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The resilient Merlot: from global growth to sustainable viticulture and winemaking in the age of climate change

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Merlot, a grape variety with a rich history and significant genetic diversity, has become one of the most influential cultivars in the global wine industry. Its adaptability to diverse climates has enabled extensive cultivation in major wine-producing regions, including France, Italy, the United States, Australia, and Chile. This adaptability, combined with its ability to produce consistently high-quality wines, underlines the importance of reviewing and understanding its future potential. Merlot originates from a cross between Cabernet Franc and Magdeleine Noire des Charentes, have endowed it with a unique versatility and resilience. These traits have not only facilitated its widespread cultivation but also made it a key player in the face of global viticultural challenges, particularly those posed by climate change. Merlot's early ripening nature and resistance to certain diseases make it an essential cultivar for regions facing increasingly unpredictable weather patterns. In this context, this review aims to highlight the importance of this grape variety by detailing the factors that contribute to its aromatic complexity and sensory appeal, which make Merlot wines are highly appreciated by both consumers and experts due to its balanced aromatic profile. As the wine industry grapples with the effects of climate change and shifting consumer preferences, understanding Merlot's strengths and potential becomes even more critical. By integrating genetic, agronomic and oenological perspectives, this work emphasizes Merlot's current significance and highlights its strategic importance for the future of global viticulture.

KEYWORDS

Merlot, wine, winemaking, fermentation, climate change, polyphenols, volatile compounds, bioprotection

Introduction

Merlot, a red wine grape cultivar with a well-documented history rooted in ancient varieties, has evolved over time to become one of the most prominent and widely cultivated grape varieties in the global wine industry. The name “Merlot” first appeared in literature at the end of the 18th century (Viala and Vermorel, 1902–1910). Its name is believed to originate from the French word “Merle,” referring to the species *Turdus merula* L. (the common blackbird), both due to the dark colour of the grapes, which resembles the bird's plumage, and because these birds are known to enjoy its early-ripening berries (Rézeau, 1997). Due to its widespread cultivation across ethnographically and linguistically diverse regions, Merlot has historically been known by various names, such as “Medoc Noir.” In France, where the grape reaches its fullest expression, it is also recognized as “Merlau,” “Crabutet Noir” in Switzerland

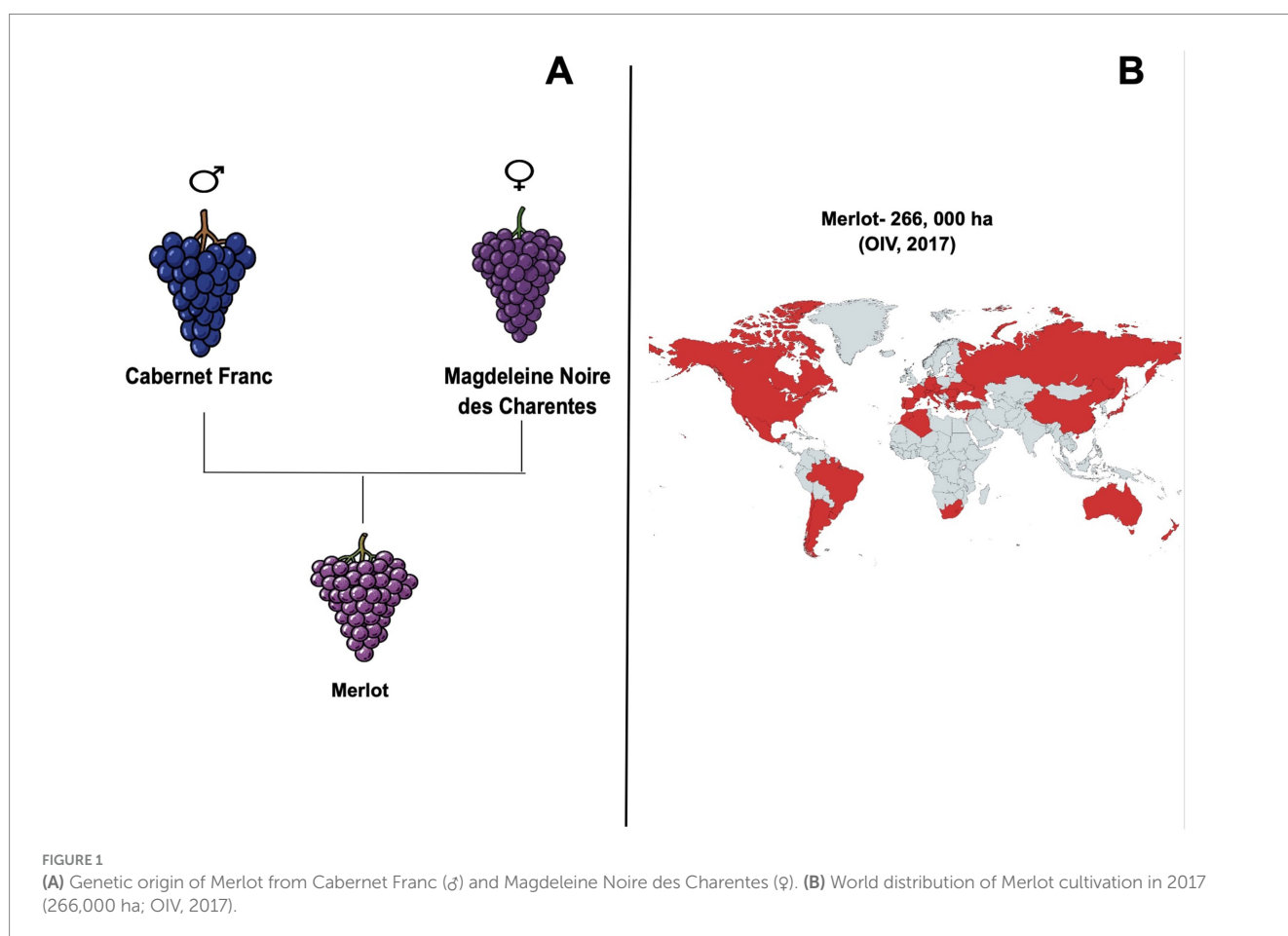
and “Bordeaux” (Bouchereau, 1843; Hardy, 1844; Artozoul et al., 1960; Rézeau, 1997; Galet, 2002; Bettiga, 2003).

By the mid-19th century, Merlot was thoroughly described at the ampelographic level by different authors (Odart, 1845; Rendu, 1857), further solidifying its place in viticultural history. Initial DNA analysis revealed significant genetic similarities between Merlot and other grape varieties such as Cabernet Franc and Carmenere (Clarke and Rand, 2010). Subsequent genetic studies have demonstrated that Merlot is indeed the result of a cross between Cabernet Franc, used as the father, and Magdeleine Noire des Charentes, which served as the mother variety (Boursiquot et al., 2009). More recently, a high-quality phased genome assembly has confirmed this parentage by using both parental genomes as references thereby resolving the previous uncertainties about the maternal lineage (Sichel et al., 2023) (Figure 1A). This diversity is particularly evident in traits such as berry size and the capacity for sugar accumulation during ripening (Lacombe et al., 2012; Sivcev et al., 2018). The international expansion of Merlot began in the mid-19th century and gained significant momentum in the late 20th century. This diffusion was initially driven by its low susceptibility to powdery mildew and its ability to produce high-quality wines. These qualities, combined with its adaptability to diverse climates, led to Merlot being cultivated extensively around the world, with significant plantings in countries such as Italy, the United States, Australia, and Chile (OIV, 2017). Notably, by 2006, Merlot became the most extensively planted black wine grape in France, covering 117,354 hectares (de la Vigne et du Vin, 2007). As an

early-ripening variety of dark blue wine grapes, Merlot is highly valued for its softness and fleshy texture, qualities that make it an excellent blending partner, particularly with later-ripening varieties like Cabernet Sauvignon, which is rich in tannins (Robinson et al., 2012).

Beyond Europe, Merlot’s significance has been recognized globally, becoming the fourth most widely planted grape variety in the world by 2017, with 266,000 hectares under cultivation, representing approximately 3% of the total global vineyard area (OIV, 2017) (Figure 1B). This international spread has been further facilitated by clonal selection, which has improved both the quantitative and qualitative traits of Merlot, making it a versatile and highly regarded variety in a range of climatic conditions (Boursiquot et al., 2009). Given the importance and multifaceted nature of this grape variety, reviewing the existing literature on Merlot provides valuable insights into its broader impact on global viticulture, making it possible to understand how this grape, with its deep historical roots, has achieved its status as one of the most widely planted varieties in the world. In this sense, this review helps to contextualize Merlot’s significance within the broader landscape of viticulture, providing a foundation for future studies and ensuring that this versatile grape variety continues to play a central role in the wine industry.

Merlot must are typically characterized by high sugar concentration and low acidity, which often results in wines with elevated ethanol levels and reduced freshness (Boursiquot et al., 2009; Hranilovic et al., 2021). This combination of traits presents both



opportunities and challenges for winemakers, who must carefully manage these factors to produce balanced, high-quality wines. One of its most famous expressions is Pétrus, the renowned estate in the Pomerol region, which produces wines primarily from Merlot, highlighting the variety's significance in high-end wine production (Robinson, 1986; Clarke and Rand, 2010). The quality and character of Merlot wines are shaped by a complex interplay of factors, making it essential to understand the elements that contribute to its unique appeal. The aromas of Merlot, ranging from fruity and floral to earthy and herbaceous, are influenced by various. Additionally, the phenolic content of the grapes, responsible for the wine's colour and structure, is affected by environmental conditions and vineyard management practices. Lastly, the fermentation process, particularly the role of yeast, significantly impacts the wine's flavour, texture, and overall complexity.

This review aims to synthesize current knowledge on Merlot's genetic background, viticultural adaptability, and oenological characteristics, with particular attention to its aromatic complexity and potential role in sustainable viticulture under climate change.

Main

The aromatic complexity of Merlot: understanding the role of volatile compounds

In the world of wine, Merlot stands out for its smooth texture and versatile flavor profile—qualities that set it apart from more tannic varieties like Cabernet Sauvignon. Its approachable, fruit-forward profile, with plush tannins and a rounded mouthfeel, contributes to its widespread popularity, appealing to both novice and experienced wine drinkers alike.

Merlot's aromatic complexity derives from different families of volatile compounds. The main groups include esters, lactones, terpenes, methoxypyrazines, norisoprenoids and higher alcohol acetates which collectively shape the distinctive bouquet of Merlot wines (Arcari et al., 2017; Allamy et al., 2018; Pons et al., 2018; Carrasco-Quiroz, 2020; Cincotta et al., 2021). Sensory descriptors frequently reported include cooked fruits such as prune, peach, and fig, as well as herbaceous notes like ivy and geranium (Pons et al., 2018).

Esters are generally one of the most abundant classes in Merlot wines and (García-Carpintero et al., 2011; Welke et al., 2012; Pereira et al., 2014; Carrasco-Quiroz, 2020; Cincotta et al., 2021). Welke et al. (2012) identified isoamyl acetate, ethyl lactate, 2-hexen-1-ol, and 3-octenol in Brazilian wines. Later, Arcari et al. (2017) identified 95 volatile compounds in Merlot samples, including those previously reported by Welke et al. (2012). *Fare clic o toccare qui per immettere*. Ethyl hexanoate, ethyl octanoate, and ethyl decanoate were detected in high concentrations. Their concentrations were also reported to increase under leaf removal in Mediterranean Vineyards, enhancing the varietal expression of Merlot (Cincotta et al., 2021). Within this group, ethyl hexanoate shows the highest odour activity value (OAV) among these esters, associated with green apple and strawberry descriptors (García-Carpintero et al., 2011). Ethyl decanoate, contributes to fruity aroma, has been reported in high concentration in wines from

Tangará, whereas ethyl octanoate contributed to the overall aroma profile (Pereira et al., 2014).

Other ester are also involved in the aromatic composition of Merlot. Diethyl succinate and ethyl lactate are associated to creamy and fruity notes (Carrasco-Quiroz, 2020), while isoamyl acetate enhances complexity with banana-like notes (Carrasco-Quiroz, 2020). Additional compounds as ethyl cinnamate, ethyl 2-methylbutanoate, and ethyl isovalerate, impart fruity and spicy notes depending on the harvest year and region (Antalick et al., 2014).

In wine, esters are formed through yeast metabolism via two main pathways, fatty acids acyl-CoA, which leads to the formation of ethyl esters, and acetyl-CoA combined with higher alcohols, which results in acetate esters (Prusova et al., 2022). Several studies have shown that medium chain fatty acids mainly octanoic and decanoic acid act as fermentation inhibitors by reducing intracellular pH and compromising yeast viability (Legras et al., 2010), under stress conditions such low temperatures of fermentation, *S. cerevisiae* could produce higher content of these compounds (Massera et al., 2021).

Through the acetyl-CoA route, yeast also generates higher alcohol acetates, including ethyl acetate, isoamyl acetate, and phenylethyl acetate. These compounds are particularly relevant to Merlot, as they enrich its fruity and floral dimensions; however, their sensory contribution is strongly concentration-dependent. At moderate levels they enhance aroma complexity, whereas excessive amounts, especially of ethyl acetate, may impart solvent-like notes (García-Carpintero et al., 2011; Peng et al., 2013; Pereira et al., 2014).

Lactone contribute additional to Merlot's wines sensory attributes δ -decalactone and γ -nonalactone are typically associated with coconut notes, while *c*-decalactone impart cooked peach aromas, respectively (Darriet et al., 2001; García-Carpintero et al., 2011).

Although generally found at lower concentrations in red wines compared to white aromatic varieties, terpenes still provide important notes to Merlot wines (Ribéreau-Gayon et al., 2006; Arcari et al., 2017). Geraniol provides rose-like aroma, while linalool is associated with floral character and borneol contributing camphor-like notes (Rocha et al., 2007; Ou et al., 2010; Pereira et al., 2014; Arcari et al., 2017; Arcena et al., 2020). The expression of these volatile compounds can also be influenced by factors such as vintage, regional climate, and viticultural practices, results in a multifaceted and dynamic sensory experience that defines Merlot wine (Arcari et al., 2017; Carrasco-Quiroz, 2020; Cincotta et al., 2021).

Methoxypyrazine add a vegetal dimension to Merlot's aroma. They are nitrogen-containing heterocyclic compounds characterized by extremely low sensory thresholds. Among them, isobutyl methoxypyrazine (IBMP) (Prusova et al., 2022). Although its lower concentrations in Merlot compared to other varieties including Cabernet Sauvignon, Cabernet Franc, and Sauvignon Blanc, IBMP still contributes to its distinctive aromatic profile (Augustyn et al., 1985), in fact is considered one of the most relevant in wines due to its markedly low threshold perception of just 15 ng/L. This compound is responsible for the green or bell pepper aromas commonly found in wines made from various grape varieties (De Boubée et al., 2000). Recent work has also highlighted how viticultural practices and climate conditions modulate IBMP expression in Merlot, underscoring the need for both agronomic and enological strategies to manage these compounds (Pickering et al., 2021).

C13 norisoprenoids represent a further group of aroma-active molecules derived from the oxidative cleavage of carotenoids during

grape maturation. β -damascenone, formed add depth to the wine's aromatic profile with its notes of baked apple, flowers and honey, and α -ionone which imparts notes of raspberry and violet (Kotseridis et al., 1999; Noguero-Pato et al., 2009; Peng et al., 2013). In summary, Merlot's aroma arises from the interplay of multiple volatile families, each imparting distinctive sensory trait. This chemical complexity defines the varietals sensory identity and underpins its relevance in both scientific research and winemaking practice.

The impact of climate conditions, vineyard management practices

Climate change linked to global warming presents new challenges for vineyard management, such as reduced precipitation, higher pH levels in grapes, and increased alcohol content (van Leeuwen et al., 2024).

The increase of pH is mainly associated with potassium accumulation in the berries under water stress and high temperatures, which promotes the precipitation of organic acids such as tartaric acid, thereby lowering overall acidity. In parallel, climate change often accelerates sugar accumulation due to faster ripening, leading to higher carbohydrate content in the must. During fermentation, these elevated sugar levels are converted into higher ethanol concentrations, which not only increase the perceived warmth of wines but can also influence chemical equilibria, further affecting acid–base balance and contributing to higher final wine pH (de Mira Orduña, 2010; Van Leeuwen and Destrac-Irvine, 2017).

Merlot has been described as anisohydric variety maintaining stomatal conductance even under limited water availability (Jiang and Zhang, 2012), this trait contributes to its relative adaptability under climate change scenarios, where increased drought frequency and water scarcity are expected (Gutiérrez-Gamboa et al., 2019; Vuerich et al., 2021). Intra-varietal diversity and phenological plasticity further support Merlot's adaptive potential in different environment (Naidu et al., 2014).

Among adaptive practices, irrigation plays a central role. Moderate irrigation (50% of crop evapotranspiration from the veraison to harvest) was shown to increase berry weight and in wines by improving chromatic properties while also enhancing consumer preference (Ribalta-Pizarro et al., 2024). Similarly, deficit irrigation under semi-arid Mediterranean conditions increased tannins and total polyphenols, particularly in the seeds, demonstrating the importance of water management in optimizing Merlot quality (Chacón-Vozmediano et al., 2021).

In this sense, several studies indicate that these changes impact the phenolic composition of Merlot wines, influencing their colour, stability, and sensory attributes. Merlot wines are known for their rich phenolic profile, including high levels of anthocyanins and other polyphenols crucial for colour stability, and antioxidant properties. This has been highlighted in studies conducted by Ivanova-Petropoulos et al. (2015), which demonstrated that Merlot wines are richer than Syrah and Cabernet Sauvignon in total acids and polyphenols, especially anthocyanins, making them deeply coloured, fresh, and suitable for long-term aging. Merlot seeds contain higher quantities of polyphenols and tannins compared to Cabernet Sauvignon (Lorrain et al., 2011), and the grapes contain higher amounts of epicatechin and catechin compared to other cultivars (Sen and Tokatli, 2014).

Furthermore, it has been reported that Merlot wines have higher concentrations of malvidin derivatives, peonidin, 10-hydroxyphenylpyranoanthocyanins, and higher acetylated anthocyanin content compared to other varieties, with lower tannin concentrations and reduced astringency and bitterness (Blanco-Vega et al., 2014; González-Neves et al., 2001; Landon et al., 2008; Tudose-Sandu-Ville et al., 2012).

In this context, temperatures play a crucial responsibility in determining the levels of the main phenolic compounds, as the synthesis of anthocyanins is sensitive to temperature. Moderate temperatures favour non-acylated forms, while higher temperatures increase acetylated anthocyanins, known for their superior colour stability (Tarara et al., 2008). In particular, elevated temperatures generally enhance the accumulation of malvidin-3-glucoside, leading to deeper and more stable Merlot colour profiles (Vişan et al., 2020).

Berry temperature, influenced by sunlight and water availability, also significantly impacts phenolic development. Increased sunlight raises berry temperature, while adequate water availability helps regulate berry cooling through transpiration. High temperatures and sunlight can accelerate ripening, potentially leading to higher sugar content but lower phenolic concentrations, which can affect the overall balance and complexity of the Merlot wine (Pavić et al., 2019). Conversely, excessive rainfall can dilute phenolic content, negatively impacting wine quality (Ferrer et al., 2016). Extreme temperatures can stress vines, redirecting resources away from phenolic synthesis and potentially diminishing wine quality. In these conditions, vineyard management practices, such as leaf removal, are crucial in shaping phenolic composition (Figure 2). In Merlot vineyards, this practice has resulted in improved cluster microclimate and enhanced pesticide penetration, thereby reducing *Botrytis cinerea* severity (Sivilotti et al., 2016). Merlot cultivation in cooler climates like Hawke's Bay, with excessive crop load and delayed ripening, can be problematic. In these cases, defoliation at veraison has been demonstrated to improve phenolic concentration and increase color intensity, increasing total monomeric anthocyanins, including malvidin-3-glucoside and quercetin-3-glucoside (Mazza et al., 1999; Spayd et al., 2002). This practice has also been reported to significantly impact anthocyanin concentrations and colour intensity in Merlot grapes, with combined treatments like cluster thinning at veraison and basal defoliation showing the most pronounced effects (Di Profio et al., 2011). The timing and method of leaf removal can vary, influencing the effectiveness of the treatment and its impact on wine quality. Defoliation also affects ripeness, impacting total soluble solids and pH, while decreasing titratable acidity, particularly when Merlot crop load is reduced (Karoglan et al., 2014). This type of field treatment has also been reported to have significant effects on the concentration and ratio of other varietal anthocyanins like delphinidin, petunidin, and peonidin (King et al., 2012; Osrečak et al., 2016).

Regional studies reveal variability in phenolic composition, with variations depending on the pedoclimatic conditions of the region. Merlot wines from higher altitudes show increased total phenolic compounds, flavonoids, and anthocyanins (Jin et al., 2017), as in the case of dehydrated Merlot grapes, which shown increased phenolic and mineral contents (Panceri et al., 2015). Moreover, Merlot shows higher variations in trans-resveratrol and trans-piceid concentrations compared to other grape varieties depending on the cultivation area (Kostadinović et al., 2012; Stervbo et al., 2007). Similarly, Merlot wines from southern regions have been reported to contain more catechin,

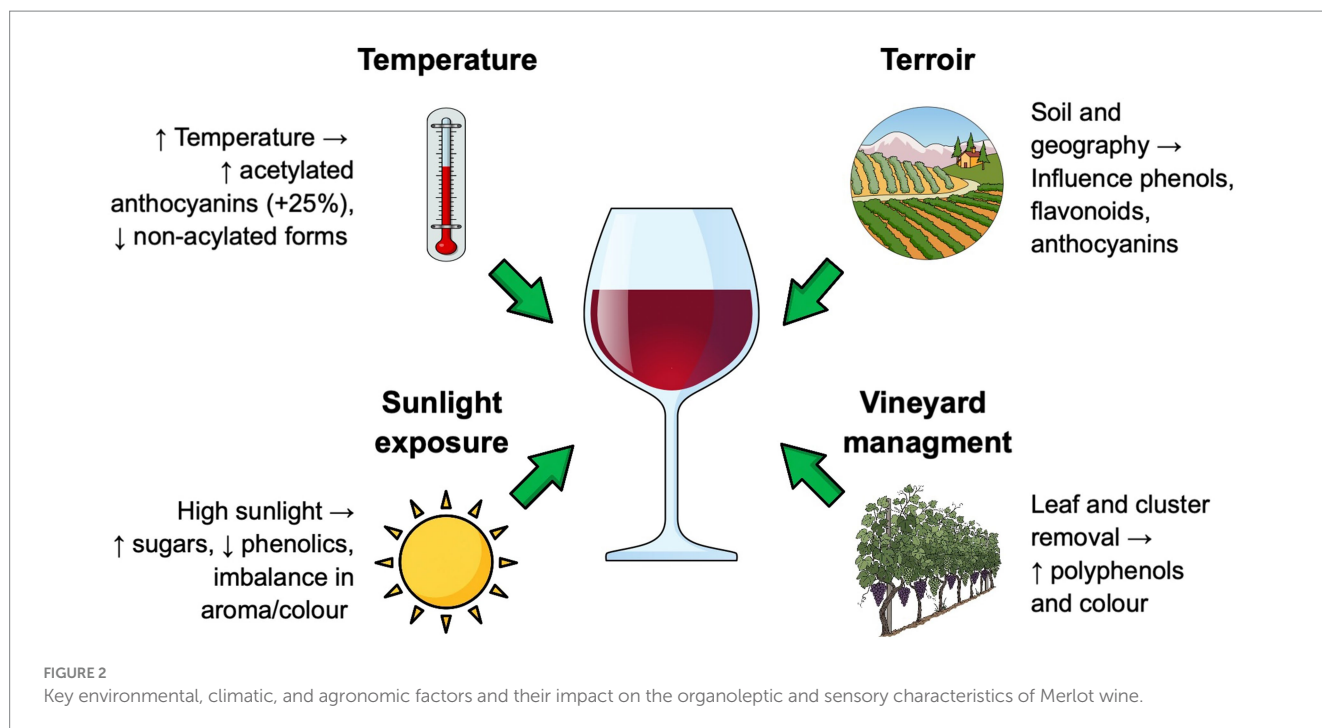


TABLE 1 Main grapevine pathogens affecting Merlot and their impact on grape and wine quality, with potential control strategies.

Pathogen/disease	Impact on Merlot	Control strategy
<i>Plasmopara viticola</i>	Increase in IBMP (isobutylmethoxypyrazine), leading to stronger green notes in wines (Pons et al., 2018)	Application of fungicides; canopy microclimate management
Grapevine leafroll disease (GLD; caused by GLRaVs, mainly GLRaV-3)	Reduction of anthocyanins and proanthocyanidins (Girardello et al., 2020); reduced sugar accumulation, increased acidity, altered phenolic composition; crop thinning ineffective (Roberts et al., 2025)	Sanitation and certified virus-free plant material; vector control (mealybugs/scale); vineyard replacement
Grapevine Red Blotch Disease (GRBD)	Reduced sugar accumulation in berries (Girardello et al., 2020)	Certified virus-free plant material; vector management
<i>Botrytis cinerea</i>	50% infection: laccase activity exceeds tannins, causing oxidative haze; 20% infection: tannins preserve colour and quality (Gancel et al., 2021)	Vineyard hygiene; fungicide applications; selective harvest
Premature Berry Dehydration (PBD)	Early dehydration, impaired sugar and nutrient transport, reduced colour, increased acidity (Matus et al., 2008)	Balanced irrigation; canopy management; pathogen monitoring
Tomato Black Ring Virus (TBRV)	Yield loss up to 66%, smaller bunches and berries, reduced grape quality, increased vegetative growth (Dewasme et al., 2019)	Certified propagation material; roguing of infected vines

epicatechin, and myricetin compared to those from northern regions (Goldberg et al., 1996).

Although Merlot exhibits several adaptive traits, comparative studies suggest that it may still be less resilient than Cabernet Sauvignon under future climate scenarios. This underlines the need for adaptive measures such as drought-tolerant clones, alternative rootstocks, or relocation to cooler regions (Baltazar et al., 2025).

Effects of pathogens and impact of agronomic treatments on Merlot wine characteristics

The phytosanitary condition of grapes is of fundamental importance to the quality of the obtained grapes. In fact, several

authors have identified how different plant pathogens can modify and contribute to the complex aromatic harmony of Merlot (Table 1). Among these, the oomycete *Plasmopara viticola* has been shown to have a significant impact on the quality of this variety, causing an increase in IBMP (isobutylmethoxypyrazine) in Merlot grapes during infections (Pons et al., 2018).

Grapevine leafroll disease (GLD) is caused by a complex of Grapevine leafroll-associated viruses (GLRaVs) including GLRaV-1, -2, -3, and -7 (Naidu et al., 2014). Among these, GLRaV is considered the most prevalent and impactful. In Merlot infection reduce anthocyanin and proanthocyanidin concentrations (Girardello et al., 2020) and impair sugars accumulation while increasing acidity and altering phenolic composition (Roberts et al., 2025).

Grapevine red blotch disease (GRBD) also affects Merlot, with reduced sugar accumulation in infected grapes (Girardello et al.,

2020). Furthermore, *Botrytis cinerea* infection affects Merlot wine quality. As reported, at 50% infection by *B. cinerea*, laccase can overpower tannins, risking oxidative haze, but at 20%, tannins effectively preserve wine colour and quality (Gancel et al., 2021). It has also been reported that Merlot vines exhibit high sensitivity to pre-mature berry dehydration (PBD), a disorder linked to phloem disruption, supposed to arise from pathogenic microorganisms and viruses, which affects fruit development by causing dehydration, disrupting sugar and nutrient transport, and leading to reduced colour and increased acidity in the berries (Matus et al., 2008). Regarding viruses, a study conducted on Merlot vines infected with Tomato Black Ring Virus (TBRV) showed significant yield reductions of up to 66%, with fewer and smaller bunches and berries. Despite slight increases in polyphenols and anthocyanins, which improved wine colour, TBRV resulted in lower grape quality, reduced vegetative growth, and more lateral shoots, leading to complicate vineyard management (Dewasme et al., 2019).

To counteract these pathogens, agronomic treatments are essential. However, several studies have shown that specific chemical compounds used for these practices can significantly affect the chemical composition and sensory attributes of wines (Table 2). For example, chiral tebuconazole residues were reported to significantly impact Merlot wine flavour and colour attributes by altering the levels of volatile compounds. The presence of these residues was also correlated with an increase in acetic acid and changes in concentrations of compounds like 2-heptanol and ethyl butyrate, which negatively impacted the wine's fruity and floral flavours (Zhao et al., 2022). Additionally, the presence of pyranoanthocyanin derivatives residues resulted in Merlot wines with a more brick-red

hue. R-tebuconazole, in particular, had the most detrimental effect on Merlot's flavour and colour, underscoring the importance of stringent quality control in wine production. Similarly, copper sprayings on vines resulted in a reduction in the varietal aroma of young Merlot wines, particularly affecting volatile thiols (Darriet et al., 2001). Conversely, to improve aromatic components and promote plant development, the use of biostimulants has been gaining ground in recent years (Colautti et al., 2023b). For instance, field application of boron to Merlot grapes was reported to significantly increase the content of anthocyanins, hydroxycinnamic acids, and flavonols, enhancing phenolic metabolism in grape skins and besides modify the phytochemical composition (Arbigaus Bredun et al., 2023) (Figure 3).

The impact of winemaking techniques on Merlot quality

Winery technologies are crucial in Merlot vinification as they significantly impact its organoleptic characteristics. From fermentation management to the selection of aging materials, each technical aspect helps shaping the wine's aromatic profile and taste.

For example, it has been observed that bentonite, a widely used fining agent in wineries for clarification, can influence the concentration of rare earth elements in Merlot wine based on its origin, thereby impacting the wine's chemical profile (Tatár et al., 2007). Additionally, combining bentonite with polyvinylpyrrolidone (PVPP) and plant proteins (PPI) as fining agents significantly affected monomeric flavanols, turbidity, and anthocyanin content in Merlot wines. Optimal results were achieved with a combination of 25% PPI, 43% PVPP, and 32% bentonite (Ficagna et al., 2020). Activated charcoal has also been shown to be particularly effective in reducing smoke taint in Merlot wines, enhancing fruit characteristics without significantly altering colour or acidity (Fudge et al., 2012).

Another technique, ultrasound application, has yielded contrasting results for Merlot. Xie et al. (2023) highlighted the benefits of combining ultrasound with low-temperature pre-treatment, noting improvements in anthocyanin and phenolic acid levels, aroma, and reduction of undesirable odours, suggesting strong application potential. Similarly, Maier et al. (2024) reported that high-power ultrasound treatment improved the extraction of polyphenolic compounds during Merlot grape maceration. Conversely, Ignat et al. (2016) found that traditional fermentation and rotating tank maceration techniques produced the most balanced anthocyanin levels in Merlot, while ultrasound maceration was less effective. The study also observed varying percentages of free anthocyanins, with malvidin being the most prevalent.

In addition to these cellar technologies, extraction dynamics during maceration are also important in shaping Merlot's aromatic profile. A recent study investigated the impact of varying seed-to-skin ratio in Merlot and found that a higher proportion of seeds led to Merlot wines with significantly increased tannin content and anthocyanin concentration, resulting in stronger colour density and a higher phenolic index (Makalisa et al., 2025).

The evolution of phenolic compounds and colour in Merlot and Marselan dry red wines throughout winemaking and aging was also studied (Zhang et al., 2024). These authors found minimal

TABLE 2 Agronomic practices influencing Merlot grape and wine quality, their impact on composition and potential management strategies.

Agronomic practice	Impact on Merlot	Control strategy
Tebuconazole residues (R/S enantiomers)	Altered volatile profile, increased acetic acid, negative effects on fruity/floral aroma and colour (R-enantiomer most detrimental) (Zhao et al., 2022)	Careful fungicide application, residue monitoring, quality control
Pyrananthocyanin residues	Brick-red hue in wines (Zhao et al., 2022)	Minimize fungicide residues through vineyard management
Copper sprays	Reduction of varietal aroma in young wines, especially volatile thiols (Darriet et al., 2001)	Optimize dosage, integrate alternative products
Biostimulants (e.g., Boron)	Increase in anthocyanins, hydroxycinnamic acids and flavonols; stimulation of phenolic metabolism (Mian et al., 2023; Arbigaus Bredun et al., 2023)	Foliar nutrient management, targeted application

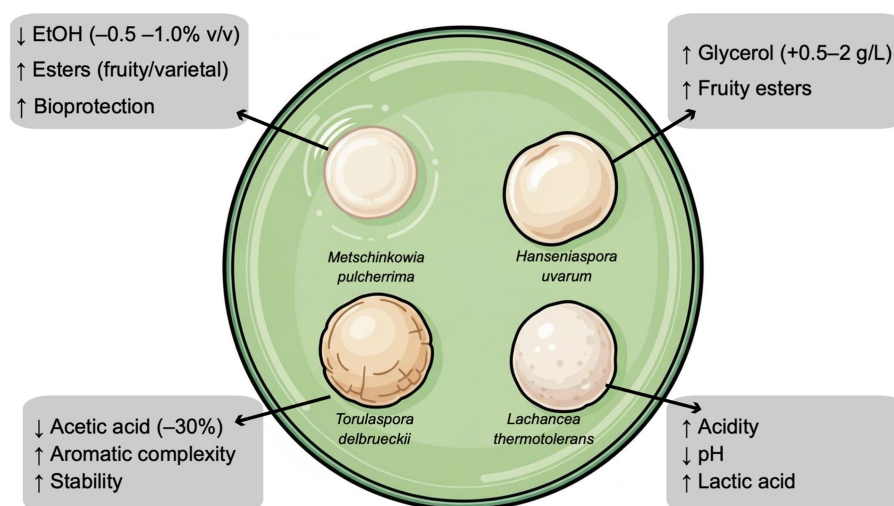


FIGURE 3

Key non-*Saccharomyces* yeast strains whose fermentative effects have been specifically studied in the vinification of Merlot grapes.

phenolic leaching during cold maceration, with rapid release during alcoholic fermentation, leading to increased pyran anthocyanins and polymeric pigments, which remain high through malolactic fermentation and storage. The wines' colour during aging is primarily influenced by anthocyanins and F-A polymeric pigments, with the red color of Merlot being closely linked to the presence of pinotins. Increased concentrations of flavan-3-ols have been correlated with enhanced color stability, indicating their potential role in mitigating color loss and instability.

Fermentation dynamics and yeast influence in Merlot wines

Grape-associated microbiota differs considerably across viticultural regions under the influence of environmental factors such as soil and climate. In Merlot these microbial signatures were distinctive enough to classify grapes by geographical origin providing strong evidence for their role in microbial terroir (Bokulich et al., 2014). Further studies confirmed this regional specificity. In Southern Brazil *Hanseniaspora uvarum*, *Issatchenkia terricola*, *Saturnispora diversa* and *Starmerella bacillaris* were identified as the dominant species on Merlot berries, showing biodiversity comparable to Cabernet Sauvignon (Mattos Rocha et al., 2022). The relevance of microbial communities extends beyond regional diversity to the fermentation process itself. In Merlot musts, distinct dynamics have been reported during spontaneous fermentations, notably the high presence of *Pichia anomala* during fermentations, leading to wines with lower alcohol percentages and increased glycerol concentrations (Clavijo et al., 2010; Li et al., 2010; Varela et al., 2017).

During spontaneous fermentation, the microbial succession has been extensively investigated. Culture-independent analyses revealed that in the early stages of alcoholic fermentation non-*Saccharomyces*

yeast are predominant before being progressively replaced by *S. cerevisiae* (Zott et al., 2008).

Another distinctive feature of Merlot fermentations is the high prevalence of killer strains during spontaneous fermentation possibly due to greater initial yeast populations on the berries compared to varieties like Cabernet Sauvignon (Renouf et al., 2008). The dynamics of these killer yeasts play a crucial role, with Merlot fermentations showing a predominance of killer strains from early stages, unlike Malbec, where a mixed population of sensitive and killer strains was observed (Sangorrín et al., 2001).

These naturally occurring antagonistic interactions within Merlot fermentation have inspired modern bioprotection strategies, where selected non-*Saccharomyces* yeast are employed to limit spoilage microorganism while reducing sulphur dioxide (SO₂). In this sense, bioprotection was successfully tested on Merlot wines, which limited the oxidation of must during fermentation and provided protection against undesirable microorganisms, such as acetic acid bacteria, helping to preserve the wine's sensory qualities (Windholtz et al., 2021a). A specific study examined the sensory profiles of sulphite-free wines made with and without bioprotection over two years. The results showed that wines treated with bioprotection, as well as those without sulphites, displayed intense notes of "Fresh blackcurrant," "Cooked black cherries," "Mint," and "Coolness" differing from wines made with the addition of SO₂. The findings showed that these yeasts effectively dominated the pre-fermentation environment, significantly influencing the final wine aroma. Specifically, bioprotection encouraged the formation of linear esters, while sequential inoculation promoted the production of acetate esters from higher alcohols, contributing to a more pronounced fruity aroma. Sensory analyses confirmed that the use of non-*Saccharomyces* yeasts enhanced the fruity qualities of the wines, further highlighting their aromatic benefits (Windholtz et al., 2021a). Another study investigated the use of *Metschnikowia pulcherrima* and *Meyerozyma guilliermondii* in combination with *S. cerevisiae* for fermenting Merlot must. The research revealed a reduction in ethanol levels in wines in which *M. pulcherrima* was

involved, compared to those fermented solely with *S. cerevisiae*. However, fermentations inoculated with *M. guilliermondii* resulted in higher ethyl acetate levels, though sensory analysis showed no detrimental effect on wine quality (Aplin et al., 2021). The bioprotective effect of non-*Saccharomyces* yeasts also relates to their ability to consume dissolved oxygen, with *M. pulcherrima* and *Torulaspora delbrueckii* proving particularly effective in limiting the growth of spoilage bacteria such as *Glucanobacter oxydans*. Notably, *M. pulcherrima* consumed oxygen more rapidly than *S. cerevisiae*, underscoring its potential for use in bioprotection during winemaking (Windholtz et al., 2023a). The addition of bioprotective yeasts such as *M. pulcherrima* and *T. delbrueckii* early in the winemaking process helps prevent must deterioration by reducing the presence of filamentous fungi. Temperature control during pre-fermentation being essential to maximize their protective effects (Windholtz et al., 2021b). Altogether, these results confirm that bioprotection enhances aroma, stabilizes must, and allows a reduction in Merlot winemaking (Alexandre et al., 2023; Windholtz et al., 2023b).

Furthermore, it is essential to characterize microbial populations for their impact on the organoleptic and safety aspects of the product. One major concern in Merlot production is the potential presence of biogenic amines (BAs). Different levels of biogenic amines, including spermidine, serotonin, putrescine, and cadaverine, have been reported in Merlot wines depending on the inoculation strategy of alcoholic and malolactic fermentation starters (Manfroi et al., 2009). Other studies have highlighted that the co-inoculation of yeast and lactic acid bacteria during malolactic fermentation in Merlot wines can reduce the content of cadaverine and tyramine (Cañas et al., 2012). The composition of microbial populations in Merlot can also be influenced by vineyard and cellar practices, highlighting the importance of management choices in modulating yeast communities and their functional impact (Colautti et al., 2023a). In this context the use of indigenous yeast strains for wine fermentation is crucial as it enhances the unique character of the terroir, promotes a more natural and sustainable fermentation process, and preserves vineyard biodiversity (Nisiotou et al., 2018). Concrete examples in Merlot support this approach. The isolation and characterization of autochthonous *S. cerevisiae* strains confirmed that indigenous populations can provide distinctive contributions, with one strain (7F) producing wines with superior colour, aroma intensity, and fruity character (Ut et al., 2022). Similarly, in Northwestern Argentina, ten non-*Saccharomyces* species were isolated from Merlot grapes, with *H. uvarum* as the most abundant. Selected strain, including *H. uvarum*, *H. vineae* and *Metschnikowia pulcherrima* exhibited favorable oenological traits such as moderate SO₂ tolerance, low volatile acidity production and enzymatic activity related to aroma release (Mendoza et al., 2019). Beyond these examples interest in non-*Saccharomyces* yeasts has significantly increased due to their technological potential (Borren and Tian, 2020; Maicas and Mateo, 2023). Yeasts like *Hanseniaspora* spp. and *Starmerella* spp., dominant in spontaneous fermentations, are known to significantly contribute to the production of aromatic compounds such as higher alcohols, esters, and terpenes, thus enhancing the aromatic complexity of Merlot wines (Renault et al., 2015). In addition, several non-*Saccharomyces* yeasts secrete enzymes such as β -glucosidases and proteases, which can

significantly affect the final aroma of Merlot wines by interacting with grape-derived precursors, a notable example is *H. vineae* which has been associated with the production of phenyl ethyl acetate, contributing fruity, floral, and honey-like notes, although its impact depends on the competitive dynamics within Merlot must (Lleixà et al., 2016). Taken together, these findings emphasise that yeast selection in Merlot winemaking is not only critical for fermentation performance but also decisive in defining the aromatic identity and overall sensory quality of the wine (Figure 3). Despite these promising perspectives, the application of non-*Saccharomyces* yeasts in Merlot winemaking at industrial scale still faces important limitations. Most studies have been conducted under laboratory or pilot-scale conditions, and large-volume fermentations often show lower reproducibility and stability (Jolly et al., 2014; Padilla et al., 2016). In Merlot specifically, *M. pulcherrima* has been associated with reduced ethanol levels, but fermentations involving *M. guilliermondii* resulted in increased ethyl acetate, which could negatively impact wine quality (Aplin et al., 2021). Moreover, non-*Saccharomyces* strains are frequently outcompeted by *S. cerevisiae*, requiring high inoculation rates and strict management to ensure persistence. While recent studies on bioprotection have confirmed their potential for reducing SO₂ and controlling spoilage bacteria (Windholtz et al., 2023b; Alexandre et al., 2023), these approaches still demand further validation under commercial winemaking conditions.

Potential of Merlot wine and grape pomace extracts in oxidative stress and neuroprotection

Several studies have highlighted the benefits of drinking moderate quantities of wine responsibly (Buljeta et al., 2023). Beneficial effects have been particularly observed in red wines, including Merlot, due to their high levels of antioxidant compounds (Landrault et al., 2001). Majkić et al. (2019) explored using a cell culture *in vitro* model the anti-inflammatory properties of Merlot wines, observing a reduction in Prostaglandin E2 (PGE2, involved in inflammation, fever, and pain) production by up to 65.5% and Thromboxane A2 (TXA2, crucial for blood clotting and vascular tone) by up to 47.9%. These reductions suggest potential cardiovascular benefits similar to a low dose of aspirin. However, no direct correlation was found between the wines' phenolic content and their anti-inflammatory effects, indicating that other compounds or synergistic effects might be at play. Martín et al. (2011) further demonstrated that Merlot red wine can protect human astrocytoma cells from oxidative damage caused by the Fenton reaction, which generates harmful radicals. This finding is significant as it implies that Merlot's antioxidants might help protect against cell damage related to various diseases, including cancer, potentially leading to new dietary strategies for improving health and preventing disease.

Additionally, the potential to extract valuable active compounds from this cultivar's grapes has been demonstrated, offering an opportunity to add value to the industry's by-products due to their high phenol and antioxidant content (Díaz et al., 2022). For example, it was reported that pressed Merlot red wine extract has higher neuroprotective activity than free run wine due to the greater extraction of polyphenols, including quercetin, catechin,

and procyanidins from the grape pomace. In particular, quercetin was found to be effective in preventing PC12 cell death and reducing the overproduction of reactive oxygen species (ROS) (Martín et al., 2012). Moreover, Merlot grape pomace hydroalcoholic extract, rich in anthocyanins, could improve oxidative and inflammatory states in arthritis patients (Gonçalves et al., 2017). These extracts also exhibited antimicrobial activity against various pathogens, including *E. coli* and methicillin-resistant *S. aureus* (Corrêa et al., 2017). Similarly, other extracts such as flavonoids, flavones, hydroxybenzoic acid derivatives, hydroxycinnamic acid derivatives, and ferulic acid methyl ester from Merlot grape pomace, showed effective antimicrobial activity mainly against Gram-positive bacteria (Ghendov-Mosanu et al., 2022).

Conclusion

Thanks to its distinctive organoleptic qualities, which include a fruity aromatic profile and a smooth, approachable taste, Merlot captivates a wide spectrum of consumers. This broad appeal has fuelled its expansion beyond traditional regions like Italy, Spain, and France to major international markets, including the United States, Australia, and Chile. In recent years, its popularity has also surged in Asia, particularly in China. The Asian market is becoming increasingly important for the wine industry, with growing demand for both imported and locally produced wines. Merlot aligns perfectly with the preferences of these emerging consumers, who often favour rounder, fruitier wines with lower alcohol content and softer tannins compared to more robust red varieties. This makes Merlot particularly suited to the expanding middle class in Asia, where an evolving wine culture is fostering new opportunities.

Merlot's adaptability to various geographical regions further strengthens its global reach. Its ability to thrive in diverse terroirs, combined with early ripening and disease resistance, makes it a strategic choice for vineyards grappling with the unpredictable weather patterns exacerbated by climate change.

As Merlot's presence continues to grow, ongoing research into this variety will be essential. With consumers increasingly focused on sustainability and ecological practices, future studies must prioritize environmentally friendly viticulture. Exploring the use of biostimulants and examining the role of environmental microbiomes, both areas where Merlot has seen limited research, will be crucial to developing sustainable farming practices that minimize chemical inputs.

Equally important are the advancements in winemaking technology. Emphasizing the role of native microbial flora can help winemakers create wines that authentically reflect the unique characteristics of their region, offering a point of distinction in a highly competitive global market. Further research into these indigenous microorganisms could lead to the development of new starter cultures that improve fermentation control and efficiency. In particular, isolating yeast strains that can withstand higher fermentation temperatures without sacrificing quality would support the industry's push towards more energy-efficient production methods. Additionally, reducing the use of traditional

additives like SO₂ by identifying effective bioprotective strains could lead to wines with a smaller environmental footprint, responding to the demand for more natural and low-intervention products.

Author contributions

EG: Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. AC: Visualization, Writing – review & editing. MP: Investigation, Validation, Writing – review & editing. GC: Methodology, Validation, Writing – review & editing. LI: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

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