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Review
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Management of Malolactic Fermentation in Warm-Climate Wines: Challenges and Inhibition Strategies

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Abstract

Background and goals

Malolactic fermentation (MLF) is a secondary fermentation process that converts L-malic acid to L-lactic acid, thereby softening acidity and contributing to microbial stability and sensory complexity in wine. Although MLF is beneficial in cool-climate winemaking, its effects in warm-climate wines can be detrimental, as these wines often have low acidity and high pH prior to fermentation. This review examines how MLF influences chemical, microbial, and sensory attributes under warm-climate conditions and consolidates strategies for its control.

Methods and key findings

Peer-reviewed research and technical studies on MLF in high-pH and high-temperature wines were synthesized to identify major challenges and control methods. Warm-climate conditions were found to intensify color degradation, increase volatile acidity, and promote spoilage by lactic acid bacteria. This review highlights several effective management tools, including molecular sulfur dioxide, lysozyme, fumaric acid, nisin, and chitosan-based treatments. Among these, fumaric acid showed strong inhibition of MLF with minimal sensory impact, whereas lysozyme and nisin offered selective microbial control.

Conclusions and significance

In warm-climate winemaking, spontaneous or poorly managed MLF can compromise acidity, color stability, and flavor integrity. Targeted control strategies allow winemakers to preserve freshness, microbial balance, and phenolic quality in high-pH wines. These findings emphasize the importance of region-specific MLF management and encourage further applied research to refine management protocols suited to warm-climate enological practices.

Key words: chitosan, fumaric acid, lysozyme, malolactic fermentation, malolactic management, nisin, wine, wine quality

Introduction

In vinification, there are two generally recognized types of fermentation. The first, and most essential, is alcoholic fermentation by yeast, in which sugar is converted into ethanol and carbon dioxide. The second is malolactic fermentation (MLF), in which L-malic acid is converted to L-lactic acid by lactic acid bacteria (LAB), lowering acidity and increasing pH. In standard winemaking practices, nearly all red wines and some white wines undergo MLF. MLF is often praised for its ability to deacidify wines, impart desirable organoleptic properties, and improve microbial stability (Lerm et al. 2010, Dimopoulou et al. 2022).

However, both winegrapes grown and wines produced in hotter climates face unique challenges—such as decreased acidity, color instability, and increased alcohol—that can be exacerbated by MLF, reducing the palatability of wines (Mozell and Thach 2014, Gerbi and De Paolis 2025, Keng et al. 2025). This review aims to provide a concise and applied overview of MLF management in warm-climate winemaking. By synthesizing current literature across chemistry, microbiology, and sensory science, we contextualize existing knowledge of the advantages, limitations, and practical inhibition options for MLF under conditions of elevated pH and temperature.

Modern Application

A key function of MLF is deacidification of wine through enzymatic conversion of malic acid, a dicarboxylic acid with strong dissociation, into the weaker monocarboxylic lactic acid. This shift raises pH by ~0.1 to 0.3 units, reducing overall acidity (Daeschel et al. 1991) and contributing to a more harmonious balance of fruit, texture, and structure that is especially valuable in cool-climate wines with high acidity (de-la-Fuente-Blanco et al. 2024). In

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addition, metabolism of citric and tartaric acids by LAB can further influence acidity. Beyond deacidification, MLF has long been recognized as central to shaping the flavor and microbial stability of wine.

Recent studies highlight how LAB adapt to ethanol and high pH, with stress responses affecting enzymatic efficiency in malate-to-lactate conversion, and point to biotechnological approaches for improved control (Fu et al. 2022). Broader reviews have also underscored species diversity and enzymatic activities (including glycosidases and esterases) that affect aroma and color stability, while outlining practical strategies for modern winemaking such as co-inoculation and strain selection (Paramithiotis et al. 2022). Collectively, this body of work shows that in addition to reducing acidity, LAB also drive a network of organic acid and aroma transformations that shape wine style. Sensory outcomes are equally significant: MLF modifies acid composition and generates aroma-active metabolites, influencing flavor, mouthfeel, and balance (Pardo and Ferrer 2022). The conversion of malic to lactic acid softens harsh acidity, enhancing roundness and fullness (Hartwig and McDaniel 1995), mitigating tart or unripe notes (Mozell and Thach 2014), and promoting smoother integration. It is also associated with buttery, nutty, and creamy attributes due to diacetyl production, with expression varying by strain (Nielsen and Richelieu 1999), though many studies confirm that MLF generally enhances buttery and vanilla-like aromas when desired stylistically (Dimopoulou et al. 2022).

MLF is also used as a tool for microbial management in winemaking. The presence of LAB can be beneficial in outcompeting spoilage microorganisms, thereby reducing the need for excessive sulfur dioxide (SO_2) additions (Virdis et al. 2021). However, the success of MLF depends on careful bacterial strain selection and inoculation timing, as strain-dependent metabolic activity and microbial competitiveness can influence fermentation reliability and sensory outcomes. Recent advancements in LAB research and commercial starter cultures have given winemakers greater control over the timing and extent of MLF, ensuring consistency in both microbial stability and sensory outcomes (Virdis et al. 2021).

Issues Associated with MLF in Hot-Climate Winemaking

Effects of warmer climates on grapevines and wine chemistry

The scale of changes to global climatic systems is unlike anything seen in thousands of years (IPCC 2023). The Intergovernmental Panel on Climate Change declared in their 2023 synthesis report that they are "virtually certain that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s", including popular viticultural areas like the Mediterranean, western North America, east southern Africa, Australasia, and nearly all of Europe and South America (IPCC 2023). Observed impacts of hot extremes include drought susceptibility, reduced water availability, and increased disastrous weather events (IPCC 2023). Even if grapevines can withstand these challenges, fruit composition is highly influenced by even the most minor changes in temperature (Mozell and Thach 2014). Recent field-based and regional observational studies consistently show that elevated growing-season temperatures are associated with earlier grape ripening and shifts in grape composition, including increased sugar accumulation and reduced acidity, resulting in must profiles that differ from historical baselines (Licurici et al. 2025).

Increased temperatures cause grape berry veraison (the onset of ripening when berries soften, change color, and begin to accumulate sugars) to occur quicker and earlier in the season, leading to lower acid production (especially malic acid), lower anthocyanins, lower methoxypyrazines, and higher sugar concentrations per grape berry (Keller 2010, Mira de Orduña 2010). Because sugar is converted to ethanol during alcoholic fermentation, higher sugar concentrations cause increased alcohol levels in finished wines (Mozell and Thach 2014). Reduced anthocyanins result in color instability. Deficiencies in malic acid may lead to microbial instability, unappealing mouthfeel, and structureless wines (Mozell and Thach 2014). Grapes with these chemical attributes become wines that lack the appeal that is provided by complex and structured mouthfeel, balanced sweet-sour taste, and herbaceous aromas (Mozell and Thach 2014).

Acidity and pH

As shown in numerous studies, the process of MLF results in higher pH values and lower acidity (Dimopoulou et al. 2022). The pH values of most wines fall between 3.0 and 3.8 (Paramithiotis et al. 2022). With increased heat waves, cool nights that contribute to acid production in grapes are becoming more scarce and pH values above 4 are commonly observed in warmer climates (and occasionally in cool climates) (Keller 2010). From an organoleptic standpoint, favorable concentrations of L-malic acid can enhance sensory perceptions of crispness, tartness, and balanced acidity (Volschenk et al. 2006). Recent research on the sensory impacts of red wine acidifiers proposed that MLF at elevated pH levels can result in an excessive amount of L-lactic acid when MLF occurs spontaneously prior to acidification, producing off-aromas described as "sweaty, lactic, and wet wool/wet dog" (Keng et al. 2025). In that study, Syrah grapes sourced from the Texas High Plains American Viticultural Area had a starting pH of 4.16 and spontaneously underwent MLF before acidifiers could be applied—a situation that can be exacerbated by field-level microbial pressure such as acid rot and associated yeast and bacterial infections under warm growing conditions, a common reality for many hot-climate winemakers (Keng et al. 2025).

Low pH is responsible not only for favorable sensory perceptions, but for microbial stability as well. Wines with a pH over 3.5 are more susceptible to spoilage bacteria like *Lactobacillus* sp. and *Pediococcus* sp., whereas a pH of 3.5 or lower inhibits microbial spoilage (Volschenk et al. 2006,

Knoll et al. 2011). There is a common belief that MLF increases microbial stability by emitting antimicrobial bacteriocins and lactic acid; this is likely true for cool-climate wines with pH values low enough to inhibit growth of spoilage bacteria (Volschenk et al. 2006). However, wines with high initial pH and wines with residual L-malic acid routinely encounter spoilage by other strains of LAB even after MLF has occurred (Volschenk et al. 2006). In a study on the enzymatic management of pH in wines, the authors concluded that "the high pH of the control wines led to microbiological instability" that resulted in musty, stale, and spoiled flavors (Botezatu et al. 2021). Taken together, these findings demonstrate that in hot-climate, low-acidity wines, MLF by any strain does not reliably enhance microbial stability and may instead exacerbate sensory and microbiological risks.

Color

In red wine, color stability relies on low pH to preserve anthocyanins; elevated pH levels enable oxidative reactions that result in color loss and browning in both red and white wines (Volschenk et al. 2006). The quantity and relative proportion of anthocyanins are the primary factors determining the color potential of red wines (Keller 2010). Numerous studies have found that higher temperatures reduce anthocyanin biosynthesis; thus, heat waves occurring during the ripening stage can damage color potential in red wines (Tarara et al. 2008). Overall, color stability is a common struggle in warm climates.

MLF also causes color loss in red wines that is independent of the increase in pH associated with MLF (Bartowsky and Krieger-Weber 2020). In a study in which control wines were pH-adjusted to match wines that had completed MLF by *Oenococcus oeni*, those that underwent MLF exhibited lower concentrations of acetaldehyde and pyruvic acid, leading to reduced color intensity and polymeric pigment content, while monomeric anthocyanins were more prevalent (Burns and Osborne 2013). Because acetaldehyde plays a key role in stabilizing wine color by facilitating the formation of stable ethylene-linked pigments, its reduction during MLF by *O. oeni* (and potentially by other LAB strains) contributes to diminished color stability (Burns and Osborne 2013, Bartowsky and Krieger-Weber 2020). Furthermore, LAB produce glycosidase enzymes that hydrolyze anthocyanin glycosides (Paramithiotis et al. 2022). This process releases anthocyanidins which are prone to degradation into colorless derivatives, reducing long-term color stability (Paramithiotis et al. 2022). In addition, microorganisms influence wine color not only through enzymatic or metabolic pathways but also via direct adsorption of anthocyanins to yeast or bacterial cell walls, reducing free pigment concentration (Tofalo et al. 2021).

Alcohol

As high alcohol wines (greater than 13% alcohol by volume) become more common with rising temperatures, sensory impacts should be considered. Research concludes that sensory perceptions of taste and odor differ depending on alcohol concentration (de-la-Fuente-Blanco et al. 2024). Typically, as ethanol concentration increases, so does the perception of bitterness as well as burning/tingling sensations (de-la-Fuente-Blanco et al. 2024). During MLF, LAB are able to decarboxylate amino acids, producing biogenic amines and fusel alcohols that raise the overall alcohol content in wine (Lerm et al. 2010). The extent to which MLF contributes to increased alcohol production in wine remains debated, but research suggests that LAB are capable of generating these compounds (Lerm et al. 2010). In high concentrations, fusel alcohols tend to impart aromas that are solvent-like and flavors that are bitter and boozy (Hazelwood et al. 2008).

Ropiness

Certain species of LAB have been found to produce oily films and gelatinous substances in wine, leading to a fault called ropiness (Ciezack et al. 2010, Coulon et al. 2012, Dimopoulou and Dols-Lafargue 2021). Ropiness occurs when LAB species go unchecked and produce extracellular polysaccharides (particularly glucan) during fermentation, increasing the overall viscosity of the wine. Many commercially selected LAB strains used to induce MLF have been screened to minimize this risk and are not typically associated with ropiness. However, warmer regions are at greater risk for ropiness if MLF occurs spontaneously, due to elevated temperatures and lower acidity that favor LAB proliferation.

Recent findings show that the ropiness defect is primarily associated with exopolysaccharide-producing strains of *Pediococcus parvulus*, *Lactobacillus diolivorans*, and *O. oeni*, which synthesize β-1,3/β-1,2-glucan polymers via a glucosyltransferase (Gtf) enzyme (Ciezack et al. 2010, Dimopoulou and Dols-Lafargue 2021). Even low concentrations of this glucan (≈12 mg/L) can markedly increase viscosity, producing the characteristic oily or "ropy" texture observed in affected wines (Dimopoulou and Dols-Lafargue 2021). The Australian Wine Research Institute recommends preventive control measures including sterile filtration or lysozyme treatment to manage potential ropiness issues (AWRI 2015). Ropy LAB such as *P. parvulus* can exhibit lysozyme resistance due to a β-glucan coating. However, this protective layer can be effectively degraded by the glucanase enzyme, and combining lysozyme with glucanase has been shown to successfully eliminate ropy *Pediococcus* strains, offering a synergistic control strategy (Coulon et al. 2012).

Mousiness

Some LAB strains metabolize amino acids such as lysine and ornithine, forming volatile N-heterocyclic compounds (such as pyridines) that are responsible for an off-flavor that resembles the smell of mice (Costello et al. 2001). The main compounds responsible for mousiness are 2-acetyltetrahydropyridine (ACTPY) and 2-acetyl-1-pyrroline (ACPY) (Costello et al. 2001). Many MLF inducing strains of *Lactobacillus* spp. and *O. oeni* have been identified as producers of these undesirable compounds (Costello et al. 2001). The formation of mousy flavors is influenced by the pH of the

wine, with higher pH levels promoting the growth of these LAB and the subsequent production of N-heterocycles. In efforts to understand microbial contributions beyond mere metabolism, previous work characterized a Gtf gene in *P. parvulus* and *O. oeni*, revealing that these LAB have the genetic capacity to form glucan polymers via glucose transfer (Dols-Lafargue et al. 2008). The presence of Gtf genes implies that LAB may modulate the wine matrix by producing exopolysaccharides that could bind or sequester aroma precursors or intermediate heterocycles associated with mousy compounds (Dols-Lafargue et al. 2008).

Citric acid fermentation

In addition to fermentation of malic acid, LAB also metabolize citric acid. This process is assumed to be the primary source of diacetyl production in wine during MLF (Nielsen and Richelieu 1999). In a study analyzing citric acid fermentation in Chardonnay by O. oeni, diacetyl production peaked when malic acid was exhausted, creating buttery and nutty flavors in the wine (Nielsen and Richelieu 1999). However, acetic acid production increased during and after MLF with the inoculated LAB still present in the wine (Nielsen and Richelieu 1999). The main pathways for citric acid metabolism by O. oeni are depicted (Figure 1); notable products are acetic acid, diacetyl, and acetoin (Nielsen and Richelieu 1999).

Prior research investigated citric acid metabolism by *O. oeni* by using model wine media containing sugars, citric acid, and varying levels of phenolic compounds, and by monitoring substrate consumption and the formation of metabolites such as acetic acid and diacetyl. The results showed that *O. oeni* co-metabolizes citric acid and sugars and that phenolic composition significantly influences the extent of citric acid degradation and associated by-product formation during MLF (Rozès et al. 2003). Under the controlled conditions of the study, acetic acid production from citric acid metabolism was observed. However, the concentrations of acetic acid produced were related to a variety of factors such as the concentrations of phenolic compounds and sugars (Rozès et al. 2003). Acetic acid is responsible for the wine fault of volatile acidity, which results in pungent vinegar flavors in wine. At high pH levels like those common in hot climates, LAB activity is less restricted, resulting in potential increased degradation of citric acid that could further increase the overall pH and production of acetic acid.

Glycerol degradation

Glycerol degradation in wine is primarily driven by LAB, which can possess the ability to metabolize glycerol through enzymatic pathways that can negatively affect wine quality. One major pathway involves glycerol dehydratase, which converts glycerol into β-hydroxypropionaldehyde (3-HPA), a precursor to acrolein. When acrolein interacts with tannins, it produces bitter compounds (Popescu-Mitroi et al. 2014). In addition, glycerol can be phosphorylated by glycerol kinase and further metabolized through glycolysis, resulting in the production of acetic acid and acetoin, creating volatile acidity in wines (Popescu-Mitroi et al. 2014). The extent of 3-HPA accumulation is strongly influenced by environmental conditions, with its production increasing as pH increases (being most pronounced at a pH of 6), an effect further exacerbated by high temperatures, particularly ~20°C (Bauer et al. 2010). Furthermore, uncontrolled or spontaneous MLF, especially in high-pH wines typical of warm climate regions, increases the likelihood of glycerol metabolism by LAB strains like *Lactobacillus* spp. (Bauer et al. 2010). A combination of environmental conditions characteristic of warm climates and uninhibited MLF increases the likelihood of excessive glycerol degradation that produces acrolein and acetic acid, resulting in bitter, pungent, and vinegary wines.

Tartaric acid fermentation

Some LAB species such as *Lactobacillus* sp. have been found to degrade tartaric acid, especially in conditions with high pH and low acidity (Krumperman and Vaughn 1966, Radler and Bröhl 1984). In a study evaluating 184 isolates of lactobacilli, 64 isolates induced tartaric acid fermentation. The isolates succeeding in tartaric acid fermentation required a tartrate broth containing yeast autolysate adjusted to pH 3.8 to 4.0, and the exclusion of oxygen (Krumperman and Vaughn 1966). The fermentation of tartaric acid by LAB led to the formation of acetic acid and CO_2, resulting in vinegar-like aromas and flavors, and in some cases, effervescence in the wine (Krumperman and Vaughn 1966). The degradation of tartaric acid can cause excessive deacidification, resulting in flat or unbalanced flavors and increasing the risk of

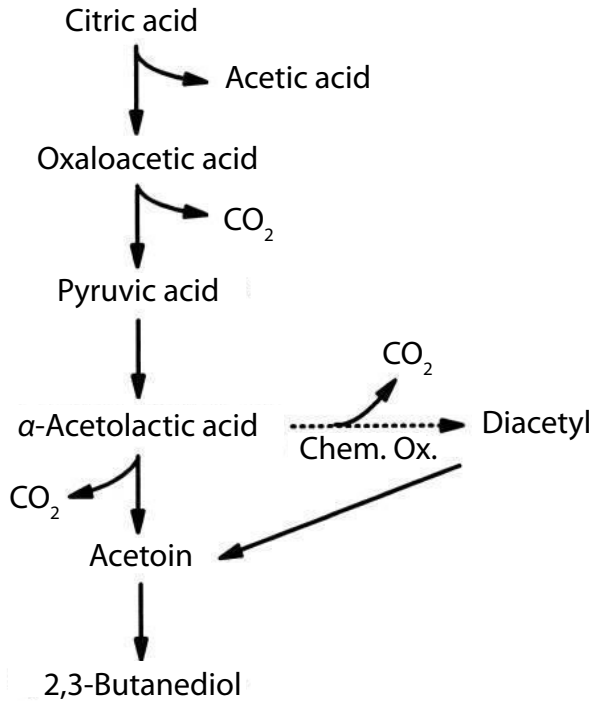

Figure 1 Main pathways for citric acid metabolism by *Oenococcus oeni* (Nielsen and Richelieu 1999).

microbial activity (Krumperman and Vaughn 1966). More recent research has confirmed that some strains, particularly *L. plantarum*, can metabolize tartaric acid via tartrate dehydratase in fruit-juice fermentations, converting tartaric acid into oxaloacetic acid in a manner similar to the citric acid degradation pathway (Ricci et al. 2019). These findings indicate that although tartaric acid is usually considered microbiologically stable in wine, microbial degradation remains possible under specific conditions and with certain LAB strains.

Chemical and Enzymatic Management Strategies

Molecular SO_2

Molecular SO_2 is a largely effective antimicrobial against LAB and inhibits MLF. Studies show that the addition of increasing amounts of SO_2 to grape must is correlated with an increase in the malic acid-to-lactic acid ratio because molecular SO_2 disrupts the metabolic processes of LAB (Quirós et al. 2012). Although SO_2 is widely used to prevent spoilage by bacteria and yeast in wine, it can also trigger allergic reactions in sensitive individuals and contribute to hydrogen sulfide formation (Gerbaux et al. 1997). Furthermore, the effectiveness of molecular SO_2 declines as pH increases (Table 1), making it challenging to stabilize low-acidity wines, which are more susceptible to LAB growth (Fang and Dalmasso 1993, Divol et al. 2012). A recent comparative study examined the effects of multiple MLF inhibition methods, including fumaric acid, chitosan, tannin-based Estaan, medium-chain fatty acids, and SO_2 in white wines. The SO_2-treated wines retained the highest concentrations of key esters such as isoamyl acetate and 1-hexyl acetate, contributing to fruity aromatic intensity (Prusova et al. 2024). These results reaffirm the capacity of SO_2 to preserve volatile compounds despite the industry's move toward reducing its use, due to health and sensory concerns.

Lysozyme

Lysozyme, an enzyme derived from hen egg white, is used as an alternative to SO_2 to regulate LAB and inhibit, postpone, or manage MLF (Gerbaux et al. 1997, Lerm et al. 2010). Lysozyme effectively targets Gram-positive bacteria by hydrolyzing peptidoglycan in the cell wall, causing osmotic lysis leading to cell death (Gerbaux et al. 1997, Lerm et al. 2010). In an evaluation of the ability of lysozyme to reduce lactic bacteria flora in musts and finished wines, the addition of 500 mg/L lysozyme to grape must effectively inhibited MLF, and a post-MLF addition of 250 mg/L to red wines aided in microbiological stabilization (Lerm et al. 2010).

Potential drawbacks to the use of lysozyme are protein-caused haziness and the precipitation of phenols, which alter both color and clarity. A study investigating the effect of lysozyme on the chemical and sensory properties of red (Cabernet Sauvignon and Shiraz) and white (Riesling) wines found that lysozyme addition led to a noticeable reduction in color density and phenolic content of red wines, an effect also perceived by the sensory panel (Bartowsky and Krieger-Weber 2020). In white wines, lysozyme did not increase browning over 6 mo but it did induce heat instability, suggesting a need for protein stabilization post-treatment (Bartowsky and Krieger-Weber 2020). Sensory assessments revealed minimal changes in aroma or palate in both red and white wines over the storage period (Bartowsky and Krieger-Weber 2020).

In another study, the addition of lysozyme to red wines led to a rapid initial decrease in color density (up to 17%) and loss of phenolic content; this was accompanied by a light precipitate that was perceptible in sensory analysis (Bartowsky et al. 2004). In white wines, lysozyme retained 75 to 80% of its enzymatic activity over 6 mo of storage and caused little change in aroma or palate, but induced heat instability (haze formation), indicating that additional protein stabilization (e.g., bentonite) may be necessary (Bartowsky et al. 2004).

Lastly, it was demonstrated elsewhere that certain ropy *Pediococcus* strains exhibit resistance to lysozyme, but combining lysozyme treatment with β-glucanase significantly enhances antimicrobial efficacy against these strains in both model media and wine matrices (Coulon et al. 2012).

Fumaric acid

Fumaric acid (FA) is an effective alternative to molecular SO_2 and lysozyme for MLF inhibition. Application of FA (1 to 2 g/L) to grape musts or wines effectively inhibited MLF, with inhibition comparable to SO_2, while maintaining higher residual concentrations of phenolic monomers (e.g., catechin, epicatechin) during aging (Payan et al. 2023). FA can also be applied to improve acid perception, freshness, and microbial stability in red wines from hot climates (Morata et al. 2019, Gancel et al. 2022, Payan et al. 2023). It has been demonstrated that FA possesses the highest acidifying power among major food acids, requiring roughly 30% less material than tartaric acid to lower pH by 0.1 units in musts and wines (Gancel et al. 2022). Despite its relatively low solubility in aqueous systems and increased solubility in hydroalcoholic media (which depends on ethanol concentration and

Table 1 Effect of pH on the concentration of molecular sulfur dioxide (SO_2) in a wine with a free SO_2 concentration of 50 mg/L (Divol et al. 2012).

pH	Molecular SO_2 (mg/L)	Molecular SO_2 (% free SO_2)
2.8	4.64	9.28
3.0	3.03	6.06
3.2	1.96	3.91
3.4	1.25	2.51
3.6	0.80	1.60
3.8	0.51	1.01
4.0	0.32	0.64
4.2	0.20	0.41

temperature), FA remains an effective acidifying and antimicrobial agent in wine (Gancel et al. 2022). The same study also showed that FA addition did not significantly alter color or phenolic composition after 70 days, indicating good enological stability (Gancel et al. 2022).

Studies assessing the effectiveness of FA compared to molecular SO_2, lysozyme, and lactic acid found that FA concentrations of 300 mg/L or higher completely inhibited MLF, and a concentration of 600 mg/L successfully halted ongoing MLF (Morata et al. 2019). Sensory evaluation panelists in triangular tests did not detect the presence of FA at either 300 or 600 mg/L when compared to control wines without FA addition (Morata et al. 2019). During the preference sensory tests, panelists perceived an increase in both body and acidity in the sample treated with 600 mg/L FA compared to a control sample without FA (Morata et al. 2019). However, at the low concentrations used for inhibition, only a slight reduction in pH was observed, with no repercussions on the sensory quality of the wine (Morata et al. 2019).

The use of FA instead of lysozyme helps maintain phenol stability, preserving the color and complexity of red wines (Morata et al. 2019). Additionally, FA reduces the need for SO_2, thereby limiting sulfite formation and potential toxicity (Morata et al. 2019). The starting pH of the wine in these studies was ~3.8, a condition generally favorable for LAB growth, suggesting that the observed inhibition of MLF was primarily due to FA rather than pH effects (Morata et al. 2019). In a 3-yr bottle-scale study, 600 mg/L FA was added to Tempranillo, Garnacha, and Viura wines; treated wines maintained malic acid levels, exhibited a decline in pH of ~0.05 to 0.10 units (from both preservation of malic acid and the acidifying effect of FA), and sustained very low volatile acidity (≈0.05 to 0.22 g/L) compared to controls (Morata et al. 2023).

Another recent study reported that 0.4 g/L FA completely inhibited MLF in white wine and helped maintain a fresher aromatic profile compared to control wines (Prusova et al. 2024). The FA-treated wines also showed the lowest concentrations of acetoin and other carbonyl compounds, aligning with previous findings that FA preserves fruit character and freshness by limiting LAB activity (Prusova et al. 2024). More research is needed to determine whether FA is effective at inhibiting MLF in wines with higher starting pH values, but FA shows promise as a tool for preserving freshness in hot-climate wines.

Nisin

Nisin is a polypeptide that attacks Gram-positive bacteria by interrupting peptidoglycan formation and cell-wall synthesis, thereby causing ion channels that lead to cell lysis (Daeschel et al. 1991). A study at Oregon State University on the efficacy of nisin at controlling MLF concluded that the addition of 100 U/mL effectively prevented MLF by inhibiting indigenous or added LAB (Daeschel et al. 1991). In a study comparing the antimicrobial activity of nisin and metabisulfite against *O. oeni* and other LAB, the minimal inhibitory concentration for nisin was 0.024 mg/L for *O. oeni* and 12.5 mg/L for other LAB (Rojo-Bezares et al. 2007). The minimal inhibitory concentration for metabisulfite was between 12.5 and 100 mg/L for *O. oeni* and between 50 and 12,800 mg/L for other LAB (Rojo-Bezares et al. 2007). However, nisin and metabisulfite were observed as having a combined effect on LAB and MLF inhibition. Metabisulfite's minimal inhibitory concentration decreased from 50 to 25 mg/L for *O. oeni* and from 200 to 25 mg/L for the other wine LAB when combined with subinhibitory concentrations of nisin (Rojo-Bezares et al. 2007). Another study confirmed these findings, asserting that the use of 50 mg/L nisin decreased the concentration of SO_2 required to inhibit LAB to a quarter of the original concentration (Fernández-Pérez et al. 2018).

In addition, nisin is not known to affect the sensory characteristics of the finished wine (Daeschel et al. 1991). Thus, nisin can be an efficient total or partial replacement for SO_2 to inhibit MLF and other LAB without perceptible changes to wine quality. Although nisin is generally recognized as safe, its regulatory approval and labeling differ by region. It is authorized as additive E234 in the European Union but not currently approved for enological use in the United States (Fernández-Pérez et al. 2018, Reuben and Torres 2024).

Chitosan

Chitosan-based materials have gained attention in winemaking as potential tools for bacterial control and management of MLF. In a comprehensive study, chitosan activity was evaluated across a wide array of wine microorganisms and it was observed that while many species are transiently suppressed, there is considerable variability in strain sensitivity (Miot-Sertier et al. 2022). Another study investigating chitosan during wine fermentation found that it controlled oxidation and undesirable microbial development during both fermentation and wine aging (Scansani et al. 2020). Chitosan's antimicrobial properties were shown to influence the chemical composition of wines fermented with various yeast species (Scansani et al. 2020).

However, it was found elsewhere that chitosan treatment in white wine did not effectively inhibit MLF; complete degradation of malic acid was observed after maturation, indicating that chitosan's antibacterial activity may be limited under certain conditions (Prusova et al. 2024). A different study noted that several LAB species implicated in mousiness, including *O. oeni* and *Pediococcus* spp., are among those most sensitive to chitosan treatment in wine, suggesting that this biopolymer could help mitigate the microbial populations responsible for producing mousy N-heterocycles (Moulis et al. 2023). Beyond its antimicrobial properties, chitosan can bind metal ions, which may slightly modify wine turbidity or clarity, although such effects are typically minor and depend on dosage and wine composition (Cosme and Vilela 2021, Velásquez 2023). This suggests that chitosan-based products can potentially control MLF, but this effect may depend on dosage, LAB strain, wine pH, and duration of contact.

Table 2 Details of defects associated with malolactic fermentation (MLF).

Defect	Conditions increasing susceptibility	Compounds modified	Compounds produced	Sensory effects	Source
Increased pH	High pH, high climatic temperatures, uncontrolled/ spontaneous MLF, malic acid addition	Malic acid	Lactic acid; ethyl lactate and ethyl acetate; propanoic acid; 2-methyl; 3-hydroxy-2,2,4-trimethylpentyl ester	Flavors described as lactic, wet wool/ wet dog, rancid, cheesy, sweaty	Keng et al. 2025
Color instability	High pH, high climatic temperatures, oxygen exposure	Anthocyanins	Glycosidases, anthocyanidins, monomeric anthocyanins	Reduced color intensity, oxidation with increased pH	Tofalo et al. 2021, Burns and Osborne 2013, Bartowsky and Krieger-Weber 2020
Increased alcohol/fusel alcohols	High pH, high climatic temperatures, high alcohol, oxygen exposure	a-Keto acids	Fusel aldehydes, fusel alcohols	Burning/tingling sensation; flavors described as solvent-like, boozy, and bitter	Hazelwood et al. 2008, Lerm et al. 2010, de-la-Fuente-Blanco et al. 2024
Ropiness	High pH, high climatic temperatures, more common in white wine	Glucose	Extracellular polysaccharides, glucan	Increased viscosity, gelatinous substances	Ciezack et al. 2010, Dimopoulou and Dols-Lafargue 2021
Mousiness	High pH, oxidative conditions, uncontrolled/spontaneous MLF	Amino acids	N-heterocyclic compounds, 2-acetyltetrahydropyridine, 2-acetyl-1-pyrroline	Mousiness	Costello et al. 2001
Citric acid degradation	High pH, uncontrolled MLF	Citric acid	Acetic acid, diacetyl, acetoin	Volatile acidity, buttery and nutty flavors	Nielsen and Richelieu 1999
Tartaric acid degradation	High pH	Tartaric acid	Lactic acid, acetic acid	Increased pH, volatile acidity, effervescence, lactic flavors	Krumperman and Vaughn 1966
Glycerol degradation	High pH (>4.0), high climatic temperatures, high postharvest temperatures (>20°C), low alcohol/low fermentable sugar, press wines, wines with prolonged lees aging	Glycerol	3-Hydroxypropionaldehyde, acrolein, acetic acid	Bitterness, volatile acidity	Bauer et al. 2010, Popescu-Mitroi et al. 2014

Table 3 Comparison of lactic acid bacteria (LAB) inhibitors for control of malolactic fermentation (MLF). MIC, minimal inhibitory concentration.

Inhibitor	Mode of action	Effective concentration/ conditions	Advantages	Limitations/drawbacks	Source
Molecular SO_2	Disrupts LAB metabolic processes, antimicrobial against yeast and bacteria	Effectiveness declines with higher pH, requires careful dosing	Widely available, dual antimicrobial and antioxidant role, reported fruity aromatic intensity	Can cause allergic reactions, may lead to hydrogen sulfide formation, less effective at high pH	Fang and Dalmasso 1993, Gerbaux et al. 1997, Divol et al. 2012, Quirós et al. 2012, Prusova et al. 2024
Lysozyme	Enzyme hydrolyzing Gram-positive bacterial cell walls, leading to lysis	500 mg/L in must inhibited MLF, 250 mg/L post-MLF stabilized wines	Effective SO_2 alternative, selective for LAB	May cause haze, phenol precipitation, color loss in reds; heat instability in whites; some *Pediococcus* spp. strains exhibit resistance	Lerm et al. 2010, Bartowsky et al. 2004, Coulon et al. 2012, Bartowksy and Krieger-Weber 2020
Fumaric acid	Inhibits LAB metabolism, slight acidification	≥300 mg/L prevented MLF, 600 mg/L halted ongoing MLF	Enhances freshness and acidity perception, preserves phenolic/ color stability, reduces SO_2 needs	Efficacy in very high pH wines not fully established, limited pH effect, low solubility (~15 g/L in wine)	Fang and Dalmasso 1993, Morata et al. 2019, Gancel et al. 2022, Prusova et al. 2024
Nisin	Polypeptide bacteriocin, disrupts cell wall synthesis and ion channels	MIC ~0.024 mg/L for *Oenococcus oeni*; 50 mg/L reduced SO_2 requirements	Very potent against LAB, synergistic with SO_2, not known to affect sensory properties	While generally recognized as safe as a food additive, nisin is not yet approved for use in winemaking in all regions.	Daeschel et al. 1991, Rojo-Bezares et al. 2007, Fernández-Pérez et al. 2018
Chitosan	Biopolymer disrupts Gram-positive microbial growth, also antioxidant	Applied during fermentation and aging	Natural product, antimicrobial, controls oxidation, limited sensory effects	May alter yeast dynamics, effectiveness as an MLF inhibitor depends on target LAB strain and dosage, found ineffective in some cases at inhibiting MLF during longer aging periods	Scansani et al. 2020, Miot-Sertier et al. 2022, Moulis et al. 2023, Prusova et al. 2024

Conclusions

This review is intended as a practical synthesis of existing knowledge of MLF risks and management strategies in warm climates to support informed decision-making in regions increasingly affected by elevated temperatures and high-pH wines. MLF presents both benefits and challenges, but because climates and soils vary, our methodologies may need to vary as well. Low acidity, color instability, and elevated alcohol levels are common challenges for winemaking in hot climates and an increasing challenge in cool climates. While MLF has been known to improve wine complexity and microbial stability, its effects in high-pH, warm-climate wines may lead to undesirable sensory and structural attributes that compromise wine quality. A comprehensive summary of the complications associated with MLF is provided (Table 2). Advances in inhibition strategies—including the use of molecular SO_2, lysozyme, fumaric acid, and nisin—offer winemakers tools to manage MLF effectively; a summary of the discussed control methods is also included (Table 3). Future research should focus on optimizing these methods for high-pH wines, with an emphasis on their sensory properties.

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Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability

All data underlying this study are included in the article.

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