

Review

Fermentative Dynamics and Emerging Technologies for Their Monitoring and Control in Precision Enology: An Updated Review

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Abstract

Alcoholic fermentation in winemaking is a complex bioprocess governed by physicochemical parameters such as temperature, density, pH, CO₂ and redox potential, which critically affect yeast metabolism and wine quality. This review provides an integrated analysis of fermentative dynamics and emerging sensorization technologies, highlighting how their combined implementation enables real-time monitoring and advanced control in precision enology. Advances in conventional physicochemical sensors, spectroscopic techniques (NIR/MIR/UV-Vis) and non-conventional devices (e-noses, electronic tongues) integrated into IoT platforms enable continuous data acquisition, overcoming traditional manual sampling limitations. Predictive modeling, including kinetic models, machine learning approaches (e.g., Random Forest, XGBoost) and model predictive control (MPC/NMPC), supports anomaly detection, optimization of enological interventions and energy-efficient thermal management, while virtual sensors based on Kalman filters improve the estimation of non-measurable states (e.g., biomass, ethanol kinetics). Despite current challenges in calibration and interoperability, these innovations foster sustainable and reproducible wine-making under climate variability and pave the way for digital twins and semi-autonomous fermentation systems.

Keywords: wine fermentation; real-time monitoring; predictive modeling; IoT enology; precision winemaking



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1. Introduction

The alcoholic fermentation of grape is an anaerobic process carried out by yeasts, in which fermentable hexoses, mainly glucose and fructose, are converted into ethanol and CO₂ [1,2]. Both sugars are phosphorylated in the cytosol and converge in the glycolytic pathway, as fructose consumption by some yeasts depends more on specific transporters than fructokinase activity, which is absent in most of these microorganisms [3]. Through glycolysis, each hexose is transformed into two molecules of pyruvate, with a net production of ATP and NADH [4]. Under anaerobic conditions, pyruvate is decarboxylated to acetaldehyde with the release of CO₂, and subsequently reduced to ethanol by alcohol dehydrogenase, regenerating NAD⁺ and allowing the continuity of the glycolytic flux [2,4,5]. From a stoichiometric point of view, the fermentation of glucose and fructose is equivalent, producing two molecules of ethanol and two of CO₂ in both cases [4,6] (Figure 1).

Glycolysis and Alcoholic Fermentation in Yeast

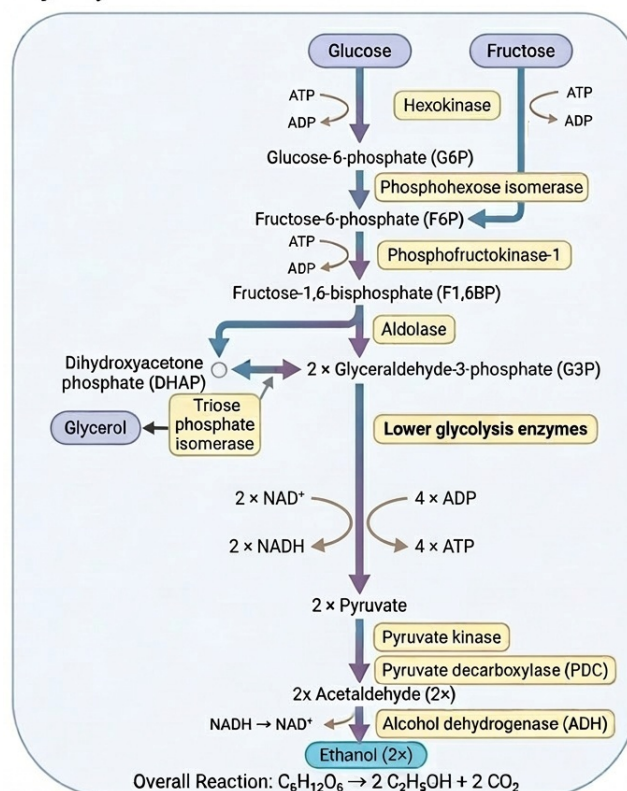


Figure 1. Simplified scheme of the alcoholic fermentation process by the yeast *Saccharomyces cerevisiae* from glucose and fructose. Source: Own figure.

In parallel to the alcoholic fermentation, numerous secondary metabolites are generated by yeast, such as higher alcohols, esters, aldehydes and organic acids that decisively influence the wine's aromatic profile. Fermentative expression depends on factors such as temperature, pH, nutrient availability, redox conditions, all of them determinants for the viability and metabolism of the yeasts present in the medium (Figure 2) [7,8].

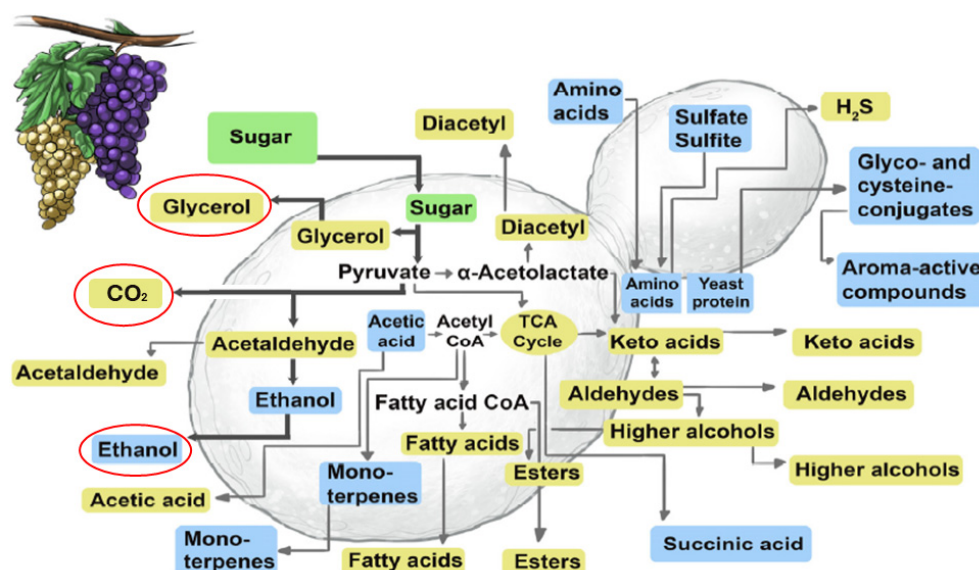


Figure 2. Derivation and synthesis of flavor-active compounds from sugar, amino acids, and sulfur metabolism by wine yeast. Source: Adapted from [9].

The most relevant variables for the control of fermentation in wines are temperature, CO₂ concentration, density, pH and redox potential. Among the controlled variables, temperature stands out as one of the most influential on fermentation speed and the formation of aromatic compounds [7,8]. CO₂ monitoring offers a direct measure of the yeast metabolic rate, while density allows estimating sugar consumption and measure fermentation rates. For its part, the redox potential (Eh) provides information on oxygen availability, the establishment of strictly anaerobic conditions and the stability of sensitive aromatic compounds. The incorporation of these signals into kinetic models and data analysis algorithms enables early anomaly detection, optimization of enological interventions and risks reduction in fermentations [8,10,11].

Recent advances in digitalization have driven the development of real-time sensorization systems capable of monitoring fermentative dynamics with much higher temporal resolution than traditional methods based on manual sampling. Temperature, density, CO₂ concentration, and redox potential sensors allow continuous evaluation of yeast metabolic activity, sugar consumption, and the progressive transition to a reducing environment typical of advanced fermentation phases [12]. The integration of these sensors with Internet of Things (IoT) platforms facilitates remote data collection and its incorporation into predictive models and automated control strategies, which is particularly useful in industrial contexts where kinetic stability and reproducibility are priorities [7,10].

In addition to these parameters, it is essential to consider alcoholic fermentation as a dynamic microbial system governed by principles that transcend the enological field. Recent studies on fermentations in the food industry have shown that processes such as progressive medium acidification, dissolved oxygen decline, metabolic pathway reorganization, and structured production of volatile compounds emerge systematically in complex fermentative ecosystems. These features include redox flux modulation by yeast, synthesis of higher alcohols and esters through pathways like the Ehrlich pathway, as well as interactions with lactic acid bacteria that affect pH, redox stability, and nutrient bioavailability [13]. Malolactic fermentation is a secondary microbiological process in which lactic acid bacteria, namely *Oenococcus oeni*, convert malic acid into lactic acid and CO₂, reducing the wine's total acidity and increasing its microbiological stability [14,15]. Currently, this process is induced in a controlled manner, especially in red wines and certain structured white wines, by inoculating selected lactic acid bacteria cultures after alcoholic fermentation completion, combined with moderate temperatures (approximately 18–22 °C), pH values generally above 3.2–3.3, low levels of free sulfur dioxide (SO₂), and adequate nutrient availability, conditions which favor lactic acid bacteria implantation [15,16]. A properly managed malolactic fermentation contributes to greater mouthfeel softness and aromatic complexity of the wine, although it can lead to the formation of compounds such as diacetyl, responsible for buttery notes whose intensity depends on the bacterial species, oxygen presence, and subsequent aging practices [17]. Conversely, when malolactic fermentation is undesirable (such as in fresh, aromatic white wines or those intended to preserve high acidity), strategies are applied to inhibit lactic bacteria activity, including strict temperature control, wine acidification, maintenance of adequate sulphite concentrations, clarification and sterilizing filtration, as well as microbiological practices that limit bacterial viability [18]. Precise control of malolactic fermentation, therefore, constitutes a key enological tool to define the wine's final style and prevent undesired sensory and microbiological deviations.

Such mechanisms provide a robust conceptual framework for interpreting wine fermentation and understanding how the microbiota responds to physicochemical gradients during the fermentative process (Figure 3).

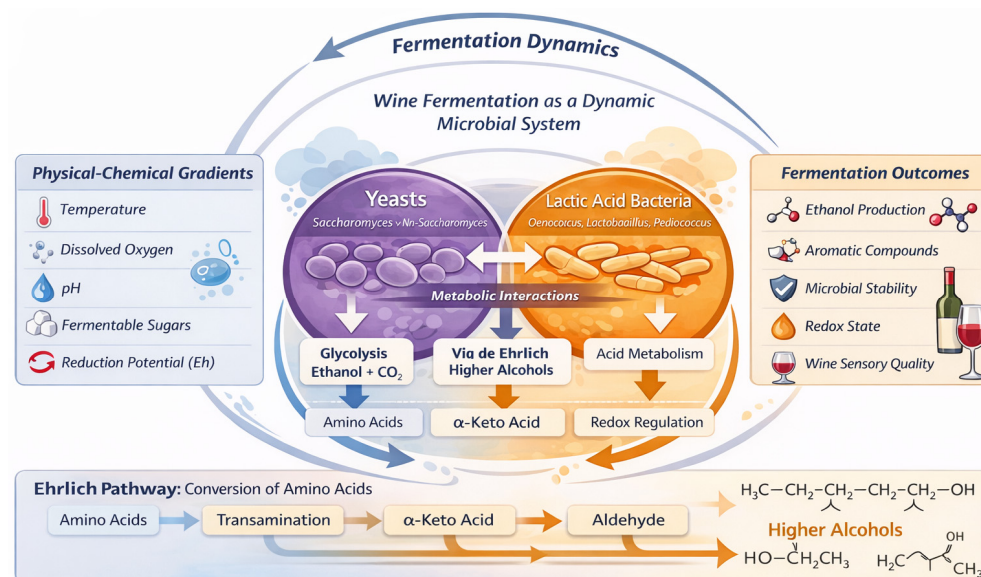


Figure 3. Conceptual diagram of wine fermentation as a dynamic microbial system. Physicochemical gradients (temperature, pH, dissolved oxygen, fermentable sugars, and redox potential) evolve during fermentation and jointly modulate the metabolic activity of yeasts and lactic acid bacteria. This microbial response includes the conversion of sugars into ethanol and CO₂, the synthesis of higher alcohols and esters through metabolic routes such as the Ehrlich pathway, and the modulation of pH and redox state, leading to a structured production of volatile compounds and the progressive stabilization of the fermentative process [19–22]. Source: Own figure.

Traditionally, wine alcoholic fermentation was managed through an eminently empirical approach, based on direct tank observation and discontinuous manual measurements. Process monitoring was mainly carried out from must density, measured with hydrometers or mustimeters, and temperature, recorded punctually with immersion thermometers [18]. pH and total acidity control was carried out through acid-base titrations outside the tank, while fermentation activity assessment was indirectly evaluated from CO₂ release intensity, density changes, or organoleptic changes perceived during the process [20]. These determinations, requiring manual sampling and off-line analysis, offered a fragmented and delayed view of fermentative evolution, with limited temporal resolution [21]. In addition, it should be noted that the yeasts involved in the process, traditionally originating from the autochthonous microbiota from the vineyard, grapes and must, were not selected as is currently done, which generated large deviations in the fermentation process between different vintages or even tanks from the same year [21].

The absence of continuous monitoring and effective thermal control, especially before the generalization of refrigeration systems, significantly increased the risk of fermentative deviations. High temperatures favored uncontrolled fermentative kinetics, losses of volatile aromatic compounds and obtaining sensorially flat or unbalanced wines. Similarly, the lack of early information on sugar consumption rate or yeast physiological state made it difficult to detect thermal or osmotic stress, increasing the probability of slow or stuck fermentations. Dependence on spontaneous fermentations and limited capacity to control parameters such as pH or redox state also favored microbiological deviations, with greater risk of undesirable metabolite production, process stops and lower reproducibility between vintages and tanks [22].

Likewise, the combination of high temperatures and elevated pH increases the risk of microbiological deviations, making it difficult to obtain consistent sensory profiles and accentuating interannual variability associated with climatic fluctuations, making the

adoption of advanced monitoring and control technologies especially valuable in these enological contexts [23].

The relevance of these technological advances transcends the scientific and technical domain, as they have a direct impact on the economic sustainability and competitiveness of the wine sector. In Spain, the vitivinicultural industry generated an annual gross value added of €22,350 million in 2023, which represents approximately 1.6% of the national Gross Domestic Product (GDP), and also includes the contribution of related sectors such as transport, marketing and wine tourism, all of them closely linked to vitivinicultural activity. From a social perspective, the sector supports around 386,110 full-time equivalent jobs along the entire value chain, playing a key role in rural development and population retention, while wine exports contribute positively to the trade balance with a surplus of approximately €3100 million, reflecting the strong international competitiveness of Spanish wines. In this context, improving fermentation control through advanced monitoring technologies is not only a matter of process optimization and product quality, but also a strategic factor for increasing efficiency, reducing production risks and strengthening the global positioning of the wine industry. This characterization is based on the report “Economic and Social Relevance of the Vitivinicultural Sector in Spain”, prepared by Afi Consulting for the Spanish Interprofessional Wine Organization (OIVE) and presented in 2025 [24].

The present review addresses the most recent advances in wine fermentation monitoring and control technologies, including physical and chemical sensors, data integration strategies, and predictive modeling, as well as some examples of its industrial applications.

2. Parameters in Wine Fermentation; Traditional and Actual Management Techniques

Biotechnological and technological strategies have been developed in recent years to stabilize and control precisely the key parameters of alcoholic fermentation. These approaches combine the use of non-conventional microorganisms, yeasts with adapted fermentative kinetics and cold processing and filtration techniques to ensure a complete and stable fermentative course and control the key parameters involved in wine fermentation [25].

2.1. Temperature

The fermentative dynamics of wine is deeply conditioned by a series of physicochemical variables whose interaction determines the yeast metabolic kinetics and, consequently, the final product's sensory profile. Among all of them, temperature constitutes the central axis of fermentative control. In white wines, the recent literature places optimal ranges between 12 and 20 °C, which maintains moderate and stable kinetics while highly thermally sensitive volatile aromatic compounds still preserve in wine [26]. In red wine vinification, higher temperatures around 20–28 °C are used to favor more vigorous fermentative kinetics and the extraction of anthocyanins and tannins during skin maceration [7], although these general guidelines show variations within the Spanish context due to the climatic, varietal, and technological diversity of its wine regions [27].

In the Montilla-Moriles Protected Designation of Origin (PDO), one of the warmest in Spain, thermal control acquires particular relevance. According to the official specifications of the PDO, during the fermentation of young dry wines the temperature must not exceed 25 °C, a limitation aimed at avoiding losses of volatile compounds and preventing stress on the yeasts responsible for the fermentative process [28]. In the case of the Jerez-Xérès-Sherry PDO, regulations do not establish specific temperatures, but enological practice favors relatively fresh fermentations, usually between 16 and 22 °C, especially in musts from the Palomino Fino grape variety destined for base wines for biological or oxidative aging. These moderate temperatures facilitate the balanced formation of acetates and short-chain

esters and allow obtaining neutral and clean wines, consistent with the region's historical profile [23]. Other Spanish regions employ diverse thermal strategies: in Rioja PDO, white must fermentations are usually maintained in a range between 14 and 18 °C, in which terpenic and other volatile compounds are retained [29], while red fermentations reach 22–28 °C, especially during intensive maceration phases [30]. In this context, this term refers to a set of enological practices aimed at maximizing the extraction of phenolic compounds during red wine alcoholic fermentation. These practices include maintaining relatively high temperatures, generally in the range of 22–28 °C, together with greater frequency and intensity of solid–liquid contact operations, such as pump-overs, punch-downs or délestage (rack and return) techniques, as well as the prolongation of maceration time. The objective of these strategies is to favor the maceration and extraction of anthocyanins and tannins, increasing the structure, chromatic stability, and aging potential of the wine, which is consistent with traditional vinification and aging styles [31,31–33].

2.2. Density

Along with temperature, density evolution constitutes one of the most used indicators in fermentation monitoring. Spanish grape musts present initial densities ranging between 1.085 and 1.105 g/mL, equivalent to sugar concentrations between 200 and 240 g/L, although in warm Mediterranean areas, such as southern Spain, values can be even higher, reaching 250 g/L or more due to high insolation and grape ripeness, which allow wine to achieve a natural 15% (*v/v*) of ethanol concentration [28,34,35]. During fermentation, density decreases progressively to values close to 0.992–0.995 g/mL, which indicates the end of fermentation and depletion of fermentable sugars [7]. This decrease is closely linked to CO₂ release, whose measurement, either directly by gravimetric sensors or indirectly by volumetric flow, allows us to characterize fermentative kinetics. Recently, it has been demonstrated that the correlation between acoustic emission and density variation can be used to estimate real-time sugar consumption, opening new perspectives for non-invasive sensorization of industrial tanks [11]. Regarding density and residual sugars, the use of strains with high fermentative power and/or fructophilic yeasts has been investigated to prevent slow or stuck fermentations, especially in musts with high fructose content or glucose/fructose imbalances. These strategies are complemented with real-time monitoring systems (CO₂ sensors, electronic densitometers, and low-cost IoT) that allow early detection of kinetic deviations and the application of corrective measures such as targeted reinoculations or nutritional adjustments [36].

2.3. pH

pH constitutes another critical variable both from a microbiological and chemical point of view. In Spain, white musts usually range between pH 3.1–3.6, while reds reach values of 3.4–3.9, although in warm southern regions like Montilla-Moriles, Jerez-Xérès-Sherry or Jumilla, higher pH initial levels often require acid-technical corrections to prevent microbiological and oxidative deviations [11]. A higher pH, combined with high fermentation temperatures, favors the proliferation of unwanted microorganisms and accelerates chemical oxidation reactions, as they reduce the effectiveness of protective agents like SO₂, leading to greater wine instability, which makes its early control essential [37].

The use of non-*Saccharomyces* yeasts such as *Lachancea thermotolerans* has become consolidated as a tool to increase lactic acid production during fermentation, raising titratable acidity (TA) and reducing pH without the need of external chemical acidification. Recent work focuses on optimizing sequential or mixed inoculation strategies with *S. cerevisiae* to maximize *L. thermotolerans* implantation and predictably modulate the wine's acid profile and microbiological stability [38].

2.4. Redox Potential

Finally, the evolution of redox potential (Eh) during fermentation reflects the system's transition from an oxygenated medium to strictly reducing conditions. Recent studies have shown that musts can start fermentation with values between +200 and +350 mV, which drop to negative ranges of −100 to −150 mV once dissolved oxygen is consumed, and yeast activity is stabilized [10]. These redox changes directly impact the stability of sensitive aromatic compounds, such as thiols and terpenes, as well as the formation of reduced metabolites associated with extreme anaerobic conditions, such as hydrogen sulfide (H₂S) [24].

In summary, the integrated understanding of these parameters (temperature, density, pH, CO₂ and redox potential) allows for the precise characterization of the fermentative state, anticipation of deviations, and optimization of both fermentative efficiency and wine sensory expression.

3. Actual Research Trends and Innovative Future Managements

3.1. Modern Sensorization and Monitoring Technologies in Enology

In recent decades, winemaking has undergone a decisive transition from analytical methods based on manual sampling and off-line analysis to continuous monitoring systems with high temporal resolution. The complex biochemical and physicochemical dynamics of fermentation, whose behavior varies on short time scales, can be affected by multiple simultaneous factors such as temperature, must composition, oxygenation, yeast viability, or metabolic kinetics. In this context, advanced sensorization has emerged as an indispensable component to improve the precision, repeatability, and efficiency of the fermentative process, allowing wineries of diverse scales to adopt more technified and less manually dependent strategies [19,39].

3.1.1. Online Physicochemical Sensors

One of the pillars of this evolution is the development of online physicochemical sensors that allow us the recording of critical parameters continuously without perturbing the fermentative process. The measurement of temperature, density, pH, and redox potential constitutes the basis on which kinetic models and predictive algorithms are built. The exhaustive review by Boulton et al. [7] highlights the relevance of these sensors in industrial fermentations and underscores the need to measure parameters that act as markers of yeast metabolism, such as density, refractive index, or redox. In industrial facilities, the integration of densitometers, load cells, and CO₂ sensors allows for the reconstructing of sugar consumption evolution and detecting sudden variations in fermentative speed that precede slowdowns or stops. Their main advantage is high registration frequency (seconds or minutes), which enables more precise characterization of fermentative kinetics compared to conventional methods based on sampling every 6–12 h [7]. However, the implementation of these systems also presents drawbacks, such as initial investment in equipment and maintenance, the need for frequent calibrations and trained personnel to correctly interpret signals, as well as the risk of generating false alarms or erroneous control decisions when predictive models are not well adjusted to each winery's specific conditions [40].

The convergence between physicochemical sensors and digital platforms has enabled the development of remote monitoring and real-time analysis applications. Among the highlighted advances is the development of electronic microsensors based on semiconductors, microchannels, and microfluidic devices capable of analyzing chemical species both in liquid and vapor phases [7,41]. Projects like Pilot test of new generation sensor integration in Catalan wineries, as a support method for decision making (VISENS) led by the Barcelona Microelectronics Institute (IMB-CNM), attached to the Spanish National

Research Council (CSIC), in collaboration with Catalan wineries, the Catalan Vitivinicultural Cluster (INNOVI), the wineries Celler La Vinyeta, Gramona, and Vilarnau (González Byass), and the companies SC Robotics and Vega Instruments, have demonstrated that measuring multiple parameters every few minutes reduces dependence on antioxidant and antimicrobial additives, such as sulfites, by improving the enologist's reaction capacity to critical process deviations [42]. Another alternative is the approach proposed by the University of Córdoba, which combines the use of IoT technology with a sensor to monitor CO₂ release during the alcoholic fermentation process in real time, providing a low-cost solution to prevent issues such as stuck fermentations [43].

An alternative method for monitoring malolactic fermentation is proposed: employing an ultrasonic portable sensor. An equation correlates the ultrasonic velocity of propagation with the malic and lactic acid concentrations. The authors were able to measure the ultrasonic propagation velocity in different aqueous-alcoholic samples of malic and lactic acids and to monitor an industrial malolactic fermentation process of Tempranillo red wine stored in industrial tanks [44].

These microsensors, operating with minimal volumes and high stability, show significant potential to extend continuous monitoring even to medium-sized wineries with limited technological resources, especially if combined with low-cost IoT platforms.

3.1.2. Spectroscopic Techniques

Beyond traditional sensors, spectroscopic techniques have acquired a central role due to their ability to provide direct molecular information without sample extraction or preparation [45,46]. Near-infrared (NIR) spectroscopy, both in transmission configurations and through optical fiber, allows us to monitor key parameters such as ethanol concentration, evolution of reducing sugars, or organic acidity, with much higher temporal resolution than chromatographic methods [47,48]. This capability is crucial for detecting sudden variations in yeast metabolic activity, which may be indicative of thermal, osmotic, or nutritional stress. The current trend is toward compact devices that integrate LED sources tuned with high-sensitivity photodiodes, capable of operating in poorly controlled conditions such as those found in industrial tanks. Recent studies have demonstrated that these systems can simultaneously estimate glucose and ethanol in fermentation with high precision, opening the door to portable and low-cost instruments that could implement spectral monitoring in the winery [49].

The use of advanced spectroscopy, combining NIR, mid-infrared (MIR), and ultraviolet-visible (UV-Vis) spectroscopy through optic fiber probes, represents a qualitative leap in the ability to analyze the fermentative process in real time. These techniques capture spectral signatures associated with specific compounds, such as ethanol, acetate, organic acids, or aromatic precursors, revealing complex information about the chemical evolution of must during fermentation [45,50]. Although these technologies present important operational challenges, such as the need for extensive chemometric calibrations, the temperature and turbidity sensitivity, and high acquisition costs, their ability to offer non-invasive real-time data represents a competitive advantage for wineries seeking to differentiate themselves through extremely precise control of biochemical evolution [51,52].

3.1.3. Non-Conventional Chemical Sensors

Another emerging field is the use of non-conventional chemical sensors, such as electronic noses (e-noses), electronic tongues, and multisensor arrays based on metal oxides or other semiconductor materials. These technologies do not directly measure the concentration of individual compounds but capture volatile patterns that act as a "fingerprint" of the must and wine state during fermentation. With the help of chemometric techniques and

artificial intelligence, it is possible to correlate these signals with critical enological parameters, detect anomalous fermentations, or predict the formation of phenolic and volatile compounds that influence the final wine's aromatic profile [41,53]. Their integration with analysis platforms opens the possibility of developing early warning systems capable of detecting deviations even before they are perceptible by classical physicochemical methods.

Winery digitalization has been strongly driven by the integration of sensors with IoT systems and cloud-based analysis platforms. Commercial solutions like Winegrid(Ílhavo, Portugal), allow us to monitor parameters, such as density and temperature, remotely and in real-time, centralizing data in digital panels that facilitate decision-making and simultaneous monitoring of multiple tanks [19,54]. These tools, combined with predictive algorithms, offer the possibility of managing fermentation from mobile devices, receiving automatic alerts, and accessing complete process histories. Parallely, various academic initiatives have demonstrated that continuous monitoring systems do not necessarily require complex or high-cost industrial instrumentation. Projects based on microcontrollers like ESP32 or Arduino Mega have enabled the development of wireless nodes capable of measuring temperature, density, CO₂ pressure, or mass variations in fermentation tanks, continuously sending data to digital platforms [39]. In addition, recent studies using ESP32 microcontrollers (Espressif Systems, Shanghai, China) for acquiring acoustic signals associated with yeast metabolic activity have shown that these devices can detect kinetic variations in real time through acoustic emission analysis, providing continuous information without the need for conventional instrumentation. These developments confirm that low-cost IoT nodes represent a technically viable and economically accessible solution for the digitalization of small and medium-sized wineries, allowing us to extend enological monitoring beyond highly modernized industrial environments [55].

Overall, these technologies represent a structural transformation in the management of fermentative processes. The synergy between physicochemical sensors, spectroscopic techniques, emerging devices, and analysis platforms allows for capturing a wealth of data that far exceeds what can be obtained through sporadic sampling (Table 1). This rich and continuous database facilitates the creation of robust predictive models, the design of automatic control strategies, and decision-making based on precise and real-time information, opening the door to increasingly scientific, reproducible, and efficient enology [56,57].

Table 1. Main technologies for sensing and monitoring employed in wine fermentation, including conventional physicochemical sensors, spectroscopic techniques, and emerging devices integrated into digital platforms. The selection of monitored variables, measurement principles, and oenological applications is based on approaches described in the recent literature on commercial fermentations and real-time monitoring systems, as well as academic and commercial developments aimed at winery digitalization and advanced fermentative process control [19,46,58].

Feature/Variable	Main Technology/Approach	Key Parameters	Main Advantages	Limitations/Drawbacks	Prevented Situations
Biotechnological and technological strategies	Non-conventional wine yeasts, strains with adapted fermentation kinetics, cold processing and filtration	pH, TA, density, residual sugars, microbial load	Fine-tuning of acidity and fermentation kinetics, allowing for the complete and stable fermentations without excessive chemical additions	Winery-specific strain selection required, need for optimized inoculation protocols, cost of bioprotective prototypes and filtration equipment	Stuck fermentations, residual sugars consumption, microbiological instability, pH deviations

Table 1. Cont.

Feature/Variable	Main Technology/ Approach	Key Parameters	Main Advantages	Limitations/Drawbacks	Prevented Situations
pH and titratable acidity (TA)	Non- <i>Saccharomyces</i> yeasts (<i>Lachancea thermotolerans</i>)	pH, TA, lactic acid	Increase in lactic acid, pH reduction without chemical agents, improved microbiological stability	Risk of deviations if implantation is not properly controlled, requirement for well-designed sequential/mixed inoculation strategies	Low acidity wines, decreased stability against oxidation and microbial spoilage
Density and residual sugars	Strains with high fermentative power and/or fructophilic yeasts; real-time monitoring	Density, glucose/fructose, CO ₂	Improved fructose consumption in unbalanced musts, early detection of changes in fermentation rate	Need for appropriate strain selection, strict nutritional control, investment in sensors/IoT	Stuck fermentations, accumulation of residual fructose, kinetic deviations leading to reductive off-flavors
Cold processing and filtration	Cold sterilization, microfiltration, ultrafiltration, mild UV combined with low SO ₂ doses	Microbial load, turbidity	Strong microbial reduction without heat, preservation of thermolabile volatiles, alternative to pasteurization	Membrane and maintenance costs, risk of fouling, need for pretreatments and membrane integrity control	Re-fermentations in bottle or tank, contamination by yeasts and bacteria, post-fermentative microbiological spoilage, turbidity after bottling
In-line physicochemical sensors	Temperature, density, pH, redox potential and refractive index probes	Temperature, density, pH, Eh, refractive index (n, IR)	Continuous recording without manual sampling, high measurement frequency (seconds–minutes), basis for kinetic models and predictive algorithms	High initial investment, frequent calibrations, need for trained personnel, risk of false alarms or poorly fitted models	Sluggish/stuck fermentations, overheating, abrupt redox changes (oxidative events or overly reductive conditions)
Digital platforms and IoT	IoT nodes, microcontrollers (ESP32, Arduino), wireless sensors, cloud-based dashboards	Temperature, density, CO ₂ , mass, pressure, acoustic signals	Remote and multi-tank monitoring, automatic alerts, continuous historical recording, accessible from mobile devices	Dependence on connectivity, cybersecurity issues, management and storage of large datasets, integration with existing winery management systems	Undetected temperature peaks, excessive pressure, kinetic deviations that would remain unnoticed with sporadic sampling
Microsensors and microfluidics	Semiconductor-based microsensors and microchannels; microfluidic devices	Dissolved species in liquid and gas phases	Very low sample volumes, high stability, high measurement frequency, potential integration in both industrial-scale and small-volume fermenters	Often at prototype stage, cost and complexity of integration, need for validation under real winery conditions	Local oxidative events, early formation of undesirable compounds (e.g., reductive precursors) that could otherwise go unnoticed

Table 1. Cont.

Feature/Variable	Main Technology/Approach	Key Parameters	Main Advantages	Limitations/Drawbacks	Prevented Situations
NIR/MIR/UV-Vis spectroscopic techniques	NIR, MIR and UV-Vis spectroscopy (fiber-optic probes, compact devices)	Ethanol, glucose/fructose, organic acids, polyphenols	Direct molecular information, non-invasive, high temporal resolution, possibility of multicomponent models through chemometrics	Need for extensive chemometric calibrations, sensitivity to temperature and turbidity, expensive equipment	Deviations in sugar consumption, onset of thermal/osmotic stress, abrupt compositional changes that anticipate the development of wine faults
on-conventional chemical sensors	Electronic noses, electronic tongues, MOS/multisensor arrays	Volatile fingerprints and flavor-related compounds	Detection of aroma and taste fingerprints, early warning of abnormal fermentations and development of sensory defects	Still emerging technology, sensor drift, sensitivity to humidity/temperature, requirement for robust AI-based pattern recognition models	Early formation of volatile sulfur compounds, aromatic deviations, appearance of oxidative or reductive notes
Commercial solutions and integrated projects	Systems such as Winegrid, SmartBarrel, VISENS-type projects (sensors + IoT + advanced analytics)	Combined set of physico-chemical and volatile parameters	Multisensor integration, cloud-based analytics, predictive models, and reduced SO ₂ usage thanks to rapid and informed intervention by the winemaker	Implementation costs, dependence on external providers, need to adapt models to each winery and grape variety	Premature oxidation, microbial contamination, excessive SO ₂ use, kinetic deviations that are not detected in time

3.2. Predictive Modeling and Intelligent Fermentation Control

Advanced monitoring of wine fermentations cannot be understood without a modeling framework capable of interpreting real-time data and transforming it into operational decisions. Traditionally, enology has relied on kinetic models derived from Monod and Hinselwood models to describe the relationship between microbial growth, sugar consumption, and ethanol production [59]. These models, although conceptually useful, present limitations when the system exhibits nonlinear behaviors, as occurs in fermentations with high polyphenolic load, high sugar content, or strong thermal gradients. Nevertheless, their simplicity allows them to be used as a basis for designing state observers and control strategies in processes where data availability is limited [60]. In this line, the kinetic model proposed by Cramer et al. [61] and later adapted by Boulton et al. [62] incorporates the simultaneous effect of temperature, initial sugar and nitrogen concentration on fermentation rate and biomass formation, allowing for quantitative prediction of the transition between normal, slow, and stuck fermentations and, therefore, defining operational temperature ranges or nitrogen supplementation needs before technological problems occur in the winery [63].

3.2.1. Data-Based Models

The increasing availability of online sensors has favored the use of data-based models, supported by machine learning techniques capable of capturing complex relationships between multiple simultaneous signals (density, CO₂, temperature, pH, redox, or NIR

spectra). Recent studies demonstrate that algorithms such as Random Forest, which is a machine learning method based on the aggregation of multiple decision trees trained on random subsets of the data, allows us to model nonlinear relationships between fermentative variables (temperature, density, pH, CO₂) and provides robust predictions even in the presence of typical winery sensor noise [64,65]. These characteristics make it particularly suitable for estimating fermentative rate, predicting stop risk, and analyzing complex spectral data; eXtreme Gradient Boosting (XGBoost), an incremental tree-based learning algorithm ('boosting'), where each tree is trained to correct the residual errors of the previous one, performs nonlinear interactions and handle sensor noise, makes it a suitable tool for predicting wine fermentation evolution, detecting kinetic deviations, and generating early alerts in enological IoT systems. These networks can predict key process variables, such as the fermentative rate, yeast physiological state, or final quality parameters, with high precision when representative training data are available [66,67]. These methodologies have shown particular utility in infrared spectra analysis, allowing for rapid and non-destructive estimation of must and wine chemical composition, with potential for fermentation monitoring [68].

3.2.2. Data Control

In the control field, classic regulation through automatic controllers (proportional integral derivative—PID) remains predominant due to its simplicity and robustness. However, its response capacity is compromised when process kinetics change rapidly or when multiple objectives must be met, such as minimizing refrigeration system energy consumption while maintaining fermentative kinetics within defined enological parameters. Therefore, growing attention has been directed toward model predictive control (MPC), which operates by explicitly predicting the future evolution of the process state, evaluating a set of possible cooling actions over a time horizon, and selecting the one that minimizes an objective function combining thermal error, energy consumption, and control smoothness [69]. The controller only applies the first action of the optimal plan and recalculates at each iteration, providing highly adaptive behavior. In its nonlinear version (NMPC), the model incorporates the nonlinear nature of metabolic heat production and heat exchangers, allowing for more stable thermal profiles and significant energy reductions compared to traditional PID [69].

3.2.3. Integration of Virtual Sensors

An emerging branch consists of integrating virtual sensors and state observers, such as the Extended Kalman Filter (EKF) and associated nonlinear variants, whose objective is to estimate process variables that cannot be measured directly (the viable biomass, instantaneous ethanol production rate, or metabolic sugar consumption rate) from combinations of accessible physical signals [70]. These observers operate in two stages: first, they perform a prediction of the fermentative state based on a dynamic model describing metabolic heat production, sugar evolution, and microbial growth; subsequently, they execute a correction, adjusting that prediction by comparison with real measurements from temperature, density, CO₂, pH, or redox potential sensors [70]. This iterative mechanism allows for real-time reconstruction of the system's biological state even when measurements are affected by noise, foam, or thermal stratifications, as demonstrated in recent applications of extended and nonlinear Kalman filters in bioprocesses [70,71]. The availability of these estimated variables enables the implementation of early warning systems, capable of detecting fermentation slowdown, or approaching stop conditions due to osmotic, thermal, or ethanol inhibition stress in advance [70]. This predictive capability is particularly relevant in warm regions, where musts present high sugar contents and elevated pH, increasing the probability of

kinetic deviations. Additionally, more advanced approaches such as Unscented Kalman Filters (UKF) or particle filters address highly nonlinear dynamics and fuse spectroscopic data with physicochemical measurements, improving observer precision and allowing for simultaneous estimation of fermentative parameters [70–72]. Overall, virtual sensors represent a key tool for process stability by providing a complete view of the fermentative state in real time and enabling faster and more precise corrective decisions [70,71].

3.2.4. Integration of Mechanistic Models, Sensor Data, and Analysis Platforms

At a more advanced level, the integration of mechanistic models, sensor data, and analysis platforms has given rise to the so-called digital twins, whose function is to virtually replicate the behavior of a real tank in real time [56]. These systems combine fermentation kinetic models, energy balances, state estimators, and data from physical sensors to generate a computational representation capable of predicting future process evolution under different operational scenarios [56]. The digital twin not only allows us to simulate how fermentation will respond to changes in temperature, oxygenation, or nutrient addition but provides a safe environment to evaluate control strategies before applying them physically, reducing the risk of overcorrection or yeast stress [56]. Recent prototypes in the agri-food sector have demonstrated that integrating online sensors (density, CO₂, pH, NIR), mechanistic models, and predictive algorithms enables significant improvements in energy efficiency, thermal profile stability, and interannual reproducibility by optimizing real-time decision-making, as shown by SmartWinery and DigitWine initiatives in wine fermentation [56,72]. In the enological context, these systems allow for anticipating kinetic deviations, for example, quickly detecting a drop in metabolic rate or an incipient risk of fermentation stop, and generating automatic recommendations based on parallel simulations. Although their adoption in wineries is still in early stages, the evolution of these digital twins points toward semi-autonomous fermentation systems, where the process continuously adapts through supervised learning and dynamic model updating, integrating both vintage-to-vintage grape variability and tank heterogeneity within the same winery.

Overall, the transition from simple kinetic models toward advanced data-based systems, predictive control, and digital platforms represents a natural evolution of modern winemaking. This technological integration not only improves operational and energy efficiency but constitutes a decisive advance toward more consistent, reproducible wines aligned with demanding quality standards.

3.3. Commercial Devices and Industrial Applications of Predictive Modeling

The integration of online sensors, predictive models, and advanced control strategies is transforming wine fermentation management, enabling improved quality, reproducibility, and energy efficiency of the process. Unlike the traditional approach based on discontinuous sampling and empirical decisions, the availability of continuous data from physicochemical and spectroscopic sensors, and virtual observers enables precise monitoring of fermentative kinetics and tighter process condition control.

Several commercial devices have been engineered for industrial application to enable real-time oversight of alcoholic fermentation processes. These systems facilitate continuous tracking of critical parameters such as density and temperature, enhancing process control and decision-making in winemaking operations.

The Wineplus 1110, developed by Winegrid (Ílhavo, Portugal), employs a lateral tank-mounted sensor with liquid-level self-compensation to deliver precise density and temperature measurements. Constructed from AISI 316 stainless steel for the probe and AISI 304 for the external housing, it features customizable visual Light-Emitting Diode

(LED) alarms integrated into an IoT platform, obviating the need for extensive data interpretation. Validation in red and white wine fermentations demonstrated its reliability, compactness, and ease of cleaning, with seamless integration into Winegrid's dashboard for real-time visualization [73].

Winegrid further provides barrel-compatible wireless monitoring via LoRa technology, capturing temperature and density while applying AI to detect anomalies, alongside solutions for secondary fermentation, barrel aging, and winery environmental conditions. Similarly, Onafis's B-evolution bung developed by Enartis (Trecate, Italy), monitors hydrology, pressure, temperatures, wine levels, and dissolved oxygen during fermentation and aging, supported by a dedicated dashboard [74].

Precision Fermentation's BrewIQ system assesses multiple variables, including dissolved oxygen, pH, gravity, pressure, temperatures, and conductivity, via Wi-Fi-enabled lateral tank installation, with configurable alerts on a control dashboard. Anton Paar's Fermentation Monitor 5100 (Graz, Austria) utilizes refractive index changes to estimate alcohol content, real fermentation degree, fermentation rate, and density in wine, beer, and spirits production, compatible with industrial communication protocols like EtherNet/IP, Modbus, and Highway Addressable Remote Transducer (HART), though lacking a cloud interface [75,76].

Ifm (Essen, Germany) has developed a real-time Brix monitoring system in wine fermentation, which employs pressure sensors (PI17 Series) enabling non-invasive hydrostatic density measurement over a representative fluid column. This approach yields high-resolution tracking of density decline during alcoholic fermentation, correlating with sugar depletion by yeast metabolism [77].

Currently, no commercial sensors target malolactic fermentation monitoring; instead, reliance falls on malate-to-lactate conversion tracking or costly chemical assays of malic acid in wine [78]. The ultrasonic portable sensor previously described in Section 3.1.1 offers a promising, economical alternative for rapid in-winery assessments [44].

The extensive datasets from these sensors support predictive modeling to expedite enologists' decisions during alcoholic fermentation. In Rioja and Somontano PDOs (Spain), machine learning algorithms (linear regression, support vector machines, regression trees, ensemble trees, and Gaussian process regression) were employed during industrial alcoholic fermentations of grape must in stainless steel tanks, to model density dynamics from thermal data like temperature gradients and cooling responses. Gaussian process regression excelled, achieving a 99% determination coefficient and 0.032 mean squared error against lab-validated densities, confirming temperature as a robust density evolution proxy across different vintages and grape varieties [79]. It would be of our interest to evaluate the use of different yeast populations, since, depending on which species or strain the fermentation process dominates, the thermal data obtained will be different due the distinctive metabolism of each strain. Recent studies have applied machine learning techniques to classify and identify distinct *S. cerevisiae* strains based on the metabolites they consume and produce under varying alcoholic fermentation conditions. Using random forest algorithms, these approaches achieved up to 74% accuracy in strain identification when leveraging comprehensive metabolite datasets. However, model performance declined notably when restricted to primary metabolites alone, resulting in higher misclassification rates [80].

Although conducted at laboratory scale, these findings hold substantial promise for future industrial applications, potentially enabling the precise determination of specific *S. cerevisiae* and non-*Saccharomyces* strains that mostly influence the sensory and chemical profile of individual wines [80].

Despite these advances, important limitations persist. One of the most relevant is dependence on the quality data: the performance of predictive models and state observers

is affected by sensor noise, thermal stratifications within the tank, and skin presence in red fermentations, which hinder precise density or CO₂ measurements. Likewise, developing robust models requires local calibration, as must characteristics vary significantly between regions, varieties, and vintages; this variability requires retraining models and adjusting parameters before each campaign [59,70]. In the case of spectroscopic technologies, their effectiveness depends on complex and matrix-specific chemometric calibrations, limiting their transfer between wineries without prior adequate adjustment.

Another limitation is operational complexity; although digital twins and predictive controllers offer significant advantages, their implementation requires advanced knowledge of modeling, digital integration, and software maintenance, hindering adoption in small wineries without external technical support. Interoperability between sensors, IoT platforms, and management systems also represents a challenge, as the lack of unified communication standards complicates integrating devices from different manufacturers. Likewise, interpreting complex data generated by machine learning algorithms requires specific training not always available in traditional wineries.

Despite these limitations, future prospects are clearly favorable. Evolution toward semi-autonomous fermentation systems, driven by digital twins that update in real time through sensor-fed prediction models, opens the door to processes capable of continuously optimizing according to must and environment conditions, as demonstrated by recent developments of digital twins applied to food fermentation control [81]. The rapid expansion of low-cost sensors, open IoT platforms, and self-adjusting algorithms will reduce entry barriers for medium and small wineries, enabling digital enology democratization. Likewise, hybrid systems integrating mechanistic models and machine learning algorithms are expected to grow, combining interpretability and advanced predictive capacity.

Overall, incorporating advanced technologies in wine fermentation represents one of the most significant transformations in modern enology. Although technical and operational challenges remain, accumulated evidence suggests their application will continue expanding, driven by the need to improve energy efficiency, ensure reproducibility, and adapt to new conditions imposed by climate change and constant quality demands in global markets.

4. Conclusions

The integration of online physicochemical sensors (temperature, density, CO₂, pH, and redox potential), spectroscopic techniques (NIR/MIR/UV-Vis), and non-conventional devices (e-noses, electronic tongues) connected to IoT platforms are of great interest in real-time control of alcoholic fermentation, overcoming the limitations of traditional manual methods. These systems enable early detection of kinetic deviations, optimization of enological interventions, and preservation of heat-sensitive aromatic compounds.

Advanced kinetic models, machine learning approaches (Random Forest, XGBoost), and nonlinear model predictive control (NMPC), complemented by virtual sensors (Kalman filters), facilitate the estimation of unmeasurable states such as biomass and ethanol kinetics, enhancing energy efficiency and reproducibility. Emerging digital twins simulate fermentation scenarios, anticipating risks from osmotic or thermal stress and paving the way for semi-autonomous systems which provide high valuable information to enologist immediately.

However, the industrial-scale implementation of both sensors and technologies that fully leverage the information and data generated by these devices remains scarce, with most studies conducted at the laboratory scale. The majority of studies and sensors focus on parameters such as density, temperature, or kinetic curves, while the real-time study of microbial populations and their dynamics during alcoholic fermentation remains a challenge.

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