

UDC 663.21026.784:543.92(4+7+292.94/.99)

MODERN TECHNOLOGIES OF WINE PRODUCTION IN THE CONTEXT OF GLOBAL WARMING AND ORGANIC APPROACH IN VINEYARD

<https://doi.org/10.15673/fst.v18i2.2911>

N. Kamenieva, Doctor of Agricultural Sciences, Professor
O. Verechuk, Ph.D. candidate
Department of Wine Technology and Sensory Analysis
Odesa National University of Technology
112, Kanatna Street, Odesa, Ukraine, 65039

Correspondence:

O. Verechuk
E-mail: olena.verechuk@gmail.com

Cite as Vancouver style citation

Kamenieva N., Verechuk O. Modern technologies of wine production in the context of global warming and organic approach in vineyard. Food science and technology. 2024;18(2):59-74.
<https://doi.org/10.15673/fst.v18i2.2911>

Цитування згідно ДСТУ 8302:2015

Kamenieva N., Verechuk O. Modern technologies of wine production in the context of global warming and organic approach in vineyard// Food science and technology. 2024. Vol. 18, Issue 2. P. 59-74
<https://doi.org/10.15673/fst.v18i2.2911>

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Abstract. The article is of practical importance for Ukrainian winemaking, as global warming can provide the country with additional regions and terroirs. Even the most pessimistic forecasts of global warming and rising temperatures on the planet leave all our zones suitable for growing grapes and expand them to the north. The article analyses modern technologies in the field of white wine production, paying attention to both new technologies that are already successfully working and those that are at different stages of research. The biggest and most meaningful challenge facing winemaking science in the context of global warming at wineries today is to minimise the impact of rising temperatures and decreasing rainfall in the vineyard. All wine production processes are interconnected, so changes will inevitably affect each of them – from the temperature regime of berries at the beginning of crushing, to technologies for maceration and must purification, to new developments and protocols for yeast inoculation, yeast feeding and aging processes in different containers. The technologies of wine production are considered, taking into account modern equipment, various chemical compounds and biotechnologies, everything related to yeast, as well as their products: enzymes, amino acids, vitamins. The directions of development of organic viticulture and winemaking have been identified, using local grape varieties, local yeast races, no additives, irregular temperature control during fermentation and less sulphites, which are more suitable for the sustainable terroirs of historical regions. Attention is also paid to interesting studies on the influence of the size of fermentation and aging tanks, as well as materials for their production. The article discusses the challenges of creating a mass high-quality and terroir wine that must meet the organoleptic qualities and technologies that are strictly prescribed by the legislation of the country of origin. The wine legislation in Ukraine is still in its infancy, so it is especially important to understand the capabilities, resources, needs of our market and the prospects of export markets in order to implement all possible adjustments as efficiently as possible.

Keywords: wine, grapes, terroir, technology, global warming, organic wines.

Introduction. Formulation of the problem

Significant advancements in technology and the development of winemaking have occurred due to globalization. Researchers now have the opportunity to focus on each individual process and elevate it to a certain level of excellence. However, contemporary challenges arise from global warming, which leads to increased accumulation of soluble solids in grapes, elevated sugar levels, and reduced anthocyanin content and acidity [1-4]. These factors can result in premature fermentation cessation or sluggish fermentation, leading to the production of lackluster wines with low acidity and poor aromatic profiles – a situation that causes economic losses for wineries. Until recently, rising temperatures had generally benefited the winemaking industry. Studies suggest that by the

middle of this century, temperatures may increase by 0.3°C to 1.7°C.

One direction of development is the movement toward natural winemaking. This approach involves using exclusively local grape varieties, indigenous yeasts, minimal additives, irregular temperature control during fermentation, and even lower sulfite levels compared to organic wines. While this method aligns well with stable terroirs and historically significant production regions, there are interesting studies regarding the impact of fermentation vessel size and materials [5].

Consumer demands are growing, and they expect high nutritional quality, natural properties, microbiological safety, and minimal chemical processing from food products. This trend encourages companies to adopt new production technologies, including those for winemaking.

Addressing the consequences of global warming is possible both in the vineyard and the winery. Large-scale interventions can occur in the vineyard, such as implementing trellis systems and protective nets, adjusting grape varieties for production, using drought-resistant rootstocks, and employing specific pruning techniques, leaf removal, late pruning, and controlled shoot growth. Additionally, modern technological developments can correct imperfections in grape quality, resulting in commercially viable wines with desirable sensory properties. These technological approaches fall into several categories: equipment (including cutting-edge machinery for necessary manipulations during winemaking), various chemical compounds that can replace or complement existing practices, and biotechnology related to yeast strains and their metabolic products (enzymes, amino acids, vitamins). Researchers face challenges related to reducing sulfur dioxide (SO₂) usage, optimizing or replacing substances used for must clarification and fermentation assistance, acidification, and creating new yeast strains. Often, one technology can address multiple challenges, and conversely, different approaches may be necessary to solve a single issue. In this article, we showcase modern winemaking technologies using the example of producing dry table wines from white grape varieties.

This article holds practical significance for Ukrainian winemaking. Thanks to global warming, the country can access additional regions and terroirs suitable for viticulture. Even the most pessimistic climate change forecasts leave all our zones suitable for grape cultivation and extend them northward. Furthermore, Ukraine historically has been a winemaking nation, and we have every opportunity to increase production volumes. Understanding and implementing cutting-edge technologies will make our future steps highly effective.

The aim of this study is to enhance the technology of white table wines under the conditions of global warming.

Work Tasks:

1. Technological Approaches for Berry Temperature Reduction.
2. Impact of Crushing and Maceration on Organoleptic Characteristics of Dry White Wines.
3. Sulfur Dioxide (SO₂) Addition Regimen and Alternatives.
4. Modern Must Clarification Techniques for White Wine Production.
5. Adjusting Nutrient Protocols in Response to Global Warming.
6. Contemporary Must Adjustment Protocols.
7. Fermentation Temperature Impact on Sensory Attributes of Dry White Wines.
8. Advancements in Yeast Research and Application Protocols.
9. Malolactic Fermentation Influence on Sensory Profiles.

10. Effects of Aging in Different Vessels on Organoleptic Characteristics.

Technological Approaches for Berry Temperature Reduction

Over the past 20 years, the diversity of white wine types and winemaking methods has significantly diminished due to global market trends, consumer taste standardization, and a general tendency among producers to adhere to accepted models. The increasing influence of wine critics on the market has undoubtedly intensified the convergence of white wines into several universally recognized types. Currently, international dry white wines fall into four categories: neutral, Chardonnay, Sauvignon Blanc, and aromatic white wines [6]. However, white wines exhibit greater stylistic diversity than red wines [7]. In fact, aside from still and sparkling wines, white wines can be either dry or contain varying residual sugar levels (ranging from a few grams to several tens, and sometimes even exceeding 100 g/dm³). These differences can arise even from wines made from the same grape varieties, as grapes are harvested at different stages of ripeness. For example, the production of high-quality German, Austrian, and Alsatian Rieslings and Gewürztraminers, Hungarian Furmint, Bordeaux Semillons, and Sauvignon Blancs, Loire Chenins, and more. The fixed acidity of dry and sweet white wines can also vary significantly (from 3 to 6 g/dm³). Additionally, dry wines can undergo malolactic fermentation, a process commonly used for red wines. Intense or neutral, often varietally driven or merely secondary products of alcoholic fermentation, white wines also exhibit more diverse aromas than red wines [6].

The main concept in white winemaking is to process grapes with the aim of immediately obtaining a finished wine with minimal future treatments. After arriving at the winery, the grapes are weighed, sorted, cooled, and pressed. The primary goal at this stage is to quickly transfer undamaged healthy berries to the press to avoid unnecessary oxidation. In fresh, disease-free grapes, various oxidative enzymes, including polyphenol oxidase (PPO), become active upon exposure to oxygen, initiating an oxidative chain reaction that leads to the formation of quinones. Oxygen's impact on grape chemistry, and ultimately on wine, begins as soon as the berry is damaged or crushed. For hand-harvested fruit, crushing is the initial process during which oxygen directly contacts the berry contents, allowing for oxidation. Conversely, machine-harvested fruit continues the oxidation process that began during harvest. While there were previously limited options to protect grape material during this processing phase, apart from the protection provided by sulfur dioxide (SO₂), modern scientific research now explores various approaches to working with grapes before fermentation begins [8].

Berry cooling: In hot weather conditions and insufficient ripening, immediate cooling of the grapes

upon arrival at the winery is necessary to rapidly reduce berry temperature and preserve aromatic compounds. Depending on the timing of cooling, this technique can initiate new polyphenol synthesis.

Partial dehydration: Dehydration refers to the dynamic process of water loss from berries, occurring either on the vine (overripening, late harvest, frost, Botrytis) or post-harvest (under controlled conditions or in open air). It combines water loss with the stress of berry aging. The intense metabolism and chemical reactions in dehydrated grapes, resulting from high temperatures and rapid water loss, lead to decreased terpenes, sesquiterpenes, acids, alcohols, complex esters, benzene derivatives, and C6 compounds, as well as increased norisoprenoids and furan, pyran, and lactone derivatives from browning reactions. All these processes contribute to the desired caramel aroma experienced by the end consumer. Notably, the grape variety plays a significant role in this technique. The primary difference in this technique lies not in the grape variety but in the temperature at which it loses moisture. Lower temperatures allow the wine to express varietal characteristics more effectively.

Ethylene, a colorless, flammable gas with the chemical formula C_2H_4 , can be used post-harvest to enhance the aromatic fraction of wine grapes.

CO_2 is employed for rapid grape or must cooling, positively impacting wine aroma. Dry ice (solid CO_2) releases CO_2 at room temperature, which can remove oxygen. However, its use has limitations requires absolutely healthy grapes and berries, grapes should be packed in perforated containers in a single layer, airtight refrigeration chambers are necessary, empirical determination of interaction time between grapes and CO_2 is essential, cost considerations.

Ozone serves as a disinfectant in winemaking, used at various stages to reduce microbial contamination in grapes and for sanitizing barrels, tanks, hoses, and bottles. Recently, ozone has been explored for food applications as well. When applied to post-harvest grapes without added sulfite, ozone enhances the fruity flavor. It has also been observed that ozone induces the formation of small quantities of sugar oxidation compounds in white grape processing. These include furfural (this compound exhibits sweet, brown, woody, bread, and caramel aromas, with a subtle phenolic content, hydroxymethylfurfural (its aromas encompass richness, oiliness, staleness, waxy notes, and caramel), and 3-Hydroxy-2,3-dihydromaltol (this compound contributes sweet, caramel, cotton candy, fruity jam, and toasted bread nuances).

Impact of Crushing and Maceration on Organoleptic Characteristics of Dry White Wines

Sampling and sample preparation for the The primary goal of grape crushing is to achieve rapid self-flow separation of the must. However, poor organization during this stage can lead to a decrease in the quality of the future wine. The impact and

effectiveness of oxidation control during crushing remain insufficiently studied; nevertheless, it's worth noting that oxidative browning at this stage causes less concern than previously. Several factors contribute to this change, including improved vineyard health practices based on research recommendations regarding mechanical harvesters and the widespread availability of refrigeration equipment [9]. Numerous studies support the relevance of using crushers in conjunction with destemmers. For instance, Ribéreau-Gayon justifies destemming only when maceration is necessary [10]. The advantage of this approach in white winemaking lies in the flexibility provided by the destemmer, ensuring efficient juice drainage. The highest-quality juice, rich in sugar content, resides between the grape skin and seeds. Filtration through the must minimizes skin contact and reduces maceration. However, it's crucial to avoid seed fragmentation, as contamination by seed oil can result in off-putting bitterness [11]. Additionally, phenolic compounds extracted from stems include catechins, flavonols (such as quercetin), and caffeic acid, contributing to the sensory diversity of future wines [12]. Stem maceration may also accelerate fermentation rates [13]. Removing leaves before crushing helps limit the production of aldehydes and alcohols. These compounds form during the enzymatic oxidation of linoleic and linolenic acids extracted from leaf cuticles. Leaf-derived aldehydes and alcohols can impart herbaceous or grassy aromas to wine. However, in small quantities, they may enhance the typical aroma of certain wines. Excessive leaf content in the must can lead to overabsorption of quercetin. If wine is bottled shortly after fermentation, quercetin may cause yellowish haziness in white wines [14]. It's also important to note that more recent studies, using improved press designs, have shown positive results with destemming [11]. After self-flow selection, a denser juice remains, necessitating pressing techniques. The standard press represents a critical point of oxygen exposure to grape components. Essentially, oxygen absorption occurs in two ways during membrane pressing – from the air volume in the empty press chamber during grape loading and from residual interstitial spaces within the grape clusters, where air interacts with the flowing juice and is subsequently drawn into the press chamber. While this process can be automated and suits industrial-scale wines, the resulting juice contains heavy solids and lacks optimal quality. Each fraction of juice (self-flow and post-pressing) ferments separately [15]. Cryoextraction and suprak extraction serve as alternatives to crushing. Suprak extraction increases sugar and phenolic extraction, reduces overall acidity, and raises pH. This technique involves cooling whole grape clusters in small boxes for approximately 24 hours in a freezer at temperatures ranging from $-2^{\circ}C$ to $-3^{\circ}C$. Suprak extraction facilitates the release of aromas and their precursors from the grapes [16]. Although phenolic

extraction from the skin is lower compared to skin maceration or immediate pressing of whole grapes, suprak extraction enhances sugar extraction by 0.3–0.6% potential alcohol. Despite its slow process and high cost, suprak extraction contributes to the expression of noble white grape aromas [6].

Maceration is an optional technological stage in white winemaking. It occurs between grape crushing and must pressing. Aromatic compounds and precursors are primarily found in the grape skin or lower cell layers of most high-quality grape varieties. However, these areas also contain substances with herbaceous aromas and bitter flavors, especially when grapes are not fully ripe, affected by rot, or grown in less favorable terroirs for quality wine production. The decision to use maceration also depends on the grape variety. Published results and winemakers' opinions regarding skin maceration and the resulting wine quality can sometimes be contradictory, as the nature of the grape (variety, health, and ripeness) and maceration conditions (temperature, vessel, and grape handling) significantly influence the outcome. According to some authors, skin contact lasting more than 12 hours leads to lower-quality phenolic wines [17,18]. However, others have found that Chardonnay skin maceration significantly improves wine aroma and structure without increasing bitterness [19]. Skin maceration gained popularity in France during the mid-1980s [16,20]. This operation yields satisfactory results with white Bordeaux varieties (Sauvignon Blanc, Sémillon, and Muscadelle), as well as with Muscat and Chardonnay, provided it is performed with appropriate material on healthy grapes (no positive response to laccase activity) and a single ripeness indicator. The technique involves transferring fully destemmed grapes to a maceration vessel using either a pump or gravity. The vessel is pre-filled with a layer of carbon dioxide gas to prevent oxidation. Sulfiting is avoided to limit the extraction of phenolic compounds. After maceration, the juice is drained, and the skins are pressed. This straightforward system offers enological advantages. The grape is moved only once, minimizing oxidation. The main drawback is press immobilization. After maceration, the juice is first collected by natural drainage (self-flow) and then by inflating the tank membrane, gradually increasing pressure (0.1–0.25–0.4 bar). This process allows for the collection of approximately 90% of the juice. The dried skins are moved to the press using a screw conveyor. Juices obtained through this method contain minimal heavy particles (200–300 NTU) and are particularly well-protected against oxidation. The maceration time varies from 12 to 20 hours, depending on the winery. Controlled temperatures (10–15°C) and oxygen absence during this period allow for appropriate extraction of aromatic compounds from the skin without significant dissolution of phenolic compounds.

Maceration of grape skins leads to a reduction in must acidity and an increase in pH. These changes are associated with the release of potassium from the skins and partial formation of tartaric acid salts. The acidity can decrease by 1.0–1.5 g/dm³, but the extent of these changes depends on the grape variety and terroir [21]. Maceration also enhances the concentration of amino acids in the juice, which contributes to improved fermentation kinetics, often observed in practice. Additionally, macerated grapes provide raw material richer in neutral polysaccharides and proteins compared to whole-cluster pressing [22]. Wines following maceration require higher bentonite concentrations for stabilization [10]. Skin maceration maximizes the aromatic potential of grapes and significantly amplifies varietal aromas without intensifying herbaceous notes. In Muscat wines, these sensory differences can be analytically interpreted by measuring free and bound terpenes. Baumes and colleagues observed an increase in free terpenes (576–742 µg/dm³) and bound terpenes (689–1010 µg/dm³) in 1989 [20]. Measurement of 4-mercapto-4-methylpentan-2-one in Sauvignon Blanc wines also highlights the evident role of maceration in varietal aroma. The concentration increases from 10 ng/dm³ in the control wine to nearly 18 ng/dm³ in the wine made from macerated grapes [6]. Minimal maceration at low temperatures often results in the production of young, fresh, fruity wines. In contrast, longer and warmer maceration typically yields wines with deeper color and more intense flavor. The latter wines may mature faster and develop a more complex character than wines made with minimal skin contact [23]. A novel technique called “cell-cracking” has been explored as a complement or alternative to traditional maceration. It involves gently pressing the must through narrow slots that separate stainless steel balls placed in a small opening, facilitating rapid aroma extraction.

Sulfur Dioxide (SO₂) Addition Regimen and Alternatives

Oxygen interacts with wine at various stages of its production, but its most significant impact is observed during early stages (harvest, pressing, and maceration) and aging. The absence of sensory analysis of finished and bottled wine following properly controlled winemaking trials remains a current gap in the study of oxygen's influence in winemaking. Another challenge lies in understanding the “right” dose of oxygen required for specific wine styles. The average rate of oxygen absorption by the must is 1–2 mL/dm³ per day, which is sufficient to induce adverse changes in aroma, color, and taste, leading to the development of oxidized aromas (stale, vegetal, with hints of dried apples, peel, and stale bread crust, sometimes sharp and chemical, with a flat, watery taste). Even small amounts of oxygen can affect the loss of characteristic fruity notes. Recent research has focused on using oxygen as a factor to achieve desired sensory characteristics, with

hyperoxygenation and microoxygenation being particularly interesting. These methods involve purposeful oxygen contact at low concentrations [24]. The main protective methods for must include sulfiting, bentonite treatment, must illumination, rapid pasteurization with sudden cooling, and must hyperoxygenation. Hyperoxygenation involves oxidizing must polyphenols to precipitate them during illumination and removing them during alcoholic fermentation. However, it is not suitable for grape varieties with high phenolic content (such as Riesling, Muscat, Gewürztraminer, and Sauvignon), as they tend to precipitate during hyperoxidation. Recent experiments with hyperoxygenation help understand the oxygen effect at the upper extreme. The impact of hyperox (Hyperox) on phenolic compounds and volatile aromatic compounds in Chardonnay, Airén, and Macabeo showed that hydroxycinnamoylhydrazones predominantly react with thiols. From a sensory perspective, Hyperox treatment resulted in higher scores for banana aroma, overall impression, and stability quality, while reducing herbaceous and floral aromas. Hyperox treatment was also combined with skin contact to enhance overall flavor potential and increase glycoside flavonol content [25,26]. When using illumination by removing sediment, the must requires additional sulfiting [10]. Illumination of the must using enzymes (gelatin, casein) has been studied and described by Milisavljević and Gayon [27]. It is essential to initiate this process not immediately but after allowing some time for SO₂ oxidation, as it negatively affects enzyme activity [28]. The effectiveness of solid CO₂ (50 g/100 kg of grapes), combined with ascorbic acid (15 g/100 kg) and added to the grapes, minimized flavonol extraction and resulted in higher HCTA concentration, indicating effective protection against oxidation. Notably, sensory analysis yielded significantly higher scores for thiol-like aromas and fermentation ethers [29].

The reduction of sulfur dioxide (SO₂) levels is a hot topic in the winemaking industry. SO₂ has been the most commonly used additive in winemaking for many years. This compound is essential for both wine producers and consumers due to its antiseptic and antioxidant properties. It effectively combats key microorganisms responsible for wine spoilage, including various yeast strains (such as *Zygosaccharomyces*, *Brettanomyces*, *Hanseniaspora*, *Pichia*, *Candida*), acetic acid bacteria (e.g., *Acetobacter* and *Gluconobacter*), and lactic acid bacteria (e.g., *Lactobacillus*, *Leuconostoc*, *Pediococcus*) [30,31]. In addition to its protective role, sulfur dioxide also helps preserve wine color and aroma.

However, excessive use of SO₂ has drawbacks. It can lead to the formation of defects by neutralizing aromatic compounds, and it may have adverse health effects, including sensitivity and allergic reactions [6].

Since 1991, the European Union (EU) has focused on limiting the use of sulfite-based preservatives in organic winemaking. These agents can cause side effects and allergic reactions in sensitive individuals [32]. The EU Commission Regulation No. 606/2009, issued in 2009, specifies a maximum limit of 10 mg/dm³ total sulfite in wine. Furthermore, the International Organisation of Vine and Wine (OIV) has gradually reduced the allowable concentration of SO₂ in wines to 150 mg/dm³ for red wines and 200 mg/dm³ for white wines. Despite ongoing debates among scientists and winemakers, there is a consensus that gradual and controlled reduction of SO₂ usage is preferable [32, 33].

Finding alternatives to sulfur dioxide remains a significant challenge in enology. While classic technologies (such as filtration) can reduce sulfur use, they may negatively impact wine characteristics, particularly sensory properties [34, 35]. Smaller filter/membrane pore sizes correlate with greater quality degradation due to their influence on wine colloidal structures [36, 37]. Researchers are exploring various avenues, including tannins, glutathione, caffeic acid, gallic acid, high hydrostatic pressure, pulsed electric field technology, lysozyme, phenolic grape extracts, chitosan, and dimethyl dicarbonate (DMDC) [38]. However, experiments with plant extracts have yielded insufficient results for widespread adoption [39].

DMDC, a chemical microbial inhibitor, has been proposed as an alternative to SO₂. Recently approved by the EU, it can be used in wines at a maximum concentration of 200 mg/dm³ during bottling for residual sugar content exceeding 5 g/dm³. In the United States, it is permitted for regular use during wine storage at concentrations up to 200 mg/dm³.

Bacteriocins, such as nisin, pediocin, and plantaricin, are small peptides produced by specific lactic acid bacteria (LAB). These compounds inhibit other bacterial species. Bacteriocins are considered ideal preservatives against Gram-positive bacteria because they are colorless, odorless, and non-toxic. Among them, nisin is commercially available and has been shown to effectively suppress spoilage bacteria in wines. Specifically, *Oenococcus oeni*, a LAB commonly found in wine, exhibits high sensitivity to nisin, with a minimal inhibitory concentration (MIC) of 0.024 µg/mL, while other LAB species have an MIC of 12.5 µg/mL. However, nisin has limited impact on yeast strains, with MIC values exceeding 400 µg/mL.

Given the specificity of bacteriocins, combined use with metabisulfite has been proposed to control spoilage bacteria and reduce sulfur dioxide levels in winemaking. Notably, the addition of bacteriocins to wine is not yet permitted, and their antioxidant capacity and impact on wine sensory properties remain unknown.

Lysozyme, on the other hand, is actively used in winemaking and continues to be studied due to its

stability and activity within a pH range of 2.8–4.2. Lysozyme is valuable for inhibiting bacterial growth in wines, particularly spontaneous LAB growth that can lead to spoilage or fermentation arrest. Its effectiveness depends on the structure of the peptidoglycan present in bacterial cell walls. Lysozyme is highly active against Gram-positive bacteria, has low activity against Gram-negative bacteria, and is inactive against eukaryotic cell walls. Using lysozyme at different winemaking stages such as before settling, during early alcoholic fermentation, and during stabilization and preservation is crucial for maintaining low histamine levels in wine. Despite being approved by the International Organisation of Vine and Wine (OIV) over a decade ago, lysozyme usage remains associated with additional costs for winemakers (including enzyme procurement, clarification procedures, and filtration).

Ultrasonication is a relatively inexpensive non-thermal processing technology used in the United States. It serves as a rapid technique for extracting color, aromatic compounds, anthocyanins, phenols, and condensed tannins at various stages of winemaking [40]. By employing ultrasonication, U.S. winemakers can accelerate grape processing by increasing the concentration of phenolic compounds, thereby reducing maceration time compared to traditional methods. Additionally, it can limit the release of astringent substances from grape seeds, which is particularly important for grapes with incomplete phenolic ripening [41].

Pulsed Electric Field (PEF) technology is another innovative method used for food and beverage pasteurization. PEF can inactivate pathogenic and spoilage bacteria at room temperature without compromising product quality [42]. Although the OIV currently recommends PEF for reducing maceration time, it does not specifically mention its use for inactivating spoilage microorganisms in wine, despite reports from several authors on its effectiveness in this aspect [43–45]. Microwave (MW) and irradiation (IR) technologies are still under investigation, and further research is needed to understand their impact on wine quality before OIV acceptance.

Ozone (O₃) is applied in beverage production, during fermentation, and for microbial inactivation post-harvest. It is considered an advanced, environmentally friendly, and versatile technology. Current studies focus on whole-berry ozone treatment before maceration, yielding positive results. Researchers hope that this technology will continue to interest scientists and lead to new technological solutions [46,47].

Ohmic heating (OH) is a process where electric current passes through a material, rapidly generating heat within the product (typically within seconds to minutes). In one study, certain aromatic esters showed an increase of 30% to 200% in musts treated with OH, suggesting that this approach could alter wine composition and impact quality. However, OH technology is still in its early stages of development,

requiring further research for future commercial application in winemaking [48].

Ultra-high pressure homogenization (UHPH) has shown remarkable results, particularly in the context of winemaking. UHPH allows for the destruction of local microorganisms in grape juices, leading to safer fermentation processes and more stable long-term wines. One of the key advantages of UHPH lies in its efficient inactivation of oxidative enzymes, which reduces browning processes while preserving sensory qualities. Additionally, UHPH opens up new possibilities for reducing or significantly minimizing the use of sulfites in wines a challenge faced by modern enology. By eliminating local microbial populations, UHPH not only facilitates the implantation of inoculated cultures but also enhances the utilization of novel fermentation biotechnologies, such as *non-Saccharomyces* yeast strains or mixed yeast-bacterial co-cultures [49].

Modern Must Clarification Techniques for White Wine Production

Wine clarification is a necessary operation to limit the phenomenon of maceration. Wine clarified through this process exhibits more varietal aromas and greater stability, a technique known since the 1960s [25]. Bentonite treatment removes large heavy particles from the wine, which are particularly prone to oxidation. Additionally, adding bentonite addresses the removal of proteins from the must [27]. Protein haze formation in white wines is a common issue in wineries. Although it is a visual defect that does not affect taste or aroma and poses no risk to human health, consumers still find this defect unacceptable. The primary proteins responsible for haze formation are thaumatin-like proteins (TLP) and chitinases (CHI), which are associated with grape pathogenesis (PR) and β -glucanase-proteins linked to grape ripening. Factors that increase protein concentration in grapes include mechanical harvesting, prolonged transportation time and distance, grape infections, and climate variations. Phenolic compounds and sulfates contribute to protein aggregation and increased haze, while polysaccharides may hinder aggregation but do not prevent it. Additionally, slight pH changes can affect protein solubility due to interactions with other macromolecules. The standard bentonite dosage in winemaking ranges from 50 to 100 g/hL and depends on the protein content in the must [2]. However, if white wines undergo aging in barrels or tanks on lees, bentonite treatment is not recommended for two reasons: it worsens organoleptic properties, and lees aging itself acts as a stabilizer for white wines. One drawback of bentonite treatment is that it removes some aroma compounds and aromatic substances from the wine. Other disadvantages of bentonite clarification include wine volume loss (3–10%) due to poor settling and swelling, as well as high disposal costs.

Currently, several alternative methods exist for wine clarification beyond the traditional use of bentonite. These methods offer potential advantages in terms of

efficiency, sustainability, and quality improvement. Let's explore some of these alternatives.

Ultrafiltration (UF). UF is a technique that selectively removes particles based on size. It can effectively clarify grape juices by removing larger molecules, including proteins and colloids. UF is particularly useful for white wines, where protein stability is crucial. **Flash pasteurization:** Rapid heat treatment can be employed to stabilize wines and prevent haze formation. Although flash pasteurization is not commonly used, it merits further investigation. **Enzymes:** Proteolytic enzymes can break down proteins, aiding in clarification. However, their impact on wine quality requires careful consideration. **Chitosan and carrageenan:** These natural polymers can bind to proteins and precipitate them, facilitating clarification [50]. Chitosan, derived from crustacean shells, is especially promising. **Zirconium dioxide (ZrO₂):** Zirconium dioxide particles can adsorb proteins and reduce haze formation. However, their cost-effectiveness needs evaluation. **Magnetic nanoparticles with plasma coating (Acra/MNPs):** This innovative approach involves using magnetic nanoparticles coated with plasma to remove protein haze [51]. While promising, it requires further research to assess any potential release of magnetic components or acrylic acid into the wine. **Zeolites:** Unlike bentonite, zeolites do not swell upon hydration. Natural zeolites offer an interesting alternative for protein removal in white wines. Additionally, their residues can be reused in agriculture. **Ultrasound:** Ultrasound technology, when applied to proteins, can prevent precipitation and reduce the need for traditional fining agents. However, its effectiveness depends on the initial protein profile [52]. **Continuous Zirconium Process:** This method stabilizes white wines by reducing overall protein concentration. Its industrial implementation should consider cost implications. **Nanoparticles:** Researchers are exploring nanoparticle technology for various applications in winemaking. Areas of interest include yeast sediment removal, filtration, light exposure control, antimicrobial action, and selective compound extraction using molecularly imprinted templates.

While these alternatives show promise, their long-term effects on human health remain a critical consideration. As scientists delve into nanotechnology and its potential implantation in the food industry, including winemaking, thorough safety assessments are essential [53].

Adjusting Nutrient Protocols in Response to Global Warming

Oxygen plays a crucial role in the context of fermentation. While freshly prepared grape juice generally contains an abundance of nutrients, predicting the dynamics of microbial development during the 72 hours typically required for *Saccharomyces cerevisiae* to dominate grape juice fermentation remains challenging. Among the factors often associated with biomass

limitation during grape juice fermentation, nitrogen stands out. Nitrogen status is easily measurable and controllable, and advancements in technology have reduced unintentional yeast growth restrictions due to nitrogen deficiency [54]. Nitrogen serves as a structural component of proteins, nucleic acids, chlorophyll, hormones, and amino acids. Ammonium and amino acids are essential primary metabolites in grapes and play a key role in winemaking, serving as the primary energy sources for yeast fermentation. However, excessive summer droughts resulting from global warming can lead to nitrogen deficiency in grape juice, disrupting the fermentation balance and resulting in white wines with limited descriptors and aging potential [54].

Research indicates significant reductions in free amino acid content and increased levels of dry-soluble compounds and proline biosynthesis in grapes from certain vine varieties cultivated under warm climate conditions with limited water availability. Proline, which is not metabolized by yeast, can lead to fermentation stalling and sluggishness when nitrogen availability is low [55].

The nitrogen composition of grapes is primarily influenced by grape variety, vineyard edaphoclimatic conditions, and viticultural practices. Researchers have explored ways to modify grape nitrogen content, but further refinement and supplementation are needed [56]. Currently, nitrogen deficiency is addressed by adding nitrogen to the must. White juices with less than 25 mg/ml ammonium cations or 160 mg/ml assimilable nitrogen should be supplemented with ammonium sulfate. Systematic analysis of assimilable nitrogen concentrations in white juices suspected of nitrogen deficiency should be conducted using the formol index [6,57].

Contemporary Must Adjustment Protocols

Adjusting grape must involves acidification, sugar correction, and deacidification. Acidification is prohibited in most cool-climate European regions, unlike New World countries. Only once, in the hot year of 2003, did the European Union permit the use of such treatments [7]. Organic acids and total acidity play a crucial role in wine sensory perception and directly influence overall organoleptic characteristics. The concentration of organic acids in grape must primarily depends on grape ripeness and variety [58]. However, alcohol fermentation alters acidity levels and content in wine, leading to either higher or lower overall acidity [59]. It's important to note that different organic acids contribute distinct sensory properties. Overall acidity, often expressed as titratable acidity, is mainly influenced by malic, citric, and tartaric acids [60]. During fermentation, several other significant organic acids such as succinic, pyruvic, lactic, and acetic acids are produced by yeast and bacteria. These acids contribute fresh, tangy, acidic, and occasionally metallic flavors to wines [61]. They also enhance wine

stability, especially in white wines [62]. Lower acidity and higher pH generally promote microbial growth, including some undesirable or harmful species [63]. Consequently, wines with high pH require more meticulous microbiological control, often involving increased SO₂ usage. Acid management includes adding acids, primarily tartaric, to grape must with high pH [64]. This practice is particularly relevant in warm viticultural regions, where tartaric acid is typically added at the start of alcoholic fermentation to prevent bacterial proliferation [59]. Liquid chromatography, ion chromatography, gas chromatography, and capillary zone electrophoresis are preferred methods for organic acid analysis [65-72]. Grape-derived acids include tartaric, malic, and citric acids. Fermentation-derived acids include succinic (imparting a salty-bitter taste), lactic (creamy flavor), acetic (volatile, sour, vinegary odor; desired level in wines: 100–300 mg/ml), and pyruvic (contributing acidity; binds SO₂) acids. Recent research has focused on factors significantly affecting organic acid production in wine. However, ongoing studies continue to refine our understanding of these processes [73,74]. For instance, elevated initial pH explains high levels of succinic and pyruvic acids [73,74]. Lower initial pH leads to increased acetic acid and reduced final amber acid content [75]. Sufficient oxygen supply is crucial during citric acid metabolism; even brief interruptions can halt citric acid formation [76]. Aeration during fermentation can enhance succinic, pyruvic, and acetic acid production [77]. Elevated fermentation temperatures increase succinic and acetic acid levels [78]. Vitamins play critical roles in yeast metabolism during winemaking. Let's explore some key vitamins necessary for yeast growth and function: Biotin (serves as a cofactor in carboxylase-catalyzed reactions. It is essential for various metabolic pathways, including fatty acid synthesis and gluconeogenesis), Pantothenic Acid (Vitamin B5, is a functional group of coenzyme A (CoA). CoA is involved in acetylation reactions, such as those occurring during the breakdown of sugars and fatty acids), Nicotinic Acid (Niacin, in the form of nicotinamide (a derivative of niacin), it participates in redox reactions. Nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP) are crucial coenzymes in cellular respiration and biosynthetic pathways), Thiamine (Vitamin B1, in the form of thiamine pyrophosphate (TPP), plays a vital role in decarboxylation reactions. TPP is a cofactor for enzymes involved in carbohydrate metabolism, including the conversion of pyruvate to acetaldehyde during alcoholic fermentation) [79]. The absence of sufficient thiamine, biotin, and pantothenate significantly reduces the concentration of succinic acid in wine while increasing acetic acid and ethanol production [80]. Low organic acid content in grape berries due to global warming, resulting in higher pH, prompts winemakers to acidify must or wine to

maintain microbiological stability and physicochemical balance. Acidification is crucial to avoid detrimental effects on wine color and sensory quality. Chemical acidification remains the most common method used by OIV member countries. It involves adding organic acids such as malic, citric, tartaric, or lactic acid to must or wine. Fumaric acid, with its strong acidifying capacity and market availability, presents an interesting alternative at a lower cost than other acids [81]. Besides chemical methods, OIV allows physical (cation-exchange resins, electro dialysis) and microbiological acidification [82]. In warm viticultural regions, the use of *Lachancea thermotolerans* a natural bioresource that gradually acidifies during the initial stages of fermentation may serve as an excellent alternative to chemical acidification [83].

Fermentation Temperature Impact on Sensory Attributes of Dry White Wines

Temperature control is a crucial component of white wine production. Let's explore its impact. High temperatures lead to active fermentation, resulting in the release of carbon dioxide. However, excessive heat can cause the loss of aromatic compounds. Fermenting at temperatures between 30°C and 35°C may lead to stuck fermentation. Secondary aromas produced by yeast at elevated temperatures tend to be coarser and less desirable. The optimal fermentation temperature for white wines is around 20°C. Slightly lower temperatures can also yield good results, especially if cooling costs are a concern [10]. According to Peynaud, slightly different fermentation temperature ranges are recommended for white wine production: between 18°C and 20°C. However, Ribéreau-Gayon suggests a range of 16°C to 18°C [10]. Research indicates that there is a correlation between lower fermentation temperatures and increased complex ester formation, as well as reduced higher alcohols [84]. Additionally, lower fermentation temperatures slow down the process [85]. Cooler fermentations are desirable for aromatic white wines, while less cool fermentations are used when a more full-bodied wine is desired [86]. Lower temperatures (10–15°C) favor the formation and retention of fruity esters, whereas temperatures between 15°C and 20°C enhance varietal aroma development in specific grape varieties [11]. Stimulation of fermentation can be achieved through yeast inoculation, starting fermentation at 18°C, adding ammonium phosphate, thiamine, and pantothenic acid, as well as providing moderate aeration. Inhibition of fermentation occurs when harvested grapes are stored in the refrigerator for up to 24 hours or when minimal or no maceration is employed [10].

Winemakers have the opportunity to influence the final product by using various fermentation vessels. Oak barrels (225 liters or barriques and 6–12 gallons or puncheons) create favorable conditions for fermentation due to their larger surface area and controlled temperature. However, drawbacks include

cost, manual labor, and the risk of microbial contamination. Neutral vessels (such as cement, stainless steel, metal-ceramic tiles, or fiberglass) allow increased production volumes and process automation but may have limitations like material toxicity, lack of cooling capability, and high cost [10,11]. Recently, clay vessels in the form of qvevris or amphorae have gained popularity. Wines aged in amphorae exhibit better sensory characteristics compared to those aged in stainless steel tanks. Amphorae allow controlled oxygen exchange and unique minerality, flavor intensity, and harmony [87]. Notably, the type of container influences mineral content, flavor-aroma intensity, structure, and harmony. Clay vessels, unlike wood, do not impart additional flavor to the wine. Key descriptors for wines aged in amphorae include notes of toasted forest nuts, subtle vegetal tones, and intense color [5]. Research also shows that clay is a superior oxygen conductor compared to concrete and granite [88].

Advancements in Yeast Research and Application Protocols

The use of yeast represents a critical decision for winemakers, influencing the creation of unique or high-quality mass-produced wines with predictable outcomes. The era of artificial yeast began approximately 30 years ago with the selection of wine yeast strains isolated from successful spontaneous fermentations. At the start of the 20th century, white winemaking employed around 30 active strains of dry yeast belonging to *Saccharomyces cerevisiae*; today, that number has exceeded two hundred [6,89]. Yeast can be either natural (wild) or artificial (cultivated). Artificial yeast strains may be selectively bred or isolated and propagated from specific regions, communities, or vineyards. One intriguing technique for introducing natural yeast involves the “pièce de cuve” method, which was widely used until technological advancements superseded it. The most critical quality for a yeast strain designated for dry white wine is its ability to fully ferment must with turbidity ranging from 100 to 200 NTU (containing up to 220 g of sugar per liter) without excessive volatile acidity. However, this ability to ferment clarified juice is not widespread among wild yeast strains, and sometimes the wild yeast inoculum lacks such strains [6].

In the context of global warming, it is essential to consider yeast behavior, including their role as SO₂ producers. Commercial dry yeast producers now take this crucial property into account during strain selection. However, when winemakers desire spontaneous fermentation, the properties of fermenting yeast strains cannot be guaranteed [90]. Different *S. cerevisiae* strains impart distinct sensory characteristics [91]. Advantages of natural yeast include complexity, uniqueness, terroir expression, and a more balanced wine [92]. Drawbacks include

unpredictability, the potential to produce significant quantities of various volatile compounds (including ethyl acetate, which can negatively impact wine quality) [93]. Advantages of artificial yeast include commercial viability, adaptability to specific tasks and raw materials, and controlled production conditions. However, drawbacks include the need for diverse nutrients (such as nitrogen, vitamins, and minerals), which can become depleted before *Saccharomyces* initiates fermentation. This depletion potentially affects alcoholic fermentation [94].

Both spontaneous and standard induced fermentations can be replaced by inoculating a mixture of local and commercial yeast strains [95]. This combination appears to reduce individual variations, resulting in a more consistent and pronounced character. Such inoculation may involve a blend of species, including *Candida stellata* and *Debaryomyces vanriji* [96,97]. As previously noted, on-site experiments remain the most reliable means of assessing the value of any practice [11]. Another option for winemakers seeking distinctive aspects in their wines is the use of cryotolerant yeasts, particularly *S. uvarum*. *S. uvarum* not only ferments at temperatures as low as 6°C but also synthesizes desirable sensory characteristics. For instance, cryotolerant yeasts typically produce higher concentrations of glycerol, succinic acid, 2-phenethyl alcohol, isoamyl alcohol, and isobutyl alcohol. They also synthesize malic acid while producing less acetic acid compared to many mesophilic *S. cerevisiae* strains [98,99]. Beyond creating unique products, yeast can address challenges posed by global warming. For example, the search for autochthonous *S. cerevisiae* strains adapted to heat-related fermentation stresses becomes crucial for producing quality wines in warm regions. Analyzing enological traits in regions potentially affected by climate change reveals a broad diversity of natural *S. cerevisiae* strains with desirable profiles. This diversity yields strains with varying enological characteristics. Microvinification and sensory tests have identified *S. cerevisiae* strains with intriguing enological properties [100]. Additionally, combining novel biotechnologies such as using *non-Saccharomyces* yeasts in sequential or mixed fermentations and non-thermal techniques for controlling wild microorganisms and oxidative enzyme activity in grapes or must can enhance wine quality in warm regions. This approach can improve the quality of neutral grape varieties or mitigate the expression of underripe grapes. Stability and longevity of these wines are also enhanced through microbial control using innovative non-thermal technologies, bio-protection, and acidification, which some *non-Saccharomyces* species provide, while also reducing SO₂ levels. A comprehensive series of studies has shown that, practically speaking, oxygen addition during the late exponential growth phase is generally the most effective method for stimulating fermentation [101]. Adding 5–10 mg O₂/dm³ is sufficient for optimal

growth in a synthetic must-like fermentation environment [102]. When combined with diammonium phosphate (DAP) addition, fermentation concludes more rapidly with lower residual sugar concentrations, even in musts that might otherwise experience stuck fermentation [103].

The widespread use of sulfiting agents significantly affects the physiology and ecology of yeast during wine fermentation. Other factors contributing to selective growth of certain yeast species over others include osmotic pressure (which increases due to global climate warming), relatively high total acidity, and low pH or ethanol levels produced during fermentation. Specific fermentation styles exhibit their own characteristic factors potentially limiting microbial development. In healthy grapevine microbiota during harvest, the dominant yeast community consists of species that do not withstand the initial hours of fermentation. These include basidiomycetes such as *Cryptococcus* or *Rhodotorula*, and ascomycetes like *Aureobasidium pullulans*. Other ascomycete species, such as *Hanseniaspora/Kloeckera*, *Candida*, *Pichia*, *Torulasporea*, *Kluveromyces*, *Metschnikowia*, or *Starmerella*, can survive longer and co-dominantly thrive during the process for several hours until *S. cerevisiae* takes control of alcoholic fermentation. Indeed, the abundance of these species significantly surpasses the number of *S. cerevisiae* cells on the grape surface. Once in contact with grape sugars, these species initiate alcoholic fermentation. However, *S. cerevisiae* (initially in small quantities) leverages its specific adaptive properties to rapidly outgrow and become the primary yeast during the mid-exponential, tumultuous phase of fermentation. Most often, only *S. cerevisiae* can be easily isolated in the later stages of fermentation. Several physiological adaptations enable *S. cerevisiae* strains to flourish during wine fermentation. They prefer fermentative metabolism, exhibit strict anaerobic growth, and display high tolerance to sulfur dioxide. Additionally, *S. cerevisiae* is more heat-resistant than other wine yeast species, which may contribute to its dominance in this environment [104]. *Saccharomyces spp.* is perhaps the only yeast species in wine capable of consuming all sugars at the appropriate fermentation kinetics, preventing fermentation delays or the prevalence of spoilage-causing microorganisms. Consequently, alternative yeasts are often used in conjunction with *S. cerevisiae* starter cultures, either sequentially or through simultaneous inoculation. Managing this process presents its own challenges, including the interaction between different inoculants, which remains an intriguing area of research [105].

The pronounced dominance of *Saccharomyces cerevisiae* in inoculated fermentations and the widespread use of specific commercial strains have prompted winemakers and researchers to seek ways to avoid visible uniformity in wines. Although diverse approaches existed in the 20th century, it is only in the

21st century that this trend has solidified. Currently, *non-Saccharomyces* yeast strains are gaining market share, distinguishing themselves from *S. Cerevisiae* [106]. Utilizing yeasts other than *Saccharomyces* allows winemakers to restore certain characteristics associated with spontaneous fermentation while maintaining microbiological control. The most recognized impact on wine quality from *non-Saccharomyces* yeasts relates to aromas [107]. These yeasts can enhance the primary wine aroma by releasing active molecules from precursors present in the must. Notably, many contributions to primary aroma such as terpenes and aromatic alcohols originate from molecules primarily found in grapes as glycosidically bound odorless precursors [108]. A crucial influence on wine aroma involves the release of varietal thiols (polyfunctional mercaptans), contributing to the characteristic fruity aroma in wines made from Sauvignon Blanc and other aromatic white grape varieties. This process depends on the activity of β -lyase [109]. Furthermore, these yeasts contribute to the complexity of secondary aromas, primarily through the production of aromatic alcohols and esters that add fruity notes [110]. As with *S. cerevisiae*, it's essential to note that the actual metabolic and technological profile depends not only on the yeast species but also on the specific strain used.

Malolactic Fermentation Influence on Sensory Profiles

After alcoholic fermentation, malolactic fermentation (MLF) may or may not occur. Winemakers make decisions regarding this process based on the grape variety and desired end product. MLF serves dual purposes: it ensures biologically stable wines while potentially diminishing freshness and aromatic qualities. The first mentions of significant acid reduction in must date back to 1864, but it was not until the 20th century that MLF gained scientific attention. In 1913, Müller-Turgau and Osterwald conducted extensive research on this phenomenon [111]. Ferre (1928) and Ribéreau-Gayon (1946) further demonstrated MLF in Burgundy and Bordeaux wines, respectively. MLF significantly impacts wine quality, especially for those with aging potential, and contributes to wine stability [15].

If desired, MLF occurs without sulfite addition, typically at temperatures between 16°C and 18°C. Wine containers should be completely filled. Proper winemaking practices, including moderate filtration, allow spontaneous MLF to begin after varying latent phases [6]. Similar to yeast selection for alcoholic fermentation, understanding wine parameters is crucial when choosing MLF inoculants. Currently, there are few MLF options on the market, all consisting of the *Oenococcus oeni* strain [89]. Recent advances in sequencing the *Oenococcus oeni* genome facilitate research strategies aimed at understanding the implementation of this critical inoculant in

winemaking [112-114]. After MLF, wines are transferred to clean tanks or barrels [86].

Lees aging provides an alternative to MLF, adding complexity to the wine but also introducing descriptors related to autolysis [10]. Daily lees stirring (*bâtonnage*) prevents oxygen dissolution and leverages the yeast sediment's reductive capacity to protect the wine from oxidation. Simultaneously, *bâtonnage* avoids the formation of reduction-related off-odors in the wine [6]. Coarse lees, obtained after fermentation, and fine lees, remaining after the removal of the former, can both be used for aging. The choice depends on the desired texture. Notably, some grape varieties (e.g., Chardonnay) benefit from lees stirring, while others (e.g., Riesling) may suffer from this procedure [86].

Effects of Aging in Different Vessels on Organoleptic Characteristics

Oak barrel aging has a rich history in modern winemaking technologies, and it has been proven to be an effective method for producing many premium wines [115]. Traditional winemaking focuses on using oak barrels in various formats, from *barriques* to *foudres* (ranging from 225 to 1000 liters), for slow and meticulous maturation. Beyond imparting oak-specific flavors, these barrels are considered ideal vessels for aging due to their gradual oxygen permeability and facilitation of tannin and colored polymer polymerization. Oak barrel aging is particularly significant for dry white wines capable of enduring prolonged exposure to oxygen. Oxidation occurs through two planes in this aging method: oxygen diffusion through the barrel walls and oxygen dissolution in the wine surface [10]. Dry white wines suitable for extended aging traditionally undergo fermentation and maturation in wooden *barriques*. This technique was prevalent in Burgundy until the technological revolution, and winemakers returned to it after the 1980s. During this resurgence, complex processes including the role of yeast exocellular and cell wall colloids, redox phenomena related to sediment presence, yeast-mediated volatile compound transformations from wood to wine, and the technology of barrel fermentation and aging were actively studied. Oak barrels exhibit good permeability, allowing oxygen molecules to slowly and steadily penetrate the wood grain and crevices between staves, resulting in gradual and continuous wine oxidation that enhances color and flavor. Additionally, tannins and other oak-derived compounds, such as glycolaldehyde, *guaiacol*, oak lactone, and *eugenol*, dissolve into the wine, improving aroma and taste and reaching the wine's peak or maturity. Similar to alcoholic fermentation, barrel aging has its drawbacks: high cost, lengthy production cycles, and the risk of microbial contamination. This technique is most suitable for expensive wines where oak aging complements the overall bouquet. For everyday wines, fermentation and aging in regular containers compensate for any aroma

deficits [6]. Once fermentation is nearly complete, barrels are topped up with juice from the same batch. If sluggish fermentation occurs, adding recently completed wine can often revive it. After alcoholic fermentation, barrels are stirred daily until sulfiting. Wines undergoing malolactic fermentation are not sulfited until it is complete. During barrel aging, stirring and topping up should occur weekly [6]. If the relative humidity in the cellar drops below 60%, water is primarily lost from the barrel wines (resulting in increased ethanol content). Conversely, when relative humidity exceeds 60%, ethanol is lost (reducing ethanol content). To minimize oxygen ingress through imperfect cork sealing, winemakers using traditional wooden stoppers often store barrels in a humid environment, ensuring the cork remains moist [94]. Wine fermented and aged in new oak contains less phenolic material than the same wine aged in equivalent barrels after fermentation. This is partly due to the co-sedimentation of extracted tannins with yeast cells and mannoproteins during and shortly after fermentation [116]. Shorter aging tends to extract a greater proportion of wood aromas, with the most valuable aspects emerging only during prolonged wine-wood contact [11].

An economical alternative to oak barrels is wine aging on oak staves. It's essential to note that sensory profiles of wines aged in barrels versus staves will differ. This discrepancy arises due to several factors: the absence of heat-induced hydrolysis of oak components (unless the chips are toasted), reduced oxygen influence (as staves lack barrel staves' structure), and variations in microbial modification of oak compounds during wine maturation. Additionally, the surface area-to-volume contact is more significant with staves, impacting the wine differently. For instance, increased absorption of oak lactones can occur [117]. Historically, certain winemaking regions have used barrels made from other woods, such as cherry, acacia, or mulberry. Sensory characteristics vary depending on the wood type. While oak imparts vanilla and smoky aromas, cherry provides intense and persistent notes of red fruits, apples, and ginger, along with softness and flavor. Wines aged in mulberry wood exhibit pronounced fresh and unripe fruit notes [5].

Future research pathways naturally evolve from combining existing gaps in knowledge from literature with new scientific resources available over the past decade. Recent advances in glycan microchip technology promise deeper insights into the role of varietal differences in berry texture, resistance to biotic stress factors, and associated phenolic extraction indices during maceration. Additional questions addressed by glycomatrices include studying the interaction between phenolics and cell wall polymers in berries at different ripening stages, which positively impacts extraction efficiency during winemaking. Furthermore, research in this direction may lead to the discovery and production of novel enzyme cocktails

with improved pectinases naturally derived and safe for winemaking applications [118].

Conclusion

This article delves into contemporary technologies within the realm of white wine production. It covers both established practices already integrated into production and emerging methods that are still in developmental stages, necessitating further research. When adopting new technologies, it is crucial to ensure that sensory and chemical properties of the wine remain unaltered and that there are no adverse effects on human health. Decision-making involves not only winemakers but also legislative considerations, particularly in countries with well-established wine production practices.

Ukraine, as a country currently rebuilding its presence in both domestic and international markets, holds a unique advantage. It can selectively embrace technologies that align with its vision while preserving the sensory characteristics of the product and ensuring affordability and safety for consumers. Let's explore some of these technologies:

1. **Equipment and Machinery:** Modern winemaking benefits from innovations in machinery and equipment. These advancements enhance efficiency and precision during various stages of production.
2. **Yeast and Fermentation:** Yeast strains play a pivotal role in wine quality. Research focuses on local yeast varieties, their impact on flavor profiles, and their suitability for specific grape varieties.

3. **Natural Wine Trends:** The shift toward organic viticulture and natural winemaking is gaining momentum. Using local grape varieties, indigenous yeast strains, minimal additives, and less temperature control during fermentation aligns with terroir-driven and historical winemaking practices.

4. **Alternative Oak Aging:** While oak barrels remain traditional, oak staves offer a cost-effective alternative. Sensory differences exist due to factors like heat-induced hydrolysis (in toasted chips), oxygen permeability, and microbial interactions. Other woods (cherry, acacia, mulberry) also influence wine character.

5. **Future Research Directions:** Glycan microchip technology opens avenues for studying berry texture, phenolic extraction, and interactions between phenolics and cell wall polymers. Enzyme cocktails with improved pectinases are promising. Additionally, research explores the impact of container size and material on aging, especially for terroir-driven wines.

6. **Challenges and Opportunities:** Balancing innovation with tradition is essential. Ukraine's nascent wine industry can strategically adopt technologies while maintaining authenticity. Tasks include creating high-quality terroir-driven wines within legal frameworks.

As we move forward, collaboration between science, industry, and legislation will shape the future of winemaking, ensuring both excellence and accessibility.

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СУЧАСНІ ТЕХНОЛОГІЇ ВИРОБНИЦТВА ВИНА В КОНТЕКСТІ ГЛОБАЛЬНОГО ПОТЕПЛІННЯ ТА ОРГАНІЧНОГО ПІДХОДУ В ВИНОГРАДАРСТВІ

Н. Каменева, доктор сільськогосподарських наук, професор, *E-mail*: kamenevavin@gmail.com

О. Веречук, аспірантка, *E-mail*: olena.verechuk@gmail.com

Кафедра технології вина та сенсорного аналізу

Одеський національний технологічний університет, вул. Канатна, 112, м. Одеса, Україна, 65039

Анотація. Стаття має прикладне значення для українського виноробства, тому що завдяки глобальному потеплінню країна може отримати додаткові регіони та теруари. Навіть найпесимістичніші прогнози щодо глобального потепління та збільшення температури на планеті залишають всі наші зони придатними для вирощування винограду і розширюють їх на північ. Проведено аналіз сучасних технологій в сфері виноробства білих вин, приділено увагу як новим технологіям, які вже успішно працюють, так і тим, що знаходяться на різних етапах дослідження. Найбільш велика і змістовна задача, яка стоїть наразі перед наукою про виноробство в контексті глобального потепління на виноробні – мінімізувати вплив підвищення температури і зменшення опадів, які відбуваються на винограднику. Всі процеси виробництва вина пов'язані між собою, тому зміни неминуче торкнуться кожного з них – від температурного режиму ягід на початку дробіння, технологій по мацерації та очищенню суслу до нових розробок і протоколів внесення дріжджів, підкормки для них та процесів по витримці в різних ємностях. Розглянуто технології виробництва вина з урахуванням сучасного обладнання, різноманітних хімічних сполук та біотехнологій, все що пов'язане з дріжджами, а також продуктів їхньої життєдіяльності: ферментів, амінокислот, вітамінів. Визначені напрямки розвитку органічного виноградарства та виноробства з використанням місцевих сортів винограду, місцевих рас дріжджів, відсутності добавок, нерегулярного контролю температури під час бродіння та меншої кількості сульфітів, які підходять більш до сталих теруарів історичних регіонів. Також приділено увагу цікавим дослідженням по впливу розмірів ємностей для бродіння, витримування, а також щодо матеріалів для їхнього виробництва. Розглянуто задачі по створенню масового якісного та теруарного вина, яке має відповідати органолептичним якостям, технологіям, які строго прописані в законодавстві країни-виробника. Винне законодавство в Україні знаходиться на етапі становлення, тому особливо важливо досягнути можливості, ресурси, потреби нашого ринку та перспективи експортних ринків, щоб максимально ефективно впровадити всі можливі корективи.

Ключові слова: вино, виноград, теруар, технологія, глобальне потепління, органічні вина.