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Review

Advancing Sparkling Wine in the 21st Century: From Traditional Methods to Modern Innovations and Market Trends

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Abstract: Sparkling wine production has changed over time due to ongoing technological developments and market adjustments. This study provides an overview of the historical context, the characteristics of raw materials and base wine, modern technologies and current trends in the sparkling wine market. Important scientific advances with potential for wide-scale applicability are highlighted, such as the investigation of unconventional grape types, the progress of winemaking methods and the effects of compositional changes on quality and sensory characteristics. In addition, the nutritional effects of bioactive components in wine are discussed. Market trends indicate a growing global demand for sparkling wines over time, driven by changing consumer preferences and the diversification of wine-producing areas. Future prospects focus on sustainability, low-alcohol alternatives and the integration of emerging technologies. Combining tradition with innovation, the sparkling wine industry continues to expand, offering new opportunities to both producers and consumers. Research on the quality of sparkling wines in the context of climate change and evolving consumer preferences is still limited and warrants greater attention.

Keywords: yeast selection; modern technologies; composition-related advances; market trend; alcohol-reducing strategies

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1. Historical Background

Sparkling wine production started in the 17th century, in France, when re-fermented wine bottles started to explode in the cellar. Pierre Pérignon, a Benedictine monk from the Monastery of Hautvillers in Épernay (1638–1715), concluded that yeast activity is responsible for this phenomenon [1] and the created pressure inside the wine bottles made them break. After replicating the phenomenon in stronger bottles and adding sugar and honey, the first sparkling wine was produced. This beverage was named Champagne after the region of origin [2]. It had a moderate alcohol concentration (approximately 10% vol. alc.) and a pressure of 1.5–2 atmospheres. Sparkling wine was initially produced from red grapes. Dom Pérignon introduced gentle pressing in the Champagne technology, which allowed minimal contact between the grape juice and solid parts. The exact grape varieties cultivated in Champagne at that time are not known, but out of the 80 types, Pinot Noir and Pinot Gris were predominant. Following the invasion of phylloxera, the vineyards were destroyed, and the existing varieties were replanted, which are still present today. Initially, the effervescent beverage was made from seven noble grape varieties, but today it can only be produced from Pinot Noir, Pinot Meunier and Chardonnay [3]. Furthermore, the name 'Champagne' can only be used for wine from the above-mentioned region. In time, the process was continuously developed and improved. To further the art of sparkling wine production, Pierre Pérignon offered instructions in his book ('The art of caring for champagne vineyards and wines') on how to harvest and obtain the lightest color from red grapes [4]. The majority of sparkling wines are made from a blend of grape varieties, but a 'blanc de blancs' comes exclusively from Chardonnay, while a 'blanc de noirs' comes only from red grape varieties (usually just Pinot Noir) [2]. Also, the book presents a method of pruning the vine in order to limit the crop, how to prevent grape damage during harvest, and highlights the importance of eliminating plant matter (rotting grapes, leaves) [4].

In the 17th century, Champagne became popular among the French and English aristocracy. Initially, sparkling wines were transported in barrels to England, where they were bottled in thick, dark glass to resist the pressure of carbon dioxide (CO_2). In 1640, Sir Kenelm Digby, an English courtier and diplomat, proposed a bottle-making process that was more durable than any other. As Champagne's popularity spread across Europe, the presence of bubbles, initially seen as a flaw, began to symbolize elegance. By the mid-18th century, re-fermentation in Champagne was confirmed, and Madame Clicquot invented riddling racks in the early 19th century to remove the cloudy appearance caused by lees. This method helped to obtain a clean and bright sparkling wine [5].

Advances in the 20th century led to improvements in sparkling wine production, particularly with the development of the *liqueur de tirage* and the second fermentation. Traditional methods like riddling remained important for clarity, but the Charmat method, which allows second fermentation in pressurized tanks, became popular due to its efficiency and economic benefits [4]. Over time, technological innovations have led to the optimization of the quality and efficiency of sparkling wine production. These advances ensure that sparkling wines consistently meet the current demands of modern consumers.

2. Raw Materials and Base Wine Production

2.1. Grapes Characteristics

When producing sparkling wines, both white and red grapes can be used. When red varieties are chosen, they are typically vinified as white wines (*blanc de noirs*). The selection of grape variety or clone depends on factors such as the geographical region, tradition, pedoclimatic conditions and yield. Depending on the country of production, the most used grape varieties to obtain well-known sparkling wines are illustrated in Figure 1. To obtain high-quality musts and base wines, it is essential to ensure optimal conditions for harvesting and processing the fruit. Therefore, the grapes are harvested manually using small buckets or crates to prevent crushing. The grapes for sparkling wine are the first to be picked, due to their high acidity levels and low pH. Also, the sugar levels are able to produce a potential alcoholic strength of 10–11% alc. vol. At the same time, it is crucial to remove clusters affected by *Botrytis cinerea*, as this fungus influences the foaming capacity of the final product. The harvested grapes are immediately transported to the winery for rapid processing to prevent the early start of fermentation.

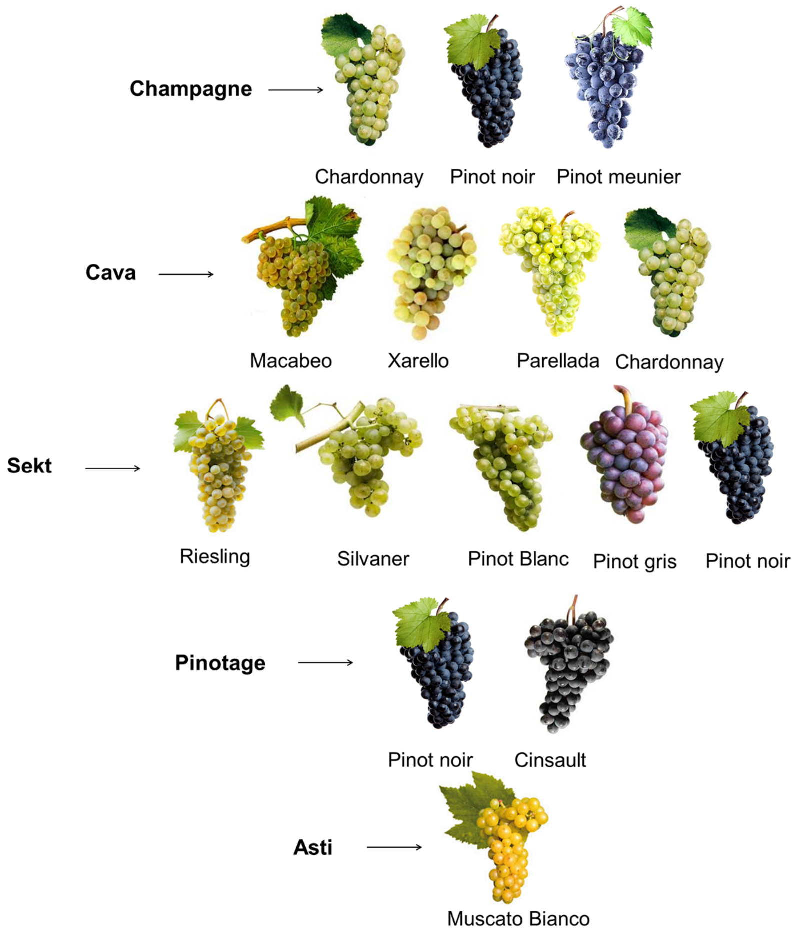

Figure 1. Grapes varieties used in sparkling wine production.

2.2. The Base Wine Production

In the winery, a gentle pressing of grapes is performed quickly, without prior crushing, at pressures of 1.5–2 bars to minimize oxidation. The pressing phase must be performed gradually and gently so as not to increase the amount of protein and polyphenol oxidase and to avoid oxidation of phenolic compounds. Also, the presence of inert gases such as CO_2 can create a very reductive working environment for the wine. The subsequent maceration stage facilitates the extraction of aroma and color compounds and is followed by a sulfur dioxide (SO_2) treatment of the must (3–8 g/hL) to prevent spontaneous fermentation. Then, pectolytic enzymes are applied, and selected yeast are inoculated. Musts with turbidity values between 200 and 400 NTU are clarified by centrifugation or static decantation (18–24 h at 6–15 °C), with the optional addition of fining agents such as bentonite or casein. During static settling, proteins, pectins, mineral cations, and phenolic compounds are partially removed [6]. Finally, they must undergo fermentation to produce a base wine with low alcohol content. It is important to note that after the second fermentation, approximately 1–1.5% alc. vol. is added, which is why a lower-alcohol base wine is preferred. The first fermentation is the time to adjust the acidity, if it is considered necessary. After the heavy lees are separated from the newly formed base wine, its evolution is carefully monitored. Left in contact with the lees, the base wine begins to develop a rounder and fuller taste [7]. The main phases for obtaining the base wine are illustrated in Figure 2.

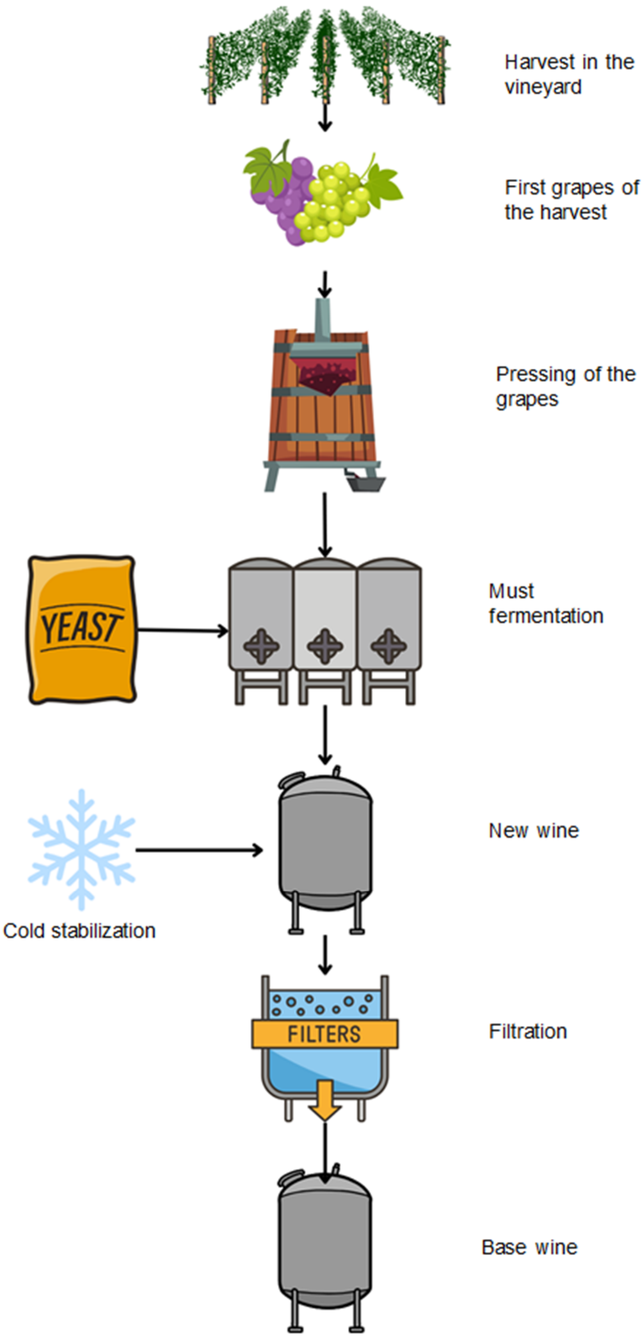

Figure 2. The main phases of producing base wine for later sparkling wine manufacture.

The next stage is the tartaric stabilization of the wine. This is obtained by drooping down the temperature of the wine to induce the crystallization of tartaric acid. The newly formed crystals create sediment at the bottom of the tank, which can be easily separated by careful pumping or filtering [7]. Once tartaric stabilization is complete, the second alcoholic fermentation can be initiated. This phase can take place either in bottles or in isobaric tanks, depending on the used production method.

2.3. Sparkling Wine Technologies

The main procedures for producing sparkling wine are the Champenoise and the Charmat–Martinotti methods, schematically represented in Figure 3. Among these, the Champenoise technique involves producing a base wine with high acidity and lower alcoholic strength, typically obtained from the first grapes picked during harvest. After tartaric stabilization, the base wine is enriched with a mixture of sugar or concentrated grape must and yeast (*liqueur de tirage*) to still wine to initiate the second fermentation. This stage takes place in sealed bottles positioned horizontally and can last up to 2–3 months, depending on the environment temperature [8,9]. Slower fermentation in a cooler environment produces smaller CO_2 bubbles, resulting in a smoother mouthfeel. Once fermentation is complete, the maturation phase begins, during which the sparkling wine remains in contact with yeast to undergo autolysis (a process in which yeast cell membrane breaks down, releasing cytoplasmic components into the liquid mass) [2]. In order to extract that yeast, the bottles undergo the riddling process. The bottles are homogenized to dislodge yeast from the sides of the bottle and disperse it in the liquid. After that, using special racks, the bottles are given an inclination of 25–30 degrees and in small increments, 1/8 of a twist; the bottles can reach a final angle of 45–75 degrees depending on the construction of the racks. The time frame for this is from 45 to 90 days depending on the sparkling wine. Automatic riddling machines such as the gyropallet are commonly used today, consisting of a pallet basket that holds more than 500 bottles. It can move in all directions and stop suddenly, facilitating the process. The disgorging process involves separating yeast sediment that has accumulated in the bottle's neck after riddling from the rest of the liquid. This can be performed either manually or using a machine. Manual disgorging can be performed with or without freezing the bottleneck to solidify the lees, allowing the internal pressure to expel them. A specialized tool is used to grip and remove the cap. In the automatic disgorging process, the bottleneck must be frozen before the bottle is placed into a machine that grips and removes the cap, allowing the pressure to expel the frozen lees. Both methods, manual and automatic, result in some product loss. Because of the pressure difference, foaming occurs when the lees are expelled. The extent of these losses depends on the skill of the person performing manual disgorging or the efficiency of the machine in the case of automatic disgorging [10].

The Charmat–Martinotti method follows a similar procedure for obtaining the base wine. The major difference lies in the second fermentation, which takes place in stainless steel tanks [10]. Due to the ability to manipulate the sparkling wine in an isobaric environment, it can be filtered and combined with the *liqueur d'expédition* (20–25 g/L of sugar is added to the base wine, followed by yeast inoculation) [11]. The sugar- and yeast-rich wine is usually transferred into stainless steel tanks. Throughout 1 to 3 months, yeast consumes the sugars, releasing CO_2 and alcohol. As a result, the alcoholic strength increases by approximately 1 to 1.5% vol. alc. Because of its effectiveness and financial advantages, the Charmat technique has become more and more common in the manufacture of sparkling wine. In general, sparkling wines obtained by the Champenoise method are perceived by consumers as having superior characteristics to those produced by the Charmat technique. Compared to the Champenoise method, this procedure preserves fresh fruit characteristics but has certain drawbacks, particularly regarding the wines' character [12]. However, Cisilloto et al. [12] compared the quality of sparkling wines obtained by the two methods. They found similar fermentation kinetics in methods, with significant differences in sugar concentration (higher in Charmat), SO_2 level, hue and turbidity. However, key parameters such as ethanol, acidity, pH, color and internal pressure did not show significant variations. Following the analysis of the content of volatile compounds, samples obtained by the traditional method (Champenoise) were characterized by higher proportions of diethyl succinate. Sensory analysis showed that the production method had a limited impact on quality, with differences mainly determined by the addition of expedition liqueur, which made the wines sweeter, less acidic and more harmonious. From a sensory point of view, no notable differences were evident between the two methods. In another study from Chile [13], it was found that wines obtained by the traditional method had higher concentrations of ethyl esters, while the Charmat procedure generated samples with more acetic esters and ketones. Given that ethyl esters are associated with aged wines, while acetate esters are linked to young wines, typical production trends are highlighted—Charmat for young wines and Traditional for older ones—although these characteristics are not exclusively determined by the fermentation method.

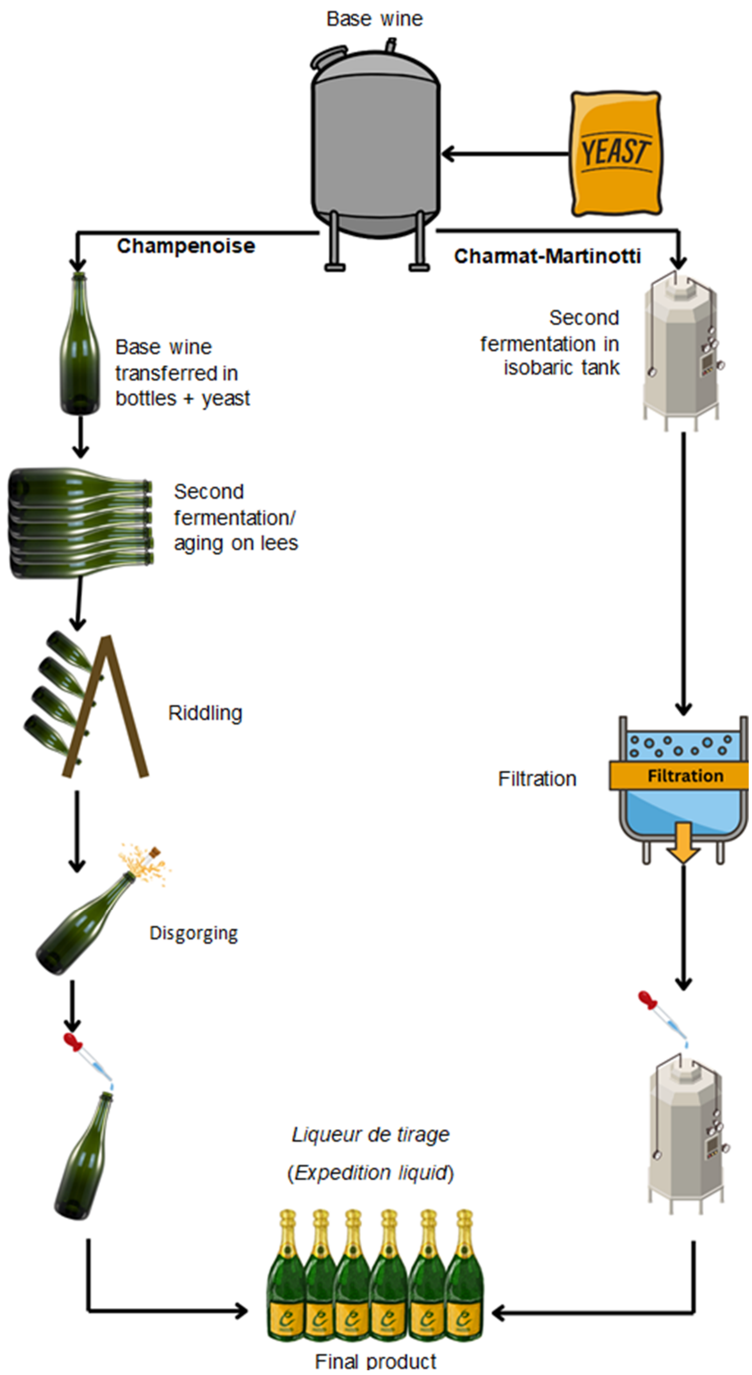

Figure 3. Champenoise (**left**) and Charmat–Martinotti (**right**) methods.

In the Asti method (Figure 4), fermentation takes place in isobaric tanks, similar to the Charmat-Martinotti technique. The must obtained from grape pressing is filtered, and selected yeasts are inoculated. Initially, fermentation occurs in an open environment, meaning the fermenting must be in contact with air. At a specific point, depending on the residual sugar content and the desired final pressure, the tank is sealed, and fermentation continues in a closed environment [14]. Once fermentation is complete, the wine undergoes cold stabilization, followed by filtration and bottling under pressure. In all presented methods, CO_2 is endogenous, meaning it is naturally produced through fermentation. Conversely, an exogenous source of CO_2 can also be found in certain wines, achieved by injecting pressurized CO_2 into the wine at a controlled temperature of -2 °C [4,15]. An important distinguishing factor is the pressure of the sparkling wine, typically measured in bars or kPa. So, sparkling wines (produced using the Champenoise or Charmat-Martinotti methods) must have a minimum pressure of 3.5 bars and contain only endogenous CO_2, while semi-sparkling wines have a pressure between 1 and 2.5 bars and may contain either endogenous or exogenous CO_2 [15]. Regarding the Champenoise method, a key differentiating factor is the aging process. This refers to the lees formed after the second fermentation, which remain in contact with the liquid mass of the sparkling wine. During this period, hydrolytic compounds such as polysaccharides, proteins, peptides, lipids, and ribonucleotides, originally contained within yeast cells, are slowly released into the wine. This contributes to distinctive aromas found in vintage Champagne and other aged sparkling wines [7].

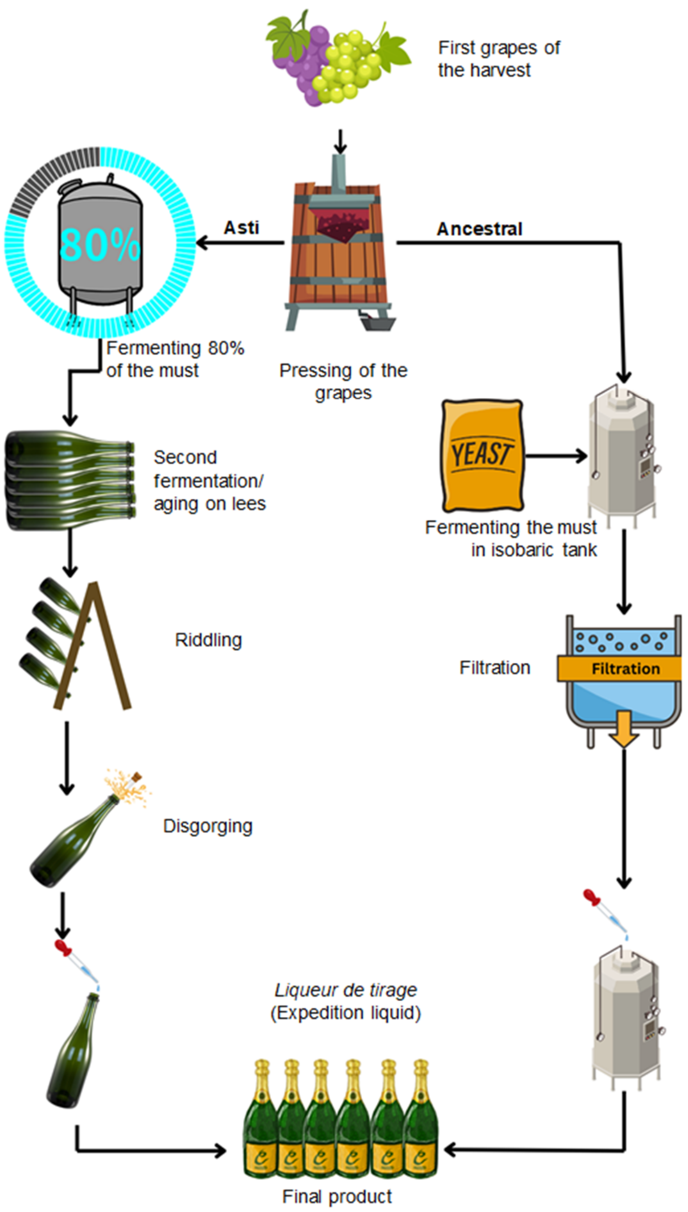

Figure 4. Asti and Ancestral method.

Another type of sparkling wine that is currently gaining popularity in both the industry and the market is obtained using the ancestral method. As with other procedures, the grapes used for this style are among the first to be harvested and pressed. After the must is clarified, it undergoes fermentation in stainless steel tanks. Unlike traditional methods, ancestral sparkling wine undergoes only one fermentation phase. When the sugar content reaches approximately 18 g/L, the fermenting liquid is homogenized and transferred into bottles, with or without the addition of a riddling agent [16,17]. Depending on the winemaker's approach, the still-fermenting wine may be filtered to reduce yeast population. After the primary fermentation, the processes of lees maturation, riddling, and disgorging are carried out similarly to the Champenoise method, but with some key differences, such as higher cloudiness and variations in CO_2 levels [18]. The challenging fermentation conditions inherent to this method can introduce potential faults due to the lack of precise control over the yeast population. High yeast populations can result in excessive autolytic notes, overshadowing other aromas and leading to an imbalanced final product dominated by yeast flavors. Additionally, excessive yeast density can delay the riddling process, making clarification more difficult [7]. Low yeast populations may lead to incomplete fermentation, preventing the wine from reaching the desired pressure levels, which complicates disgorgement due to insufficient internal pressure. Compared to the Champenoise method, ancestral sparkling wines typically contain higher concentrations of gluconic acid, total proteins, and polysaccharides, contributing to their unique mouthfeel and sensory profile [17].

3. Modern Advances in Sparkling Wine Technologies

3.1. Exploration of New Grape Varieties

Throughout history, viticulture and oenology have been influenced by global events, such as the phylloxera invasion in the 19th century, the two world wars and climate change. All these cumulative factors have generated interest in the research and development of sustainable grape varieties that offer new and improved sensory characteristics and resistance to future climate conditions and diseases.

In the semi-arid tropical wine-growing regions of northeastern Brazil, particularly the São Francisco Valley, Syrah and Chenin Blanc have adapted well to high-quality sparkling wine production. Chenin Blanc is characterized by important concentrations of 2,3-butanediol, 3-ethoxypropan-1-ol, diethyl succinate, and ethyl decanoate, while Syrah is distinguished by benzaldehyde, butyric acid and various acetates. Notably, the region's high temperatures, intense solar radiation and year-round irrigation enable vines to produce two harvests annually [19,20]. In the same region, Caliari et al. [21] analyzed five different grape varieties for sparkling wine production: Moscato Embrapa, Villenave, Niagara, Goethe and Manzoni Bianco. Of these, Moscato Embrapa, derived from a Muscat variety, is primarily used for producing aromatic table wines in Brazil. It is a cross between Couderc 13 and July Muscat, first obtained in 1983, and has been utilized on a small commercial scale. The resulting wine is characterized by a subtle Muscat flavor, an intense aroma, and a light-yellow color [22]. Villenave, developed in Bordeaux as a cross between Walsh Riesling and another unknown variety, has a yellow color, floral aroma, and good acidity, demonstrating strong potential for sparkling wine production. The Niagara variety is a *Vitis labrusca* white grape, widely cultivated in Santa Catarina, Brazil, and described as rustic [22]. Goethe is a hybrid grape with 87.5% *Vitis vinifera* and 12.5% *V. labrusca*. It has a high yield, large berries (approximately 6 g per berry), and thin skin. Brought to Brazil by Italian immigrants, the Goethe grape played a key role in securing the first geographical indication for the Santa Catarina state [23]. Manzoni Bianco, also known as Incrocio Manzoni, is a cross between Riesling and Pinot Blanc. Its acidity and sugar levels peak at full ripeness, making it a valuable choice for winemaking [24]. The sparkling wines obtained from Moscato Embrapa and Villenave showed a higher concentration of esters, such as isoamyl acetate, ethyl hexanoate, ethyl octanoate, linalool, as well as octanoic and hexenoic acids (Table 1). The authors highlighted significant differences in the volatile profile between the three grape varieties—Moscato Embrapa, Villenave, and Niagara—and the Goethe and Manzoni Bianco varieties. A possible explanation for this distinction is that the latter two share a greater genetic similarity with *V. vinifera*, whereas the first three varieties belong to *V. labrusca* [21].

Given that in hot and dry regions such as the Mediterranean, harvesting at optimum ripeness of grapes can be connected with insufficient acidity for sparkling wine production, the use of non-conventional varieties such as Maresco and Grillo can represent an effective alternative for obtaining optimal acidity levels. Maresco, a lesser-known variety cultivated in Italy's Apulia region, not only exhibits high acidity but also contributes distinct aromatic characteristics. Its profile includes floral (attributed to linalool and phenyl acetate), fruity notes and fatty nuances (due to important levels of isoamyl acetate, ethyl hexanoate, ethyl octanoate and ethyl decanoate) [20].

In Spain, Pérez-Magariño et al. [25] analyzed eight types of sparkling wine made from different autochthonous grape varieties (Verdejo, Viura, Malvasia, Albarín, Godello, Prieto Picudo and Garnacha) using the Champenoise method. The impact of lees maturation was assessed at three intervals: 3, 6 and 9 months. The results showed that the wines with the highest concentrations of volatile compounds, such as esters and acetate alcohols (responsible for fruity aromas) were those made from Albarín, Verdejo, Godello and Prieto Picudo. During lees maturation, an increase was observed in the levels of ethyl esters, ethyl lactate, and γ-butyrolactone, alongside a decrease in citronellol and geraniol. Additionally, Albarín and Prieto Picudo exhibited the highest total biogenic amine concentrations during lees maturation. The sensory panel expressed the greatest interest in wines made from Albarín, Verdejo, Godello and Prieto Picudo, with Albarín and Godello displaying significantly higher olfactory intensity compared to Malvasia and Viura wines. These grape varieties were all described as having fruity aromas, especially citrus and exotic fruit notes.

Doncieux et al. [26] studied the Voltis variety, a new climate-adaptive and mildew-resistant hybrid grape introduced in the Champagne region of France. With strict regulations limiting its cultivation to Champagne and ongoing exploration of its potential, this variety remains in the early stages of development. Once the first batches of Champagne are produced, Voltis will undergo evaluation by the European Union (EU) after a 10-year period. In response to the EU's initiative to reduce pesticide usage in vineyards, one proposed solution has been the development of fungus-resistant grape varieties [27].

In China, a new red grape variety named Meili was developed from *V. vinifera* species. This variety exhibits high resistance to cold temperatures and diseases such as *Plasmopara viticola* and *Sphaceloma ampelinum* [28]. In a study conducted by Song et al. [29], sparkling wine was produced from Meili grapes using a variation of the Charmat–Martinotti method, in which the second fermentation was carried out in the same tank, similar to the Asti method. The samples were bottled once fermentation reduced the sugar content to below 4 g/L and were then stored at 4 °C for five months. Compounds such as isoamyl acetate, 2-phenylethanol, and ethyl acetate were predominant in the analyzed samples. The sparkling wines obtained from Meili grapes were distinguished by intense notes of pineapple, apple and roses.

Table 1. Overview of non-conventional grape varieties for sparkling wine production.

Geographical Region	Grape Variety	Genetic Origin	Oenological Characteristics Compared to Classical Varies	Sensory Characteristics	References
Brazil	Moscato Embrapa	Couderc 13 × July Muscat (Brazil)	✓ higher protein content ✓ higher values of trans-resveratrol ✓ highest concentrations of isoamyl acetate, ethyl hexanoate, ethyl octanoate	Intense Muscat and fruity notes (banana, green apple, pineapple)	[21,30]
	Villenave	*V. labrusca* × Riesling renano (France)	✓ higher concentrations of isoamyl acetate, ethyl hexanoate, ethyl octanoate	Optimum acidity, floral and fruity notes	
	Niagara	*V. vinifera* × *V. labrusca* from Santa Catarina State (USA)	✓ higher protein content ✓ lower values of epicatechin ✓ *trans*-resveratrol was not detected ✓ higher concentrations of isoamyl acetate, ethyl hexanoate and 2-phenyl ethanol	Fruity notes (green apple)	
	Goethe	Carter × Black Hamburg (USA)	✓ higher value for color intensity ✓ higher levels of tyrosol	High yield, fruity aroma	
	Syrah	Dureza × Mondeuse Blanche	✓ great amounts of benzaldehyde, butyric acid, and some acetates	Fruity notes	[19,20]
	Chenin blanc	Sauvignon blanc × Trousseau	✓ important levels of 2,3-butanediol, 3-ethoxypropan-1-ol, diethyl succinate, and ethyl decanoate	Fruity aroma	[20]
Italy	Maresco	-	✓ high acidity ✓ important content of linalool, phenyl acetate, isoamyl acetate, ethyl etanoate, ethyl decanoate, octanoic acid	Floral, fruity and fatty notes	[20]
	Grillo	Catarratto Bianco Comune × Muscat d'Alexandrie	✓ high acidity ✓ high amounts of organic acids	Herbaceous and vegetal, floral, and exotic fruit notes	[20,30]
Spain	Albarín	-	✓ rich amounts of fatty acids, ethyl esters and alcohol acetates ✓ higher content of biogenic amines	Citrus, exotic fruits High aroma intensity	[25]
	Prieto Picudo	? × Savagnin blanc		Fruity, intense odors	[26]
France	Voltis	Villaris × VRH3159-2-12	-	-	[28]
China	Meili	Merlot × Riesling × Muscat	✓ higher concentrations of esters, fatty acids and shikimic acid derivatives	Pineapple, apple, roses	[29]

3.2. Technological and Composition-Related Advances

3.2.1. Sustainability and Production Optimization

An overview of the key topics most frequently studied is presented in Table 2. Initially, winemakers focused on optimizing sparkling wine production by reducing time and costs. Over time, attention was directed towards environmental issues and ensuring sustainability [31]. To ensure quality, base wine fermentation is typically conducted at low temperatures, requiring significant energy to cool the grape at the start and throughout the process. Giovenzana et al. [32] investigated the impact of selected *Saccharomyces cerevisiae* strains at higher-than-standard fermentation temperatures. The results obtained showed that the inoculation of this yeast in the production of the base wine from the Franciacorta variety had positive effects on energy saving without affecting the physicochemical and sensory characteristics.

Table 2. Key aspects of sparkling wine production.

Technological Phase	Main Focus	References
Production optimization	Reducing costs and time; focus on sustainability	[31]
Primary fermentation at higher temperatures	Energy savings without negative effects on quality	[32]
Pressing and maceration	Influence of different pressing forces on potassium levels, acidity, polyphenols and antioxidants	[23,33,34]
	Increased phenolic content when pressing with nitrogen flow is used	[34]
Yeast selection	Use of immobilized yeast, co-inoculation and their influence on volatile fraction and sensory profile	[2,35–37]
Secondary fermentation	Differences in physicochemical and volatile parameters depending on inoculation method	[38]
Aging on lees	Yeast autolysis and its effects on wine composition and quality	[39–42]
	Ultrasound utilization, enzymes activity and microwaves application to accelerate the autolysis process	[43–45]
Storage conditions	Changes in chromatic and sensory features	[46]

Several studies have explored grape pressing and maceration techniques in sparkling wine production [23,33,47,48]. The maceration phase is particularly important for enhancing phenol extraction and increasing the yield of free-run must, leading to a less turbid must [47]. According to Dumas et al. [48], the acidity of the must was influenced by the pressing method, as different mechanical forces resulted in varying levels of potassium extraction. Heavier pressing methods produced must with higher polyphenol content, greater radical scavenging power, increased browning index, and higher levels of glutathione [23]. Additionally, Boselli et al. [34] found that pressing under a nitrogen flow resulted in a 20% increase in phenolic compounds.

Further research is necessary to investigate energy savings under various conditions (diverse grape varieties, white and red vinification, different oenological equipment and environmental temperatures), to determine how applicable this result is to other winemaking contexts.

3.2.2. Yeast Selection and Inoculum

Over time, great importance has been given to the selection of yeast for improving sparkling wine quality. The majority of existing studies have focused on enriching the aroma profile of sparkling wines under the influence of different yeast combinations. Peinado et al. [49] investigated the co-immobilization of *S. cerevisiae* and the filamentous fungus *Penicillium chrysogenum* in biocapsules. During fermentation, the fungus perished, serving as an inert support for yeast, which retained most of its catalytic activity. These biocapsules have been tested in various fermentation processes, including sweet wine, bioethanol and sparkling wine production [35]. Additionally, yeast flocculation can be considered a natural form of yeast immobilization [50]. This characteristic is particularly desirable in yeast used for traditional sparkling wine production, leading to its consideration as a key technological characteristic for starter culture selection [36].

A study conducted by Cotea et al. [2] analyzed the volatile profile of sparkling wine made from Muscat Ottonel using different commercial yeast strains. Utilizing the Champenoise method, they first created a base wine with 10.5% vol. alc. (after reducing the initial alcohol content from 12.5 to 10.5% vol. alc. through reverse osmosis). The *liqueur de tirage* was performed with 24 g/L sugar and four different commercial yeast strains (IOC FIZZ™, IOC DIVINE™, LEVULIA CRISTAL™ and IOC 18-2007™). The resulting sparkling wines were aged on lees for fifteen months at 12 °C. The sparkling wines obtained using LEVULIA CRISTAL™ and IOC 18-2007™ yeast strains exhibited lower volatile acidity and total SO_2 levels, with a reduced elderflower aroma and a slightly diminished fruity profile compared to the other samples. Conversely, the sparkling wines produced with IOC FIZZ™ and IOC DIVINE™ had a more pronounced elderflower aroma, as well as enhanced yeasty and fruity notes. Among the four samples, the sparkling wine obtained from IOC FIZZ™ stood out in both sensory and chemical analyses, showing the highest concentration of aroma compounds and overall balance.

Berbegal et al. [38] obtained no significant influence of IOC 18-2007™ on the second fermentation kinetics of Macabeo white base wine. For inoculum preparation, authors compared the GPY medium (glucose, peptone, yeast extract) and the traditional *pied de cuve* method (inoculum was combined with the *tirage liqueur* and introduced into bottles where the second fermentation occurred following the Champenoise method). After nine months of aging, the sparkling wines exhibited notable differences in physicochemical parameters, particularly total acidity, foamability, foam persistence, and total polysaccharide content in samples inoculated with yeast grown in a GPY medium. Regarding volatile compounds, sparkling wines inoculated with GPY-cultured yeast showed higher concentrations of esters, alcohols and fatty acids. Even if no significant statistical differences were observed in the sensory profile (visual and aromatic attributes), wines fermented with *pied de cuve* yeast received higher aromatic notes than those inoculated with GPY-grown yeast.

In another study, Verdejo sparkling wines from two consecutive vintages were produced using the Champenoise method [51]. The use of immobilized yeast had no impact on the main enological parameters or the effervescence of the sparkling wines. The data indicate that immobilized cells led to differences in only a few analytical aspects. Wines fermented with immobilized yeast exhibited higher free amino nitrogen levels but lower concentrations of neutral polysaccharides and total proteins. The volatile composition of both wine types was largely similar, except for variations in isobutyric acid and benzyl alcohol content. Sensory evaluation revealed no major differences in organoleptic characteristics, with consumers noting disparities only in color acceptability, while judges detected differences in dough-like notes.

Several authors analyzed the impact of non-*Saccharomyces* yeast on the production of sparkling wines. Comitini et al. [37] have evaluated the influence of several non-*Saccharomyces* strains, such as *Torulaspora delbrueckii*, *Metchnikowia pulcherrima*, and *Pichia kluyveri*, either individually or in co-inoculation with *S. cerevisiae*. Aroma compound analysis revealed that *T. delbrueckii*, in combination with *S. cerevisiae*, led to higher concentrations of total alcohols, total lactones, 3-methyl-1-butanol, 2-methylpropanol, 1-butanol, and 2-phenylethyl acetate, while producing lower levels of β-phenylethanol, 1-hexanol, ethyl lactate, ethyl decanoate and ethyl octanoate. This combination was primarily used for base wine production. Similarly, *M. pulcherrima* co-inoculated with *S. cerevisiae* resulted in increased levels of total higher alcohols, total major and minor esters, total lactones, 3-methyl-1-butanol, 2-methylpropanol, diethyl succinate, 2-phenylethanol, ethyl acetate, ethyl isovalerate and methyl vanillate, while showing lower concentrations of methionol, acetaldehyde, ethyl lactate, ethyl decanoate, ethyl octanoate, butyl acetate and linalool acetate. This combination was also utilized in base wine production [52]. For the second fermentation in bottles and a maturation period of four months on the lees, *Saccharomycodes ludwigii* and *Schizosaccharomyces pombe* exhibited higher production of diacetyl, acetoin, 2-methyl-1-butanol and ethyl acetate, while producing lower quantities of acetaldehyde, 2,3-butanediol and isoamyl acetate [39].

According to Ivit et al. [39], *S. ludwigii* presented a high tolerance to SO_2 and produced up to 12% vol. alc. The authors highlighted the high potential of *S. ludwigii* for applications in sparkling and still wine production due to its ability to produce high amounts of glycerol, isoamyl acetate, 2-phenylethanol, polysaccharides and β-glucosidase. *S. pombe* was associated with undesirable sensory characteristics in wine, as it can increase volatile acidity, acetaldehyde, acetoin, and ethyl acetate levels. However, it also possesses interesting metabolic properties, including malic acid dehydrogenation, high autolytic polysaccharide release [53], reduction in gluconic acid [54] and increased production of pyruvic acid while reducing biogenic amine and ethyl carbamate formation [55]. In accordance with Ivit et al. [39], *S. ludwigii* exhibited lower acetaldehyde production than *S. pombe* and *S. cerevisiae* in both white and red sparkling wines. In accordance with González-Royo et al. [52], *M. pulcherrima* produces high amounts of β-glucosidase and contributes to the decrease in wine volatile acidity when used with *S. cerevisiae*. Gobert et al. [56] presented a minor difference between the concentrations of the main volatile compounds when both *S. ludwigii* and *S. pombe* were inoculated, compared to *S. cerevisiae*. The authors postulated that the possible differences presented in many studies could be a result of the nitrogen preferences of yeast.

Velázquez et al. [57] postulated that the sequential inoculation of *T. delbrueckii* and *S. cerevisiae* contributes to the increasing of sparkling wines' protein content and improves their foaming properties. The authors observed increased levels of volatile compounds (ethyl propanoate, isobutyric and butanoic acids, different alcohols and phenols). Their findings suggest that *T. delbrueckii* should be inoculated alone only under strictly controlled conditions (increased pressure and high alcohol level). The samples obtained with this yeast mixture were characterized by increased levels of residual sugars, low CO_2 formation and reduced bottle pressure. Additionally, *Zygosaccharomyces* species tend to overproduce acetic acid in sparkling wines.

Tofalo et al. [58] studied the impact of *S. cerevisae*, *T. delbrueckii*, *Starmerella bacillaris*, *S. cerevisiae* with *S. bacillaris* and *T. delbrueckii* with *S. cerevisiae* on the quality of sparkling wines obtained from Trebbiano and Pecorino grapes from Ortona-Italy. After the second fermentation, the aging on the lees phase lasted 9 months. According to the presented data, the use of mixed non-*Saccharomyces* and *S. cerevisiae* starter cultures for the Champenoise method of sparkling wine production yields promising results. Non-*Saccharomyces* yeast (especially *S. bacillaris*) contributed to the production of sparkling wines with distinctive sensory features. Although *S. bacillaris* did not complete the secondary fermentation when inoculated as a pure culture, its co-inoculation with *S. cerevisiae* enhanced its autolytic potential, which played a pivotal role in defining the sensory profile of the sparkling wines. These results highlight that selecting yeast strains with different autolytic potentials represents a valuable strategy for improving the autolysis process during the aging phase and modulating the sparkling wines' sensory profile. *S. bacillaris* has been described as a high consumer of fructose, psychrotolerant and osmotolerant yeast by Englezos et al. [59]. *S. bacillaris* has also been utilized as a co-starter together with *S. cerevisiae* by Nisiotou et al. [60] because of its tendency to consume the fructose providing the glucose to *S. cerevisae* during the middle and final stages of the fermentation process.

Cravero et al. [14] studied sparkling wine made from Chardonnay (Chile) aged with yeast derivatives. In their research, they used two commercial inactivated dry yeasts from *S. cerevisiae* and three experimental yeast derivatives for secondary fermentation: yeast autolysate, yeast protein extract, and inactivated dry yeast from *T. delbrueckii*. Their findings revealed that, over relatively short aging periods of 9–18 months, the inactivated dry yeast from *T. delbrueckii* proved to be the most effective yeast-derived product. After 9 months of aging, it helped preserve the fruity characteristics of the Chardonnay sparkling wine. However, after 18 months on yeast, there was a decrease in protein content, although the samples exhibited the highest potential for polysaccharide enrichment and notable antioxidant activity. This suggests that prolonged aging on yeast could be possible without causing browning in the final product. The commercial derivatives showed variations mainly based on aging time. The protein extract led to an increase in bubble size and an effervescence that tasters found fruitier on the nose. In contrast, yeast autolysate was perceived to have more intense bakery notes such as toast.

Despite their potential to enhance complexity in sparkling wines, non-*Saccharomyces* yeasts face significant practical and regulatory challenges. Although strains like *T. delbrueckii*, *M. pulcherrima* and *L. thermotolerans* can enhance aromatic complexity and mouthfeel, their effects remain inconsistent due to variability in fermentation conditions, strain selection and interactions with *S. cerevisiae*. Furthermore, managing fermentation becomes more difficult due to their reduced ethanol tolerance, which frequently necessitates co-inoculation to guarantee total sugar depletion [58].

3.2.3. Aging on Lees and Storage

Tudela et al. [61] investigated the ultra-structural changes in yeast during prolonged aging of sparkling wine. The wine was analyzed at different moments, using a starter yeast sample as a reference. Yeast isolation was performed using centrifugation and cryo-immobilization onto plates. After nine months, most yeast cells exhibited plasmolysis, with the cytoplasmic membrane completely detached from the cell wall. Analysis of yeast at thirty and forty-eight months revealed that the cell wall consisted of a two-layer structure: an amorphous inner layer and a fibrous outer layer. Autolysis led to extensive intracellular disorganization and even some loss of cellular components during the process. Cytoplasmic degradation was observed at nine months, with the nucleus and mitochondria still present in some cells even at forty-eight months. The study concluded that cytoplasmic degradation continued throughout the aging process, even after 48 months in bottles.

Benucci et al. [46] studied the impact of storage conditions on the color and sensory profile of rosé sparkling wines over nine months after disgorging. Samples stored at 30 °C in the dark showed increased color intensity (16%) and burnt notes, while those exposed to UV at 5 °C experienced significant discoloration (over 20%) and unpleasant aromas (like wet wool). Wines stored at 5 °C in the dark had the least changes, suggesting that low temperatures and the absence of light help maintain wine stability.

The aging of sparkling wine involves the contact between the newly formed wine (after the second fermentation) and yeast deposit. This process typically begins 2–4 months after fermentation [40]. The autolysis of the lees is characterized by the release of intracellular yeast contents (e.g., amino acids, peptides, fatty acids and polysaccharides [41,62]. The autolysis process is influenced by physical factors such as temperature, pH, alcohol content and yeast strain [63], making it a complex process [64]. To achieve the desired results, yeast-derived products have been introduced to facilitate and optimize this process [41]. Recent studies have explored various methods for enhancing the aging process and improving the quality of sparkling wines. Gnoinski et al. [43] investigated the effects of autolysis manipulation through three treatments: microwave, ultrasound, and enzyme preparation. Using Chardonnay and Pinot Noir grapes from Tasmania, the study demonstrated that these treatments effectively disrupted yeast cell structures, increasing cell permeability and facilitating faster transfer of compounds to the wine. While the β-glucanase treatment was slower to show results, both microwave and ultrasound treatments were more efficient in accelerating yeast autolysis and compound release. Ultrasound has also been studied for its impact on lees aging in sparkling wines. The results published by Pons-Mercadé et al. [65] showed that the concentration of polysaccharides and protein compounds in sparkling wines obtained by the Champenoise method for nine consecutive harvests was not significantly influenced by the duration of aging in contact with yeast. These data contradict the conclusions of other previous studies, the explanation being that these macromolecules are simultaneously released from yeast and removed by precipitation, absorption and/or enzymatic degradation.

In a separate study, Lasanta et al. [44] focused on the use of ultrasound-treated lees in red sparkling wine made from Tempranillo grapes. The ultrasound treatment at 90% amplitude significantly enhanced the wine's profile, enriching it with polysaccharides, esters, terpenes and certain acids, contributing to floral and fruity sensory characteristics. These findings suggest the potential for using yeast from the first fermentation to improve the aging process of sparkling wine after the second fermentation. Additionally, La Gatta et al. [45] experimented with this approach for aging on lees, further supporting its viability in sparkling wine production.

A study by Focea et al. [42] demonstrated a significant change in the metal and organic acid content of Muscat Ottonel sparkling wine over the aging period. The results showed that the levels of potassium and calcium increased during the first six months before slightly decreasing over time. Magnesium and sodium decreased during the second fermentation, while manganese, zinc, iron and nickel increased during the first six months of aging. Iron levels continued to rise at eleven months of aging. In a separate study, Charnock et al. [66] found significant differences in metal content in sparkling wine from a single vineyard in Canada, comparing wines made using the Champenoise and Charmat–Martinotti methods. The Charmat–Martinotti procedure resulted in higher levels of boron, chromium, nickel and strontium, with boron being present in all sparkling wine samples tested. Another approach to the second fermentation involves trapping yeast in a permeable membrane, allowing the transfer of substances [67]. By immobilizing yeast in biocapsules, production costs can be reduced by up to 80%. De Lerma Nieves et al. [68] studied the effects of prolonged maturation of yeast in sparkling wines made with calcium alginate over a period of thirty-two months using yeast immobilization and bio-immobilization techniques. The results showed that these techniques can lead to higher levels of volatile compounds, resulting in a more complex aroma profile. The use of alginate also contributed to a higher concentration of ions in the final product. This ion concentration may facilitate the formation of insoluble tartaric salts, which can negatively affect the foaming properties of sparkling wine and cause visual issues because of the presence of tartaric salts [68].

3.3. Nutritional-Related Effects of Wine Components

It is well known that wine plays an important role in creating human relationships, socializing, and helping to relax. In general, consumers' worries regarding the impact of wine consumption on the body concern the sugar, alcohol and SO_2 content in wine. Consumer opinion may differ in different countries due to differences in cultural and social backgrounds. According to Peršurić et al. [69], Croatian consumers clearly recognized the health benefits of moderate wine consumption and perceived them as important. In recent years, studies have explored the potential health benefits of moderate wine consumption (the focus being on the still wines), suggesting it may help prevent cardiovascular diseases and cancer (French paradox) and reduce mortality associated with these conditions worldwide [70,71]. These effects are largely attributed to polyphenols and their antioxidant properties [72]. In this context, Rodriguez-Nogales et al. [73] reported that the use of β-glucanases in sparkling wine production enhanced its antioxidant activity. Vauzour et al. [71] suggest that daily moderate consumption of Champagne wine may improve vascular performance and working memory in animals due to high polyphenol content. Moreover, wines' bioactive compounds manifest important benefits on oral and intestinal microbiomes, as well as for neurodegenerative disorders (like Alzheimer's) [74,75] and atherosclerosis [76].

Due to the allergenic action of the use of SO_2 in winemaking, Giovenzana et al. [32] conducted a study on the reduction in sulfite content in base wine. The results did not provide a concrete alternative for efficient substitution of SO_2. Similar results were also shown by Fracassetti et al. [77]. Further studies are needed to explore effective alternatives for reducing SO_2 content in wine while maintaining quality, as well as to better understand the long-term health inferences of moderate still and sparkling wine consumption.

3.4. Market Trends

The sparkling wine market has expanded significantly over the past two decades, reaching 20 million hL in 2018 (almost a 60% increase since the beginning of the 21st century). The EU remains the main producer, accounting for 70–80% of global output, with Italy and France leading production. While traditionally concentrated in a few countries, emerging producers such as the UK, Portugal, Brazil and Australia have experienced notable growth in recent years. From Figure 5, it can be observed that after 2014, imports showed a significant reduction but remained at higher levels compared to the early 2000s. A secondary increase is observed around 2018–2020, followed by a gradual decrease. In general, imports are dominated by sparkling wines of fresh grapes (excluding varietal wines), especially during the 2010–2014 period. This suggests a flow in demand for general sparkling wines that do not fall under specific PDO (Protected Designation of Origin) or PGI (Protected Geographical Indication) categories. In 2023, EU production declined by approximately 8%, with Italy, France and Germany as the top producers. PDO wines (Champagne, Cava, Asti and Prosecco) maintain a constant but smaller segment, while general sparkling wine imports drive market trends. The increase in 2018–2020 could be linked to market recovery, marketing strategies or special events [78,79].

Figure 6 illustrates the evolution of sparkling wine exports from the EU in the 21st century. During this time, the EU has seen a strong expansion in sparkling wine exports, driven primarily by Prosecco, followed by Champagne and Cava. It is emphasized that the demand for varietal and non-PDO sparkling wines is increasing, reflecting changing consumer preferences worldwide [78,79].

Since the early 2000s, global sparkling wine consumption has steadily increased, except for a decline in 2009–2010 due to the economic crisis. From 2002 to 2018, demand grew at an average annual rate of 3%, reaching 19 mil. hL in 2018 and expanding its share of total wine consumption from 5 to 8%. Key factors driving this growth include the deseasonalization of consumption (moving beyond holiday celebrations) and a wider price range, making sparkling wine more accessible. Consumption is now more frequent, including as an aperitif or cocktail ingredient. Meanwhile, the share of the six largest consuming countries fell from 76% in 2008 to 70% in 2018, as emerging markets contributed to an increase of 1.7 mil. hL in consumption [78,79].

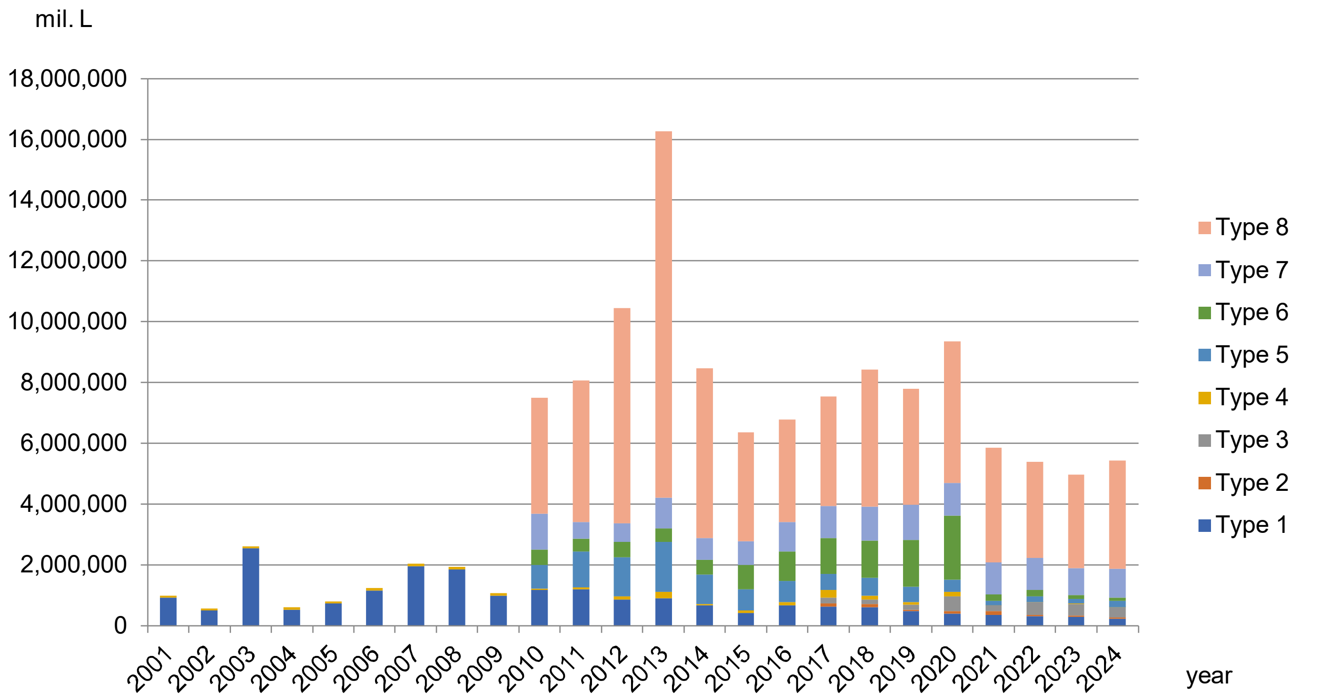

Figure 5. Sparkling wine imports in EU during the 21st century. Type 1-Champagne (with PDO); Type 2-Cava (with PDO); Type 3-Prosecco (with PDO); Type 4-Asti (with PDO); Type 5-Sparkling wine of fresh grapes with PDO (excluded Asti, Champagne, Cava, Prosecco); Type 6-Sparkling wine of fresh grapes with a PGI; Type 7-Varietal sparkling wines of fresh grapes without PDO and PGI; Type 8-Sparkling wine of fresh grapes (excluded varietal wines) [79].

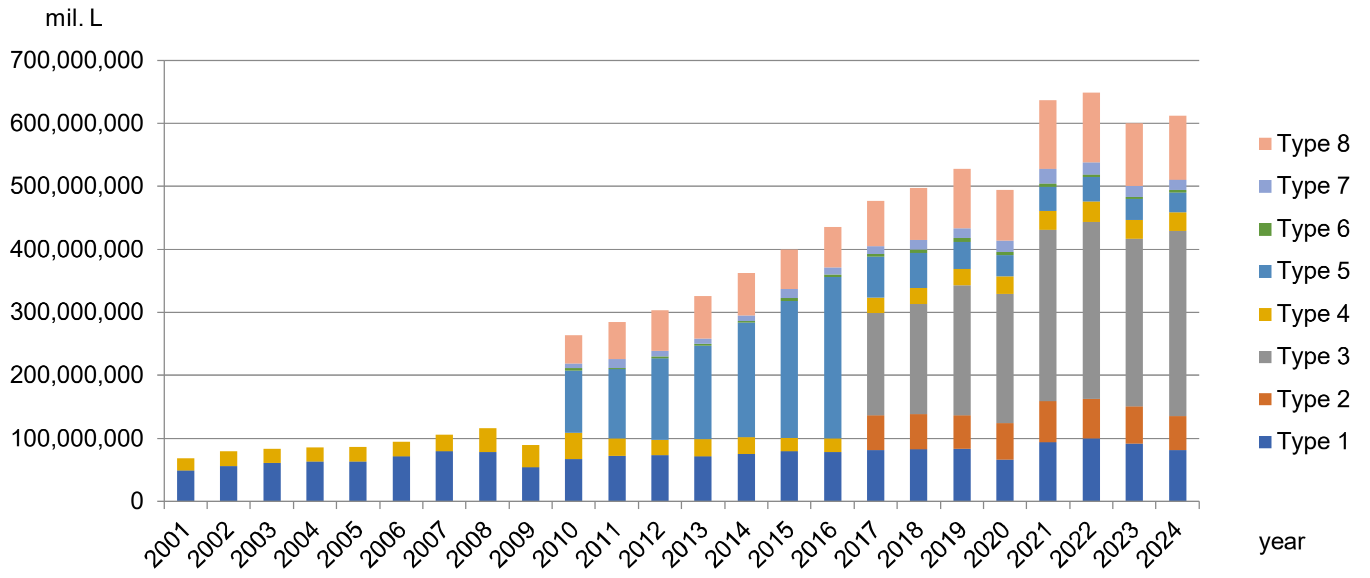

Figure 6. Sparkling wine exports from the EU during the 21st century. Type 1-Champagne (with protected designation of origin-PDO); Type 2-Cava (with PDO); Type 3-Prosecco (with PDO); Type 4-Asti (with PDO); Type 5-Sparkling wine of fresh grapes with PDO (excluded Asti, Champagne, Cava, Prosecco); Type 6-Sparkling wine of fresh grapes with a protected geographical indication (PGI); Type 7-Varietal sparkling wines of fresh grapes without PDO and PGI; Type 8-Sparkling wine of fresh grapes (excluded varietal wines) [79].

4. Future Perspective and Conclusions

Given its high market value, ongoing research aims to refine production techniques and better understand the mechanisms that contribute to its distinct characteristics. Achieving optimal quality remains a challenge for winemakers, as it depends on multiple factors, including yeast selection, grape variety and processing methods. The use of non-conventional grape varieties presents opportunities for innovation, offering unique aromatic profiles while maintaining physicochemical properties comparable to traditional cultivars. At the same time, evolving consumer preferences are shaping the industry [80]. A crucial aspect of both sparkling and still wine production is the aroma profile. Research into the formation of Maillard reaction-associated compounds in sparkling wine could provide insights into enhancing aroma complexity, particularly in Champenoise method sparkling wines [45].

The fruit wine market is increasingly shifting towards assortment diversification through innovative formulations, advanced technologies and alternative raw materials. In this context, fruits like tangerine, koji [81,82], plum and apple [83] have been proposed as promising alternatives for still and sparkling wine production.

One of the most significant trends is the increasing demand for lower-alcohol wines (9–13% vol. alc.), driven by health consciousness and social factors such as stricter traffic regulations [84,85]. However, climate change has led to higher sugar accumulation in grapes, resulting in increased alcohol levels in wines. To counteract this, several strategies have been explored, including the use of musts with lower sugar content, selective yeast strains and controlled fermentation stoppage to limit ethanol production. Additionally, advanced technological approaches, such as thermal and membrane-based processes, have been investigated to adjust alcohol concentration. While thermal treatments can negatively impact volatile compounds [86], membrane-based methods like nanofiltration and reverse osmosis offer more effective solutions by reducing alcohol content while preserving sensory attributes [87]. Reverse osmosis has been successfully applied in sparkling wine production, lowering alcohol levels while maintaining key physicochemical properties [2,88]. Furthermore, changes in vineyard management (such as modifying harvest date) have been introduced to mitigate excessive sugar accumulation in grapes. These combined approaches highlight how the industry is adapting to both evolving consumer preferences and the challenges posed by climate change. Reducing the sugar content of the must through early harvesting and partially dealcoholizing wines has proven effective in obtaining wines with reduced alcoholic strength. However, production costs and efficiency remain critical concerns for the sparkling wine industry [13]. Advances in fermentation, aging techniques and alternative processing methods aim to optimize both time and resources without compromising quality. As the market continues to evolve, the adaptability of sparkling wine (whether in terms of alcohol content decrease, SO_2 reduction, production methods or assortment diversity) ensures its continued relevance in an increasingly health-conscious and dynamic consumer background.

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