemijskih doprinosa, otvaraju nove mogućnosti za oblikovanje stilova pjenušavih vina uz održavanje visoke kvalitete i konzistentnosti proizvoda. Buduća istraživanja trebala bi biti usmjerena na optimizaciju odabira kvasaca za pojedine sorte grožđa, unapređenje učinkovitosti autolize te razvoj održivih tehnoloških praksi za proizvodnju visokokvalitetnih pjenušavih vina s prepoznatljivim senzorskim identitetom.

Ključne riječi: sekundarna fermentacija, autoliza, hlapljivi spojevi, stabilnost pjene, aromatska kompleksnost, hibridni sojevi

INTRODUCTION

Sparkling wines are produced in various regions across the world, each characterized by distinct agro-ecological and pedological conditions for cultivating different grape varieties. The production of sparkling wines has been steadily increasing each year, which has also driven greater interest in scientific research within this field. Particular attention is directed toward improving existing production methods through sustainable practices, with a focus on reducing costs and processing time.

According to data from the International Organisation of Vine and Wine (OIV) (2023) on the global sparkling wine market for 2022, sparkling wines were the only category of wine to record an increase in both production volume and market value. Although sparkling wines account for only 11% of the total global wine production, they represent 23% of the total global market value, placing them as the second most valuable wine category, immediately after bottled still wines. France, Italy, and Spain are the largest producers and exporters of wine, contributing 38%, 28%, and 17%, respectively, to the total value of exported wine in 2022.

Sparkling wine production involves two main stages. In the first stage, a base wine is produced from white grapes (*blanc de blancs*) or black grapes (*blanc de noirs*), with the latter vinified as white wine (without skin contact). Although the most common outcome is white wine, in some cases—such as rosé Champagne—a wine with a pink hue may be produced by allowing brief skin contact or by adding a small amount of red wine. The second stage consists of secondary fermentation in the bottle (traditional or Champenoise method) or in a pressurized tank (Charmat method).

There are several key steps in sparkling wine production, the first of which is harvest—determining the optimal harvest date when the grapes reach the appropriate level of maturity. This is a highly complex task influenced by numerous factors, such as climatic conditions, rainfall, disease pressure, pests, and the specific characteristics of the vintage. It is essential to ensure adequate vine protection, sufficient moisture, and balanced fertilization. Grapes intended for sparkling wine production are harvested at a technological maturity that differs from that required for still wine production. At this stage, the most important parameters include sugar concentration, total acidity, and pH. The optimal sugar concentration ranges between 17.5 and 20 °Brix, enabling the production of base wine with approximately 10–11% vol. alcohol. A high alcohol content in the base wine is undesirable, as alcohol increases further during the second fermentation. Total acidity should be relatively high, between 7.5 and 10 g/L, to ensure freshness, stability, and flavor intensity. The optimal pH ranges from 2.9 to 3.2, as a lower pH enhances microbiological stability, color preservation, and foam stability. The aromatic profile of the grapes at harvest should be moderate to neutral, since the characteristic aromas of sparkling wines primarily develop during secondary fermentation and yeast ageing. Primary processing is conducted under controlled conditions to obtain the highest possible quality base wine. This is followed by the addition of sugar and yeast to bottles or tanks, initiating secondary fermentation.

Yeasts have a profound influence on the sensory quality of wine, particularly on effervescence—affecting the amount of initial foam, bubble size and speed, and foam persistence. Yeast autolysis and the duration of ageing on lees are among the most important processes in shaping the character of sparkling wines. The degree of yeast autolysis significantly affects the chemical composition, biochemical reactions, and aging time, all of which contribute to sensory properties and foam characteristics. During alcoholic fermentation, yeast synthesize various secondary metabolites that enhance aromatic complexity. The yeasts most commonly used are *Saccharomyces* spp., selected based on their physiological and technological characteristics (autolytic potential, effect on foam, fermentation dynamics, etc.) (La Gatta et al., 2016).

YEASTS IN WINEMAKING

Various yeast species and strains can be used to conduct alcoholic fermentation for the production of base wines intended for sparkling wine. However, when performing secondary fermentation, the choice of yeasts is more limited and determined primarily by their tolerance to the demanding fermentation conditions. Recent studies indicate advancements in the development of interspecific hybrid wine yeasts that ferment efficiently while generating new flavors and aromas. *Saccharomyces cerevisiae* is the standard yeast used in fermentation because of its tolerance to high sugar and ethanol concentrations during winemaking. Through hybridization of wine yeast strains with other members of the *Saccharomyces* genus, scientists have created a range of hybrid strains with genomic contributions from different species. In the study conducted by Marangon et al. (2023), results demonstrated that interspecific yeast hybrids can be successfully used in sparkling wine production, yielding wines with chemical and sensory attributes similar to those produced with conventional commercial *Saccharomyces cerevisiae* strains. The conclusion was that these new hybrid yeasts can successfully complete secondary bottle fermentation without significant changes in the chemical composition of the wine compared to commonly used commercial *Saccharomyces cerevisiae* strains.

Commercial yeasts used for primary and secondary alcoholic fermentation differ substantially. Yeasts for primary fermentation are selected based on criteria such as high fermentation rate and low production of volatile acidity, along with other desirable features, whereas yeasts for secondary fermentation are chosen for specific technological properties (Martínez-Rodríguez et al., 2001). Yeast strains used in secondary fermentation must be capable of fermenting at lower temperatures and under pressure in wine containing at least 10% alcohol by volume.

During secondary fermentation and extended ageing on lees, interactions between yeast cells and wine constituents trigger various biochemical reactions, including the release of free amino acids, peptides and other compounds released during yeast autolysis. These changes contribute to modifications in the volatile composition and sensory profiles of sparkling wines. In particular, wines aged on yeast lees for longer periods (e.g., 15–18 months) have been associated with a sensory profile that includes more complex aromatic descriptors such as honey, butter, and notes of toasted bread, alongside fruit and floral nuances, indicating enhanced aromatic complexity and organoleptic richness with lees contact (Sartor et al., 2021). Furthermore, these wines exhibit greater body and a finer, more persistent effervescence, contributing to the elegance of sparkling wines (Riu-Aumatell et al., 2006). The Charmat method, in which secondary fermentation takes place in pressurized tanks, results in sparkling wines characterized by freshness, elegance, and delicate aromas due to shorter lees contact. Such wines display a fresher and fruitier profile, as extended yeast contact is absent, and they tend to have a less complex aroma dominated by esters responsible for fruity notes. Additionally, the faster production process offers greater economic efficiency, although this characteristic is not always directly aligned with the overall quality of sparkling wines (Caliari et al., 2015).

In addition to the traditional and Charmat methods, increasing attention has recently been directed toward the ancestral method of sparkling wine production. Unlike the traditional approach, the ancestral method involves bottling the wine before the completion of primary alcoholic fermentation, allowing fermentation to finish in the bottle without the addition of tirage liqueur. This process results in distinct fermentation dynamics, yeast populations, and metabolite release, which ultimately influence the chemical composition and sensory properties of the final wine.

Recent comparative studies have demonstrated that wines produced by the ancestral method generally exhibit lower alcohol content, higher concentrations of polysaccharides, and a more harmonious sensory profile, characterized by softer effervescence, enhanced mouthfeel, and more pronounced fruity and varietal notes. These characteristics are largely attributed to dif-

ferences in yeast activity, fermentation kinetics, and lees composition when compared to the traditional method (Just-Borràs et al., 2024).

A schematic comparison of the technological steps involved in the traditional and ancestral methods, including variations in yeast population levels, is presented in Figure 1. These technological differences have practical implications for sparkling wine style, as the traditional method is generally associated with more pronounced autolytic complexity and tertiary aromas, whereas the ancestral method tends to preserve fresher fruit-driven and varietal characteristics (Just-Borràs et al., 2024).

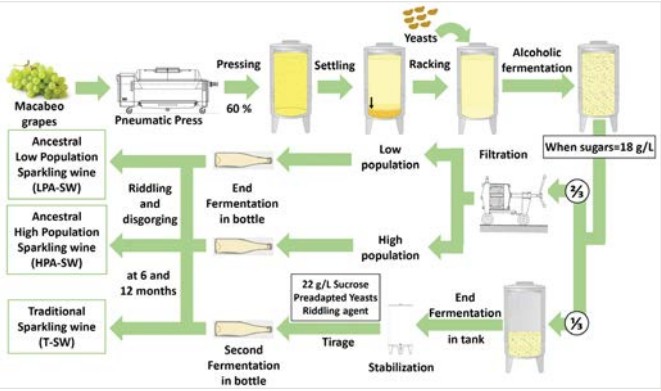


Figure 1. Schematic representation of the technological process for producing sparkling wines obtained using the traditional method (T-SW) and the ancestral method with low (LPA-SW) and high yeast populations (HPA-SW). The traditional method involves a distinct second fermentation and prolonged lees ageing, generally resulting in greater autolytic complexity and more developed tertiary aromas, whereas the ancestral method relies on a single fermentation process that preserves fresher fruit-driven and varietal sensory characteristics (Source: Just-Borràs et al., 2024)

The aromatic profile of sparkling wines is shaped by the interaction between the chemical composition of grapes and must, fermentation methods, yeast selection, and harvest timing. The main contributors to sensory aroma originate from three primary sources.

Primary aroma compounds derive from the grapes themselves and include terpenes, methoxypyrazines, and C13-norisoprenoids, which impart characteristic fruity and floral notes already present at the base-wine stage (Ubeda et al., 2017).

Secondary aroma compounds are formed during fermentation through yeast metabolism and include esters, higher alcohols, fatty acids and aldehydes, all of which contribute to the complexity of the wine's aromatic profile. Esters are responsible for fruity aromas such as ethyl octanoate (apple), isoamyl acetate (banana), ethyl butanoate (pineapple), and ethyl hexanoate (green apple). Higher alcohols contribute to structure and aromatic complexity, including phenylethanol (rose), isobutanol (herbal notes), and isopentanol (fruity notes). Fatty acids (caproic, caprylic, and capric acid) are lipid-metabolism by-products that enrich the wine's texture with creamy and nutty nuances. Aldehydes and ketones further shape the aromatic profile: diacetyl is responsible for buttery notes, while furfural imparts nutty and caramel tones (Martí-Raga et al., 2016).

Tertiary aroma compounds develop during wine ageing as a consequence of yeast autolysis and contribute to increased sensory complexity, improved texture, and enhanced foam quality in sparkling wines (Pons-Mercadé et al., 2021).

Yeast autolysis during secondary fermentation

During secondary fermentation, interactions occur between yeast cells and wine constituents, triggering numerous chemical and enzymatic reactions that result in changes to the organoleptic properties of sparkling wines (Figure 2) (Buxaderas and López-Tamames, 2012; Gallardo-Chacón et al., 2010; Miličević et al., 2017). Enzymes within yeast cells degrade cellular components, releasing various compounds into the wine; this process may last for months or even years, depending on the wine style and desired characteristics. Todd et al. (2000) demonstrated that the interaction between different yeast populations during bottle fermentation can promote autolysis and accelerate the release of yeast-derived proteins into sparkling wines, suggesting practical implications for lees aging strategies in sparkling wine production. Autolysis, which begins two to four months after the completion of secondary fermentation, involves the breakdown of yeast cell components, with

proteolytic enzymes such as protease A playing a key role, particularly under acidic conditions (Lurton et al., 1989). In sparkling wine, proteolytic activity decreases during active bottle fermentation and in the following months, whereas after approximately nine months of aging, internal proteolytic activity increases substantially (Feuillat and Charpentier, 1982). During Champagne aging, proteolytic activity may also vary depending on the yeast strain used (Leroy et al., 1990).

Yeast autolysis is crucial for shaping sparkling wine quality through the gradual release of yeast-derived compounds that enhance texture, foam stability, and aromatic complexity. By selecting appropriate technologies and optimising lees ageing duration, oenologists can promote these beneficial effects and improve the sensory quality of sparkling wines (Alexandre and Guilloux-Benatier, 2006; Pons-Mercadé et al., 2021). According to Marangon et al. (2023), yeast strain selection can significantly influence the variability in the concentrations of compounds released during autolysis, particularly proteins and polysaccharides. Some strains release greater amounts of mannoproteins, which may affect key quality parameters such as color, foam, aromatic composition, and sensory attributes. Future studies should focus on specific parameters—including aromatic profile, foaming properties, and sensory characteristics of wines produced from different grape varieties—as well as on potential alternative production methods, such as tank fermentation.

Different sparkling wine styles employ autolysis in varying ways to achieve their distinctive characteristics. For example, in the Champagne region, wines typically age on lees for at least 15 months, often much longer, resulting in complex aromas and a rich texture. Spanish Cava usually ages on lees for a minimum of nine months, providing freshness and subtle yeast-derived notes. In contrast, Italian Prosecco seldom undergoes extended autolysis, although some premium producers occasionally age the wine on lees to achieve additional complexity.

Saccharomyces yeasts

The use of commercial starter cultures in alcoholic fermentation enables process control without the formation of potentially undesirable compounds (Comitini et al., 2017). Yeasts of the genus *Saccharomyces* are of fundamental importance in the wine industry, particularly in the production of sparkling wines, where they are responsible for carrying out primary and secondary fermentation. Their ability to adapt to diverse fermentation conditions, their tolerance to ethanol, and their capacity

Origin	Compound type	Proven or potential impact on sparkling wine	References
Cell content	Nucleoside, Nucleotide	Flavouring agent	Leroy et al. (1990); Charpentier et al. (2005); Courtis et al. (1998)
	Amino acid, Peptide, Protein	Aroma precursors, Foam quality, Sweet and bitter taste	Feuillat and Charpentier (1982); Moreno-Arribas et al. (2000); Malvy et al. (1994)
	Protein	Sweet and bitter taste, Foam quality	Polo et al. (1992)
	Lipids	Foam quality	Gallart et al. (2002)
Cell wall	Glucan	Foam quality	Andres-Lacueva et al. (1997); Moreno-Arribas et al. (2000)
	Mannoprotein	Increase in mouthfeel	Bertuccioli and Ferrari (1999)

Figure 2. Origin of chemical compounds released during yeast autolysis and their impact or potential impact on sparkling wine (Source: Alexandre and Guilloux-Benatier, 2006)

to produce volatile aromatic compounds make them indispensable in sparkling wine production. *Saccharomyces cerevisiae* is known for its reliability and versatility, being characterized by rapid and complete fermentation even under challenging conditions such as low temperatures and high alcohol content. It is also valued for its neutral aromatic profile, which allows the varietal characteristics of the grapes to be fully expressed.

Selecting an appropriate yeast strain can significantly influence fermentation kinetics, the aromatic profile, foam stability, and the overall quality of the wine. Different commercial strains may offer specific advantages, such as enhanced fermentation rate, greater ethanol tolerance, increased mannoprotein release, and the formation of various aromatic compounds, including esters and higher alcohols. For example, some flocculent strains exhibit high autolytic activity, which promotes faster maturation on lees and improves foam quality, persistence, and the aromatic complexity of sparkling wines (Di Gianvito et al., 2018). Additionally, the use of strains with pronounced "killer" activity in co-fermentation with sensitive yeasts may accelerate autolysis and shorten wine maturation time (Lombardi et al., 2015).

González-Jiménez et al. (2020) investigated the influence of the commercial *S. cerevisiae* strain P29, used for sparkling wine production, and the G1 “flor” yeast strain commonly used in sherry production, on the formation of aromatic esters during the secondary fermentation of traditionally produced sparkling wines. The study demonstrated that the G1 strain has potential for use in sparkling wine production, as it provides a richer and distinctive aromatic profile, increasing stylistic diversity and offering potential for fine-tuning sensory attributes.

In a study conducted on sparkling wines made from the 'Grk' grape variety, wines fermented with the Lalvin EC1118® strain exhibited the highest alcohol content (12.5% vol.) and the lowest residual sugar (4.5 g/L), indicating its high fermentation efficiency (Brleković, 2022). In another study by Šikač et al. (2022), several commercially available *Saccharomyces* strains used for secondary fermentation of white sparkling wines produced by the traditional method were compared to determine their impact on the aromatic profile. Using gas chromatography–mass spectrometry (GC-MS), a total of 93 volatile compounds were identified across ten chemical groups, with statistically significant differences observed among treatments.

The most pronounced differences were found in the concentrations of esters, higher alcohols, lactones, norisoprenoids, and terpenes, with some compounds exhibiting odour activity values (OAV) greater than 1, indicating a direct contribution to the wine’s aroma. The ProElif® (PE) treatment showed the highest concentrations of esters such as isoamyl acetate, ethyl hexanoate, ethyl octanoate, and ethyl decanoate, contributing fruity and floral notes reminiscent of banana, green apple, and chamomile. Elevated levels of lactones (e.g., γ-butyrolactone, γ-nonalactone), responsible for coconut and caramel aromas, were also detected, in addition to the highest concentrations of fatty acids (hexanoic, octanoic, decanoic), which contribute to body and complexity.

The Uvaferm BC® treatment resulted in the highest norisoprenoid concentrations, notably β-damascenone, known for enhancing fruitiness and diminishing green notes. Higher levels of cis-3-hexen-1-ol, associated with herbaceous and fresh green aromas, were also observed. Conversely, the Lalvin EC-1118® treatment exhibited the highest total terpene concentration—particularly β-myrcene, linalool, and citronellol—which impart floral and citrus notes. Additionally, this treatment showed the highest concentration of volatile phenols, such as 4-ethylphenol and 4-vinylguaiacol, although most remained below sensory perception thresholds.

Taken together, these studies highlight that different *Saccharomyces* strains contribute differently to the sensory expression of sparkling wines. Beyond ensuring efficient fermentation, yeast selection may influence aroma complexity, foam properties, and overall wine quality, thereby offering opportunities to diversify sparkling wine styles.

Non-Saccharomyces yeasts

Non-*Saccharomyces* yeasts are becoming increasingly important in winemaking due to their ability to enhance the aromatic profile and sensory characteristics of wine (Morata et al., 2019). The most used species include *Torulaspora delbrueckii*, *Metschnikowia pulcherrima*, and *Pichia kluyveri*, which contribute to greater aromatic complexity and reduce the concentration of undesirable compounds such as volatile acids. Their presence has a positive effect on wine texture and foam properties, contributing to greater mouthfeel and sensory complexity in sparkling wines (Berbegal et al., 2022). Their use in starter cultures allows for greater aromatic diversity, emphasizing stylistic variations and characteristics of individual vintages. However, despite these advantages, non-*Saccharomyces* species often exhibit lower robustness and poorer resistance to stressful enological conditions compared to *Saccharomyces* yeasts (Pérez-Torrado et al., 2017). Since simultaneous inoculation with *Saccharomyces cerevisiae* leads to a rapid decline in viability, sequential inoculation is recommended as a more efficient fermentation strategy (Berbegal et al., 2022).

In addition to polysaccharides and mannoproteins, these yeasts play a key role in the formation of fermentative compounds—particularly esters responsible for fruity and floral aromas in wine. Through increased β-glucosidase activity, an enzyme that hydrolyses non-volatile glycosides, they release aromatic monoterpenes, thereby enriching the wine's aromatic profile (Vilela, 2020). According to Viana et al. (2008), certain genera have specific roles in ester synthesis: *Hanseniaspora* produces the highest levels of 2-phenylethyl acetate, contributing honey and rose notes; *Pichia* generates significant amounts of isoamyl acetate (banana) and isobutyl acetate (sweet fruit); *Torulaspora* excels in the production of ethyl octanoate, responsible for buttery and fruity aromas. As noted by Rojas et al. (2001), the formation of fruity esters depends on oxygen availability—in aerobic conditions their synthesis increases, while low-oxygen conditions result in lower concentrations. Nevertheless, oxygen management requires caution because aerobic conditions, although sometimes used to modulate metabolism, may increase the risk of excessive volatile acidity production in certain non-*Saccharomyces* strains (Ciani et al., 2016).

Benito et al. (2019) conducted research on multiple non-*Saccharomyces* species and concluded that these yeasts represent a powerful tool in modern enology for creating new wine styles, enhancing quality and aromatic complexity, and addressing technological challenges such as alcohol, acidity, and color management. Due to their diverse metabolic capabilities and influence on sensory properties, their use in combination with *S. cerevisiae* in controlled fermentations is increasingly encouraged. Furthermore, more species are expected to become available for enological applications in the future. Some species, such as *Metschnikowia pulcherrima* and *Pichia kluyveri*, increase the levels of esters, thiols, and terpenes, thereby enhancing the fruity and varietal character of wines. *Lachancea thermotolerans* produces significant amounts of lactic acid, lowering pH and increasing total acidity, which is particularly beneficial in warm viticultural regions. *T. delbrueckii* and *L. thermotolerans* can reduce acetic acid levels compared to *S. cerevisiae*, preventing the formation of undesirable vinegar-like aromas. Other species (e.g., *Meyerozyma guilliermondii*, *Schizosaccharomyces pombe*) promote the formation of stable pigments (such as vitisins) and increase color intensity and stability. The use of non-*Saccharomyces* yeasts can reduce wine alcohol content by 1–2% vol., which is significant given the rising demand for lower-alcohol wines. Increased glycerol synthesis and polysaccharide release positively influence mouthfeel, contributing to roundness and softness. On the other hand, the industrial application of these species faces critical limitations such as a lower ethanol tolerance (often below 6–8%) and high sensitivity to standard SO_2 doses, which can result in fermentation inconsistency and undesirable residual sugar (Ciani et al., 2016; Morata, 2022; Morata and Loira, 2016). The market now offers a range of commercial non-*Saccharomyces* preparations, including *T. delbrueckii* (e.g., Biodiva™, Prelude™), *L. thermotolerans*

(Concerto™), *M. pulcherrima* (Flavia®), *P. kluyveri* (Frootzen®), and *S. pombe* (ProMalic).

In addition to improving aromatic complexity, these yeasts can stabilize the color of red wines by forming vitisins—pigments more resistant to oxidation and color loss (Medina et al., 2016). Co-inoculation with *S. cerevisiae* increases the synthesis of vitisin B, which is chemically more stable than free anthocyanins (Medina et al., 2016). Loira et al. (2015) demonstrated that sequential fermentation with *T. delbrueckii* further enhances color stability, while *Schizosaccharomyces pombe* is highly effective in forming oxidation-resistant pigments. These findings highlight the potential application of non-*Saccharomyces* species such as *Torulaspora delbrueckii* and *Schizosaccharomyces pombe* in the production of white wines and sparkling wines with extended lees aging, due to their ability to enhance aromatic complexity and color stability through the synthesis of oxidation-resistant pigments. These yeasts also influence the synthesis of acetaldehyde, a compound that reacts with phenolic components of wine and contributes to the formation of complex aromas (Medina et al., 2016). It is important to note that improperly managed fermentation with wild or poorly selected non-*Saccharomyces* strains may lead to the occurrence of off-flavors, such as ethyl phenols, which impair the sensory quality of the wine (Morata and Loira, 2016). Overall, the diverse metabolic capabilities of non-*Saccharomyces* yeasts provide valuable opportunities to modulate wine style and sensory expression. However, their successful application requires careful strain selection and optimisation of fermentation conditions to maximise their technological and sensory benefits.

Innovative methods in yeast application

Modern enology offers a wide range of possibilities for the application of yeasts.

The method of yeast application is determined by the species and strain used, as well as by the desired wine characteristics that the producer aims to achieve.

Inoculation with selected starter cultures ensures controlled fermentation and a predictable aromatic profile. According to Berbegal et al. (2022), the appropriate selection of inoculum can optimize fermentation and minimize the formation of undesirable by-products such as hydrogen sulfide. Selected strains are adapted to specific fermentation conditions, including different pH values and temperatures, allowing greater flexibility in meeting enological requirements.

Sequential inoculation involves adding *S. cerevisiae* after non-*Saccharomyces* yeasts have been fermenting for a defined period. Combining different yeast species allows for increased aromatic complexity and improved utilization of nutrients from the must. In the study by Martí-Raga et al. (2016), sequential inoculation of various *Saccharomyces* and non-*Saccharomyces* strains resulted in higher diversity of volatile compounds, enhancing the overall sensory profile of sparkling wines. This method also improves adaptation to fermentation conditions, reduces the risk of fermentation arrest, and contributes to improved wine stability.

Encapsulated yeasts represent an innovative technology in sparkling wine production, enabling better control of fermentation, reduced lees formation, and improved sensory properties of the final wine. Their use can influence various aspects of production, including the chemical composition and organoleptic characteristics of the finished product (Alexandre and Guilloux-Benatier, 2006). Encapsulation allows for easier removal of yeast cells after fermentation, reducing the need for traditional processes such as remuage and disgorging. Additionally, encapsulated yeasts lower the risk of contamination, allow more precise control of fermentation duration, and improve product consistency.

Plavša et al. (2021) compared the effects of free and encapsulated yeasts and concluded that encapsulated yeasts enhanced foam stability and resulted in a more pronounced aromatic profile, emphasizing red and dried fruit notes as well as herbal nuances—attributes associated with esters such as isoamyl acetate, ethyl hexanoate, and ethyl octanoate.

Similarly, Călugăr et al. (2024) investigated the impact of encapsulated *Saccharomyces cerevisiae* during secondary fermentation using the Champenoise method and reported significant modifications in volatile compound composition and sensory complexity of the final sparkling product. These findings further confirm that yeast encapsulation can modulate ester formation and overall aromatic expression during secondary fermentation.

The study by Miličević et al. (2017) demonstrated that the use of alginate-immobilized *Saccharomyces cerevisiae* cells during secondary fermentation does not result in significant changes in key physicochemical parameters of sparkling wines, including pH, alcohol content, total and volatile acidity, or the main volatile aroma profile, nor in the sensory properties of the wines, when compared to fermentation with free yeast cells. In contrast, Fernández-Fernández et al. (2022) focused on the technological aspects of using encapsulated yeasts and concluded that this approach ensures a stable secondary fermentation, with comparable pH values, residual sugar levels, and alcohol content, as well as similar sensory characteristics after ageing. The authors further emphasized that the application of immobilized yeasts can simplify riddling and disgorging operations without negatively affecting wine quality. Overall, these studies suggest that the benefits of immobilized yeasts are primarily technological rather than sensory, as most authors reported comparable wine composition and sensory quality relative to free yeast fermentations. Their main advantage therefore, lies in process optimization and simplification of sparkling wine production.

A study on rosé sparkling wine made from the 'Teran' variety compared encapsulated *ProElif*® (*S. cerevisiae*) and free *Fermol Blanc* (*S. bayanus*). Encapsulated yeasts accelerated sugar degradation during secondary fermentation, shortening fermentation time by 55%. These wines had lower total extract, dry extract, and ash but showed higher concentrations of phenolic compounds—including anthocyanins, flavonols, flavanols, and stilbenes—which may enhance color and antioxidant properties (Plavša et al., 2021). Taken together, these results indicate that yeast encapsulation during secondary fermentation can significantly modulate both the phenolic matrix and sensory attributes of rosé sparkling wines, enhancing color stability, antioxidant capacity, foam properties, and ester-driven aromatic expression (Plavša et al., 2021).

Optimizing fermentation conditions can significantly influence yeast metabolism and direct the formation of volatile compounds by selecting appropriate yeast strains and carefully controlling key technological parameters. Lower fermentation temperatures generally favor the retention and formation of fruity esters, while proper nutrient management, particularly the availability of nitrogen sources, supports balanced yeast activity and promotes the synthesis of desirable aromatic compounds. Together, these practices contribute to improved organoleptic quality and a more expressive aromatic profile of wine.

Research in yeast genetics has led to the development of hybrid yeast strains that combine beneficial traits of different species and strains. These hybrids may exhibit increased ethanol tolerance, improved fermentation at low temperatures, and optimized ester production. According to Berbegal et al. (2022), such yeasts may become key tools in future sparkling wine production due to their stability and ability to ensure consistent product quality.

Additionally, inducing autolysis can enhance wine body and aromatic complexity by accelerating the release of mannoproteins, polysaccharides, and peptides. Methods such as the use of enzymatic preparations or adjustments to storage conditions allow better control over these processes and help achieve the desired sensory attributes in a shorter period of time. These innovative methods enable winemakers to tailor sensory properties, enhance fermentation performance, and improve overall wine quality while aligning with modern market trends and growing demand for authentic wine styles (Enartis, 2019).

Although further research is needed to optimize these technologies for different grape varieties and wine styles, current results show that encapsulated yeasts offer numerous advantages, including improved fermentation control, reduced formation of undesirable by-products, and enhanced sensory qualities. Their use may also reduce the need for classical yeast removal procedures, simplifying sparkling wine production.

The use of indigenous yeast strains has been increasingly explored as a strategy to enhance sensory diversity and reinforce the regional identity of sparkling wines. The exploitation of native *Saccharomyces cerevisiae* populations during in-bottle secondary fermentation has been shown to introduce greater variability in volatile composition, thereby contributing to more distinctive aromatic and sensory characteristics compared with those obtained using standardized commercial starter cultures (Vigentini et al., 2017). Furthermore, recent studies on sparkling wines produced from traditional grape varieties have demonstrated that the use of native yeasts can support the expression of microbial terroir, preserving region-specific attributes and contributing to wine typicity. This approach is gaining attention among producers seeking to differentiate their products, emphasize terroir-driven characteristics, and reduce dependence on commercial yeast strains that may lead to sensory uniformity (Basile et al., 2025). However, the use of indigenous yeasts may also introduce greater variability in fermentation performance, requiring careful monitoring to ensure consistent wine quality.

SENSORY PROPERTIES OF WINE

Composition and activity of yeasts during fermentation are crucial for the development of wine sensory properties, particularly in sparkling wine production. In addition to enabling the conversion of sugars into alcohol and carbon dioxide, yeasts synthesize volatile compounds that shape the aromatic profile of the wine. Their role is essential in releasing primary aromas and in the formation of esters, higher alcohols, and aldehydes, all of which contribute to the expression of fruity, floral, and complex aroma notes. Furthermore, yeast autolysis contributes to the development of texture, foam quality, and sensory complexity during sparkling wine ageing. The use of different *Saccharomyces cerevisiae* and non-*Saccharomyces* strains allows for the adjustment of fermentation conditions and fine-tuning of the sensory profile, while lees aging further influences the perceived characteristics of the wine. Innovative fermentation approaches, such as the use of encapsulated yeasts, simplify the production process without compromising sensory quality. In the production of base wines for sparkling wine, control of fermentation parameters plays a key role in preserving varietal aromas, balancing acidity, and shaping the overall wine structure. The selection of appropriate fermentation techniques, yeast combinations, and aging duration enables winemakers to tailor wines to the desired sensory profile. During secondary fermentation and lees ageing, yeast activity continues to shape the sensory identity of sparkling wines, particularly through its influence on foam characteristics and overall flavour perception. These findings provide opportunities to optimize production methods and create wines with improved sensory attributes and greater consistency in quality.

Influence on the sensory profile of the base wine

It is important to note that, in addition to yeasts, many other factors influence the sensory properties of wine, such as grape variety, cultivation conditions, technological processing procedures, and aging time. The combination of all these factors has a significant impact on the overall sensory quality of the base wine. Some of the key parameters affected include colour and colour stability, flavour attributes, completeness of fermentation, and the balance between acidity and sweetness.

Sawyer et al. (2022) conducted a study examining the impact of lees aging versus ageing without lees on the aromatic profile of base wine over different periods (6, 12, and 24 months). The results showed that wine aged without lees exhibited higher concentrations of oxidative compounds (aldehydes), which contribute to more complex aromas with nutty and honey-like notes. The oxidative potential was more pronounced due to the

absence of the protective effect of lees. Wines aged on lees, however, showed lower concentrations of oxidative compounds due to the antioxidant protection provided by the lees, as well as higher levels of polysaccharides. The sensory profile of these wines was enriched with autolytic compounds such as sotolon (spicy-caramel notes), homofuraneol (caramel), 2-phenylacetaldehyde, and 2-phenylethanol, which contribute honey, floral, and ripe fruit aromas. Additional compounds, including methional, 2-methylbutanal, and 2-methylpropanal—characteristic of nutty and mature wine aromas—were also identified. The study concluded that the choice of treatment strongly determines the chemical and sensory profile of the finished wine, with lees aging proving particularly beneficial for the development of complex and desirable aromas, especially within a 24-month period.

Hickert et al. (2024) investigated the influence of different *Saccharomyces cerevisiae* strains and their co-inoculation with *Torulaspora delbrueckii* on the chemical and sensory characteristics of a 'Chardonnay' base wine intended for sparkling wine production. The authors reported that fermentation with different *S. cerevisiae* strains resulted in significant differences in sulfur dioxide concentration and volatile acidity, highlighting the impact of yeast strain selection on key enological parameters. Furthermore, co-inoculation with *T. delbrueckii* led to increased concentrations of several volatile esters, including ethyl acetate and 2-phenylethyl acetate, which are associated with fruity and floral aromas. Sensory evaluation confirmed that wines produced with the *S. cerevisiae* - *T. delbrueckii* combinations exhibited more pronounced floral and tropical fruit notes and a more clearly defined aromatic profile compared to wines fermented with *S. cerevisiae* alone. These results demonstrate that yeast selection and co-inoculation strategies can significantly enhance the aromatic complexity and sensory quality of base wines used for sparkling wine production.

Makarov et al. (2021) studied the influence of five different yeast strains on the sensory properties of base and young sparkling wines made from 'Cabernet Sauvignon' using the traditional bottle-fermentation method. The aim was to identify the optimal strain capable of preserving varietal aromas and improving wine quality without introducing pronounced yeast-derived off-notes. The results indicated that the strain marketed as Odesskiy Chernyi-SD13 produced the most favourable outcomes, characterised by enhanced aromatic complexity, deeper colour intensity, and a harmonious, velvety taste. Among base wines, samples fermented with this strain achieved the highest sensory scores—7.83/10 for the rosé wine and 7.82/10 for the red wine. The aromatic profile of the rosé wine was described as complex and berry-fruited, whereas the red base wine was recognised as varietally expressive, with pronounced berry aromas, a balanced flavour, and a well-structured mouthfeel.

Sensory evaluation of the young sparkling wines further confirmed the superiority of this strain. The rosé sparkling wine received a score of 9.03/10 and was described as clean and fresh, with fruit and candy-like notes and a well-balanced CO_2 presence that contributed to elegance and freshness. The red sparkling wine fermented with the same strain received the highest overall sensory score of 9.05/10, characterised by a fruity and berry-like bouquet, a full and well-structured taste with pronounced tannins, and a long, harmonious finish.

Beyond aromatic and flavour characteristics, this strain also demonstrated superior physicochemical properties. Wines produced with Odesskiy Chernyi-SD13 showed the highest foam capacity (1150 cm^3), indicating favourable textural and visual effervescence characteristics. These wines also contained the highest proportion of bound CO_2 (up to 24.93%), as well as the highest total phenolic content (1103 mg/dm^3) and the most intense colour, suggesting enhanced structure and improved stability. The study concludes that yeast selection plays a crucial role in shaping both the sensory and technological attributes of sparkling wines, with Odesskiy Chernyi-SD13 standing out as an optimal strain for achieving aromatic complexity, varietal expression, and balanced flavour in sparkling wine production.

Taken together, these studies indicate that different strategies can be used to enhance the sensory quality of sparkling wine base wines. Lees ageing primarily contributes to greater aromatic complexity and oxidative protection, whereas yeast selection and co-inoculation strategies offer opportunities to modulate aroma expression and improve technological performance.

Influence on the sensory properties of sparkling wines

The influence of yeasts on the sensory properties of sparkling wines is a key factor in their production, since different yeast strains can significantly affect the aromatic profile, foam structure, and overall wine quality. Cotea et al. (2021) investigated how four commercial *Saccharomyces cerevisiae* strains (IOC FIZZ™, IOC DIVINE™, LEVULIA CRISTAL™, IOC 18-2007™) influence volatile compounds in sparkling wines of the 'Muscat Ottonel' variety, and found that the selected yeasts caused changes in ester and terpene composition, leading to different sensory profiles of the wines (Cotea et al., 2021).

Similarly, Eder et al. (2020) investigated the influence of different *S. cerevisiae* strains (EC1118, *S. bayanus* C12, and IFI473I) on sparkling wines produced from the 'Torrontés Riojano' variety, and found that *S. bayanus* C12 exhibited the best foam stability, which is extremely important for the texture of sparkling wines. Furthermore, Marangon et al. (2023) compared hybrid yeasts with standard commercial yeasts in the production of English sparkling wines and found that basic chemical parameters remained stable, while foam stability and sensory attributes varied due to differences in the yeasts' ability to release polysaccharides. Romano et al. (2022) reviewed the role of yeasts in wine aroma development and highlighted that both *Saccharomyces cerevisiae* and non-*Saccharomyces* yeasts significantly influence the formation of volatile compounds, including esters, higher alcohols, and sulphur-containing compounds. The authors emphasized that yeast selection plays a crucial role in shaping fruity and floral sensory attributes and contributes to the overall aromatic complexity of wines, including sparkling wines. Differences observed among the studies indicate that yeast selection should be regarded as a strategic tool in sparkling wine production. Beyond ensuring efficient fermentation, individual strains can shape aroma expression, foam behaviour, and sensory perception, thereby contributing to the development of distinct sparkling wine styles.

In addition to yeast strain selection, physical conditions during secondary fermentation also play an important role in shaping the aromatic profile of sparkling wines. In particular, CO_2 pressure has been shown to modulate yeast metabolism and the synthesis of volatile compounds during bottle fermentation, leading to measurable changes in ester composition and aroma expression (Martínez-García et al., 2017). Several studies have explored the use of immobilized or encapsulated yeasts during secondary fermentation. These systems can facilitate the removal of yeast after fermentation and may reduce or even eliminate the need for riddling, thereby simplifying the production process (Fernández-Fernández et al., 2022; Miličević et al., 2017). Most research reports no major differences in basic oenological parameters compared to traditional free-yeast fermentation, although slight variations in aroma composition and sensory attributes may occur depending on the encapsulation matrix, yeast strain, and fermentation conditions. Another major aspect of sparkling wine production is yeast autolysis during lees ageing, which contributes to foam quality, texture and the sensory complexity of sparkling wines.

In a study by Lambert-Royo et al. (2022), the impact of yeast-derived enological products on the quality of sparkling wines was tested, showing that each product had a different effect. The yeast used for secondary fermentation was Lalvin EC1118® *Saccharomyces cerevisiae bayanus*, and the tirage liqueurs varied. Two of the five products were commercial specific inactivated yeasts from *S. cerevisiae*: Optimum White™ (OW) and Pure-Lees Longevity™ (LO). The remaining three were experimental: yeast autolysate (AL), yeast protein extract (PE), and inactivated *Torulaspora delbrueckii* NSC19 yeast (TD). All treatments were tested at two concentrations: 5 g/hL and 10 g/hL.

The most perceptible sensory changes occurred in wines treated with the commercial products Optimum White™ and Pure-Lees Longevity™. Results showed that for sparkling wines aged for a short period (9 months), the addition of 5 g/hL yeast protein extract and inactivated NSC19 *T. delbrueckii* yeast could help preserve volatile compounds essential for fruity aromas. For longer ageing (18 months), NSC19 *T. delbrueckii* was the most effective. Most yeast-derived products reduced the protein content of the wine, with no significant differences between doses. Yeast autolysate was the best at enriching wines with polysaccharides and produced wines with high antioxidant activity, making it a potentially excellent choice for preventing browning during long-term ageing. Effects on foam properties were highly variable and dependent on ageing duration. However, wines treated with 10 g/hL yeast autolysate and Optimum White™ showed the best foam quality and stability. Sensory analyses did not always correlate with physical measurements, and differences between treatments were minimally noticeable, likely due to insufficient variation between applied dosage levels. The study concludes that examining higher dosages could provide more conclusive information regarding the sensory impact of these yeast products on sparkling wine quality.

The final sensory profile of sparkling wines depends on a series of production decisions, including yeast selection, fermentation conditions, and the use of yeast-derived products, each of which can influence wine quality in different ways.

CONCLUSION

Yeasts play a key role in the production of sparkling wines, not only as drivers of the fermentation process but also as factors that significantly influence their sensory properties. Their use in primary and secondary fermentation enables control over the chemical composition of the wine, the development of its aromatic profile, texture and foam stability. In this context, the choice of yeast strains has a decisive influence on the final wine quality, with *Saccharomyces cerevisiae* remaining the standard, while the application of non-*Saccharomyces* yeasts and hybrid strains opens new possibilities for improving flavour complexity and effervescence.

One of the most important processes shaping the characteristics of sparkling wines is yeast autolysis, which contributes to the development of texture, foam quality, and aromatic complexity. Longer ageing on lees enriches wines with biscuit, nutty, and toasted notes, whereas shorter ageing preserves freshness and fruity expression. Depending on the technological procedure, the traditional method produces fuller and more complex wines, while the Charmat method yields fresher and lighter wines intended for earlier consumption.

Recent research comparing the traditional and ancestral methods has shown that the fermentation technique has a direct impact on the sensory profile of the wine. The ancestral method, although it requires precise process control, results in wines with lower alcohol content, higher levels of polysaccharides and a more harmonious sensory profile, with more pronounced fruity and varietal characteristics. Such wines are often perceived as more natural and authentic, which further increases interest in this type of production.

Innovations in enology, such as the use of encapsulated yeasts, sequential inoculation or indigenous yeast strains, allow further optimisation of fermentation processes. The use of new enological products based on inactive yeasts has proven beneficial for increasing foam stability and prolonging aroma persistence, while research on hybrid yeast strains shows potential for more precise shaping of wine composition and sensory properties.

Future research should focus on a deeper understanding of the interactions between yeast strains and specific grape varieties, as well as on approaches to accelerate autolysis without compromising wine quality. Continued innovation in yeast selection and fermentation management will help producers develop high-quality sparkling wines while maintaining authenticity and adapting to evolving market demands.

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