| | |
|---|---|
| **Секція Економіка** | |
| **УДК 338.45:663.2:658.5** | |
| **Дата першого надходження статті до видання** | 2026-01-15 |
| **Дата прийняття статті до друку після рецензування** | 2026-02-28 |
| **Дата публікації/оприлюднення** | 2026-02-28 |


# Pre-Investment Economic Model for $CO_2$-Based Adaptive Temperature Regulation in Wine Fermentation

**Maiia Fedash**
Founder & Executive Scientific Director, Principal Investigator,
American Center for Applied Nutritional Systems & Public Health (AC-ANSPH), Sacramento, California, United States
e-mail: mayafedash@gmail.com
https://orcid.org/0009-0001-2157-7349

**Abstract.** Alcoholic fermentation ties up vessel capacity and consumes labour, energy, and corrective inputs; sluggish or stuck batches may also reduce contribution margin through rework, delayed turnover, or quality markdown. This article develops a pre-investment economic model for $CO_2$-based adaptive temperature regulation in wine fermentation. The evidence combines a targeted review of research available by 31 December 2025 with document-based analysis of eight Chardonnay fermentations described in an unpublished 2025 R&D report. All six adaptive trials reached a report-defined dry endpoint, while both non-feedback comparison trials showed adverse kinetics; however, temperature exposure, yeast strain, and juice handling were not matched, and the report contains no numerical raw dataset. The economic model defines equivalent annual net benefit as $\Delta\Pi = A + L + K + Q + E - Csys(M)$. Direct event loss is decomposed across mutually exclusive fermentation-outcome classes, $A = N\Sigma p_0 k\ r_k L_k$, and annual total cost of ownership is allowed to increase with the number of equipped vessels M. For a single event class, the A-only break-even rule becomes $r^* = \lambda/q$, where $q = Np_0$ and $\lambda = Csys/Lf$; break-even on this component alone is feasible only when $q \geq \lambda$. Thus scale does not automatically improve project economics: additional batches reduce the required effect only when expected loss exposure grows faster than system cost. A second decision rule uses the expected value of sample information to determine whether a prospective field validation is worth its cost. The proposed dataset links each batch to event class, residual sugar, labour, vessel-days, quality, cooling electricity, chiller performance, and system ownership cost. The model converts sparse technical evidence into testable economic thresholds without substituting hypothetical ROI for unobserved cash flows.

**Keywords:** wine production economics, alcoholic fermentation, adaptive temperature regulation, carbon dioxide monitoring, break-even analysis, total cost of ownership, vessel capacity, value of information.

# Модель попередньої оцінки інвестиційної доцільності адаптивного регулювання температури бродіння за даними $CO_2$

**Федаш Майя**
засновниця та виконавча наукова директорка, головна дослідниця,
American Center for Applied Nutritional Systems & Public Health (AC-ANSPH), м. Сакраменто, Каліфорнія, США
e-mail: mayafedash@gmail.com
https://orcid.org/0009-0001-2157-7349


e-ISSN: 2786-586X

**Анотація.** Спиртове бродіння пов'язане із зайнятістю виробничих ємностей, витратами праці та енергії, а уповільнене чи зупинене бродіння може спричиняти додаткові витрати на коригувальні операції, затримку обороту ємностей і зниження вартості продукції. У статті розроблено економічну модель попередньої оцінки інвестиційної доцільності адаптивного регулювання температури бродіння за даними про виділення $CO_2$. Інформаційну основу становлять вибірковий тематичний огляд досліджень, доступних до 31 грудня 2025 року, і документальний аналіз восьми випадків бродіння сусла сорту Шардоне, описаних у неопублікованому звіті про НДДКР 2025 року. Усі шість дослідів з адаптивним регулюванням було виброджено до сухого стану за критерієм вихідного звіту, тоді як в обох порівняльних дослідах без регулювання за сигналом $CO_2$ зафіксовано несприятливу кінетику. Водночас температурні режими, штами дріжджів і обробка сусла не були зіставними, а числовий первинний масив відсутній. Економічна модель визначає еквівалентний річний чистий ефект як $\Delta\Pi = A + L + K + Q + E - Csys(M)$. Прямі втрати розкладено за взаємовиключними класами результату бродіння: $A = N\Sigma p_0 k\, r_k L_k$, а еквівалентні річні витрати на володіння системою залежать від кількості оснащених ємностей M. Для одного класу подій критерій беззбитковості за складовою A набуває вигляду $r^* = \lambda/q$, де $q = Np_0$, $\lambda = Csys/Lf$; здійсненність такого сценарію потребує $q \geq \lambda$. Отже, збільшення масштабу саме по собі не гарантує кращої економіки: поріг знижується лише тоді, коли очікувані втрати зростають швидше за витрати на систему. Додатково запропоновано використання очікуваної цінності вибіркової інформації для рішення про доцільність польової валідації. Для подальшого розрахунку потрібен облік у розрізі партій: клас події, залишковий цукор, праця, резервуаро-дні, показники якості, електроенергія охолодження, COP холодильної установки та повні витрати на володіння системою.

**Ключові слова:** економіка виноробства, спиртове бродіння, адаптивне регулювання температури, моніторинг $CO_2$, аналіз беззбитковості, сукупна вартість володіння, використання ємностей, цінність інформації.

## Introduction

**Relevance of the problem.** Alcoholic fermentation uses scarce winery resources: tank time, labour, cooling capacity, nutrients, and management attention. Slow or incomplete fermentations can extend vessel occupancy and require corrective work, while quality defects may reduce saleable value. Ukrainian studies place winery digitalisation within management development and competitiveness [1; 2]; a broader agro-industrial study likewise treats resource-efficient technological renewal as a competitiveness factor [3]. For fermentation control, the investment question is process-specific: whether the incremental cash-flow benefit generated by better decisions is sufficient to recover the annual cost of sensing, integration, actuation, maintenance, and data handling.

**Analysis of recent research and publications.** Giovenzana et al. compared automated and conventional fermentation management using fermentation duration, labour, nutrients, oxygen, water, energy, and variable costs, and found that the economic result depended on winery scale [4]. Girotto et al. argued that centralised process data can help identify resource inefficiencies in winery operations [5]. Advanced-process-control research supplies the financial logic: technical improvement must be translated into incremental cash flows and compared with project cost [6; 7]. Howard's information-value theory adds the decision dimension by valuing information according to the economic consequences of the decisions it changes [8]. Enterprise-level evidence from French organic wineries also associates digitalisation with financial performance, although it does not identify the effect of fermentation control [9].

Technical research has expanded the available monitoring and control options. Reviews cover sensors for oenological processes and commercial fermentation monitoring [10; 11];

$CO_2$-rate-based control has been modelled explicitly [12]; SmartBarrel and Winnie illustrate multi-sensor and modular monitoring systems [13; 14]; and a low-cost IoT device demonstrated real-time $CO_2$ monitoring for detecting stuck fermentation at laboratory scale [15]. A dataset of 222 commercial red-wine fermentations shows why a simple temperature narrative is insufficient: summary temperature measures did not significantly predict successful completion across that dataset [16]. Energy and tank-management studies further show that temperature policy changes both heat-removal requirements and production scheduling [17–20]. Classic enological work describes the multiple causes of stuck and sluggish fermentations [21], while online $CO_2$-based kinetic prediction predates current digital platforms [23; 24].

**Identification of the unresolved part of the problem.** The literature provides sensors, fermentation models, energy methods, and general economic assessment tools, but it does not provide a compact winery-level rule that links a prespecified fermentation outcome to its incremental cash-flow consequence, allows system cost to vary with the number of equipped vessels, and states when the expected technical effect can reach break-even. This gap is important when technical evidence is limited to pilot observations and the winery must decide whether a larger validation study is economically worth conducting.

**Purpose of the article.** The purpose is to develop a pre-investment economic model for $CO_2$-based adaptive temperature regulation that links fermentation outcome classes with direct event losses, labour, vessel capacity, quality, energy, and annual total cost of ownership, and to derive decision rules for both equipment adoption and prospective field validation.

**Scientific novelty.** The contribution is an application-specific extension of established process-control economics: event losses are separated by outcome class, total cost of ownership is allowed to contain fixed and per-vessel components, the break-even condition is expressed as a feasibility boundary, and the next validation stage is evaluated through the value of sample information.

**Practical significance.** A winery can use the model with its own production records to determine whether break-even is attainable, identify which missing measurements affect the decision most, and design a field trial that produces the labour, capacity, quality, energy, and reliability data required for a full investment appraisal.

## Methodology

**Research methods.** The study combines a targeted narrative review, document-based descriptive analysis of reported trial outcomes, and process-economic modelling. Google Scholar and publisher platforms were searched with combinations of “wine fermentation monitoring”, “$CO_2$ fermentation control”, “stuck sluggish fermentation”, “fermentation energy”, “process control economics”, “value of information”, and “wine production economics”. Peer-reviewed studies were retained when they addressed fermentation monitoring or control, resource use, industrial control economics, or investment decisions. Ukrainian-language studies on winery management and agro-industrial competitiveness were additionally screened to retain the domestic economic context [1–3].

**Data sources.** The pilot evidence comes from I. Burdinskyi's unpublished 2025 R&D report, “Feedback Control of White Wine Fermentation Kinetics: Experimental Development of an Adaptive $CO_2$-Based Real-Time Fermentation-Rate Control” [22]. The document describes eight Chardonnay fermentations, including six adaptive trials and two comparison trials without $CO_2$-based feedback, with plotted trajectories, interventions, and endpoint descriptions. It provides no numerical observation-level dataset; batch duration, energy use, and within-batch variability therefore remain unavailable. The literature base comprises peer-reviewed economic, engineering, and oenological studies [1–21; 23–26].

**Analytical tools.** Pilot outcomes were coded from the wording of the report; silence was not interpreted as evidence that an event was absent. For prospective validation, outcome classes must be defined before data collection. A practical severity scheme is: normal


e-ISSN: 2786-586X

completion; sluggish fermentation that completes without restart; and stuck fermentation requiring restart or reinoculation. The final dry-wine endpoint should be confirmed analytically by glucose plus fructose rather than by hydrometer alone; the OIV defines dry wine as no more than 4 g/L, or up to 9 g/L under its acidity condition [26]. Capital expenditure is converted to an equivalent annual amount with a capital-recovery factor. Unless a winery applies its own tax model, the screening equations are stated in real, pre-tax terms, so the discount rate and cash-flow inputs must be expressed on the same basis.

**Research limitations.** The documentary pilot is small, heterogeneous, and not randomised; the two comparison fermentations were later warmed, so feedback and thermal exposure are not isolated. Trial 1.1 has no explicit sluggish/stuck classification, and laboratory residual sugar was not reported. The pilot is therefore used to identify event types, not to estimate event probabilities or treatment effects. The economic model is uncalibrated until winery-specific cost, utilisation, and reliability data are supplied.

## Results

The 2025 report monitored outlet $CO_2$ in all eight Chardonnay fermentations. Adaptive vessels used the gas-flow signal to select temperature within preset bounds. The two comparison vessels did not use fermentation rate to determine temperature, but both were subsequently warmed; they are therefore described here as non-feedback comparisons rather than fixed-setpoint controls. Temperatures are converted to degrees Celsius in Table 1. The report's early target was about 0.5 °Brix/day until approximately 11 °Brix, followed by a target near 1 °Brix/day subject to an upper temperature of 17.8 °C [22].

Table 1

**Outcomes reported for the eight Chardonnay fermentations in the 2025 pilot**

| Trial | Fermentation and control mode | Temperature policy | Reported outcome |
|---|---|---|---|
| 1.0 | Spontaneous, hyperoxidised juice; non-feedback comparison | 14.4 °C initially; later warmed | Stopped near 5 °Brix; reinoculated afterwards |
| 1.1 | Spontaneous, hyperoxidised; adaptive | 14.4-17.8 °C | Report-defined dry endpoint; no $H_2S$ recorded; sluggish/stuck status not explicitly stated |
| 1.2 | Spontaneous, reductively handled; adaptive | 14.4-17.8 °C | Report-defined dry endpoint; no sluggish phase or $H_2S$ recorded |
| 1.3 | Spontaneous, reductively handled; adaptive | 14.4-17.8 °C | Report-defined dry endpoint; no sluggish phase or $H_2S$ recorded |
| 2.0 | Q-Citrus, inoculated; non-feedback comparison | about 11.1 °C early; later warmed | Completed after a sluggish late phase and additional operator attention |
| 2.1 | Q-Citrus, inoculated; adaptive | 12.2-17.8 °C | Regular kinetics and report-defined dry endpoint; no $H_2S$ detected |
| 2.2 | Q-Citrus, inoculated; adaptive | 11.1-17.8 °C | Regular kinetics and report-defined dry endpoint; no sluggish phase or $H_2S$ recorded |
| 2.3 | Selectys L'Elegante, inoculated; adaptive | 11.1-17.8 °C | Report-defined dry endpoint after reductive $H_2S$-associated off-odour near 12 °Brix and a sluggish late phase |

Source: compiled by the author from [22].


e-ISSN: 2786-586X

All six adaptive trials reached a report-defined dry endpoint. Four adaptive trials were explicitly described as having regular kinetics or no sluggish phase; Trial 1.1 reached the reported endpoint but its sluggish/stuck status was not explicitly stated, and Trial 2.3 had a sluggish terminal phase after a reductive $H_2S$-associated off-odour. Trial 2.3 also used a different yeast strain, so the odour event cannot be attributed to the feedback policy. The two non-feedback comparisons showed adverse kinetics. Because yeast, juice handling, and thermal exposure differed, these observations do not isolate the value of $CO_2$ information from the effect of temperature itself.

Each monetised consequence is assigned to one incremental benefit category. This prevents the same labour minute, tank-day, quality markdown, or kilowatt-hour from entering more than one term (Table 2).

Table 2

**Incremental benefit categories and total-cost-of-ownership inputs**

| Economic component | Symbol | Measurement basis | Incremental cash-flow rule |
|---|---|---|---|
| Direct event losses | A | Baseline probability and verified reduction for each prespecified outcome class; corrective materials, rework, disposal, other direct costs | Includes only direct event costs not entered in L, K, Q, or E |
| Labour and monitoring | L | Sampling/intervention time, labour rate, laboratory and monitoring consumables | Incremental labour and consumable change attributable to adoption |
| Released vessel capacity | K | Change in vessel-days × marginal contribution of capacity actually usable for additional saleable production | Zero when capacity is not binding or extra throughput has no positive contribution margin |
| Quality and markdown | Q | Rejected or discounted volume, price/contribution difference, verified chemical and sensory outcome | Positive or negative; excludes costs already included in A |
| Energy | E | Cooling/heating electricity × tariff; heat-removal data converted through measured chiller COP where necessary | Positive or negative under the actual thermal policy |
| Annual total cost of ownership | Csys(M) | Annualised fixed and per-vessel CAPEX plus fixed and per-vessel OPEX, calibration, maintenance, data/support, training, downtime-related service cost | Charged once as the equivalent annual cost of the adopted configuration |

Source: developed by the author.

The equivalent annual net benefit of adoption is:

$$\Delta\Pi = A + L + K + Q + E - Csys(M) \quad (1),$$

where ΔΠ is the equivalent annual net benefit; A is the expected reduction in direct costs caused by defined fermentation outcome classes; L is the change in labour and monitoring


e-ISSN: 2786-586X

consumables; K is the marginal contribution from usable vessel capacity; Q is the monetised change in product quality; E is the change in energy cost; and Csys(M) is the equivalent annual total cost of ownership for M equipped vessels.

$$Csys(M) = CRF(i,T) \times (Fcap + ccapM) + Fopex + copeM \quad (2),$$

where Fcap and Fopex are fixed capital and recurring costs, ccap and cope are per-vessel capital and recurring costs, i is the real discount rate, T is useful life in years, and CRF(i,T) = i(1+i)^T / [(1+i)^T - 1]. This specification does not assume economies of scale: they arise only if expected economic exposure grows faster than total system cost.

$$A = N \times \Sigma_k p_{0k} \times r_k \times L_k \quad (3),$$

where N is annual batch count; k indexes mutually exclusive outcome classes; $p_{0k}$ is the baseline probability of class k; $r_k$ is the relative reduction in that class attributable to adoption; and $L_k$ is the direct event loss not already entered in L, K, Q, or E. $L_k$ may depend on batch volume, so larger tanks can increase the loss exposure per event.

For a single event class, let $q = Np_0$ be the expected number of events per year and λ = Csys/Lf, where Lf is the direct loss per event. The A-only break-even condition is:

$$r^* = \lambda / q \quad (4).$$

Table 3

**Feasibility map for the direct-event-loss break-even screen**

| Expected events per year q | λ = 0.5 | λ = 1.0 | λ = 2.0 |
|---|---|---|---|
| 0.5 | 100% | Infeasible | Infeasible |
| 1 | 50% | 100% | Infeasible |
| 2 | 25% | 50% | 100% |
| 5 | 10% | 20% | 40% |
| 10 | 5% | 10% | 20% |

Source: author calculations; r* = λ/q. Values above 100% are infeasible on A alone.

The table separates two composite drivers that matter for the single-event screen: expected event count q and the cost-to-loss ratio λ. For example, λ = 1 requires complete elimination of one expected event per year when q = 1, but only a 20% reduction when q = 5. If q < λ, avoided direct event loss cannot repay the system even at r = 1; economic justification would then require positive contributions from L, K, Q, or E, a lower ownership cost, or a larger loss per event.

A full appraisal requires the batch-linked production and accounting records in Table 4. The dataset separates event frequency from event severity, records the number of equipped vessels M, and converts heat-removal requirements into electricity through the measured coefficient of performance (COP) of the refrigeration system.

Table 4

**Minimum dataset for winery-level economic validation**

| Data block | Unit of observation | Required variables | Economic output |
|---|---|---|---|
| Outcome definition and chemistry | Each batch | Initial °Brix; planned completion horizon; prespecified sluggish/stuck rule; laboratory glucose + fructose at endpoint; event class | Baseline $p_{0k}$ and verified $r_k$ |
| Batch scale and equipment scope | Tank/batch/ season | Batch volume; vessel ID and capacity; annual batch count N; number of equipped vessels M | Loss scaling $L_k(V)$; cost scaling Csys(M) |
| Interventions | Each event | Type, timing, materials, dose, labour | Direct event |


e-ISSN: 2786-586X

| | | time, reason | cost within $L_k$ |
|---|---|---|---|
| Labour and sampling | Each batch | Number of samples/interventions; minutes; labour rate; consumables | Labour component L |
| Energy | Tank/batch | Temperature trajectory; cooling/heating electricity; heat removed if available; chiller COP; tariff | Energy component E |
| Capacity | Tank/season | Tank-days; utilisation; queue; feasible additional throughput; contribution margin | Capacity component K |
| Quality | Each batch | Residual sugar; chemical indicators; blinded sensory score; markdown/rejection | Quality component Q |
| Digital system | Installation/ year | Fixed and per-vessel CAPEX/OPEX; useful life; real discount rate; integration; calibration; repair; data/support; training; downtime | Annual Csys(M), full ΔΠ, NPV/payback after validation |

Source: developed by the author.

The field-validation decision can also be valued. Let $V_a$ denote the economic value of action a (for example, adopt or do not adopt) and D the prospective trial data. The expected value of sample information is EVSI = $E\_D[\max_a E(V_a|D)] - \max_a E(V_a)$. A prospective validation has positive information value when EVSI exceeds the incremental cost and disruption of the trial [8]. This rule directs measurement effort toward uncertainties capable of changing the investment decision rather than toward data collection for its own sake.

## Discussion

**Interpretation of the results.** The feasibility condition $q \geq \lambda$ defines the boundary at which avoided direct event losses can recover annual system cost. For a single outcome class, the result depends on two composite quantities: expected annual event count $q = Np_0$ and the cost-to-loss ratio $\lambda = Csys/Lf$. Scale therefore has no automatic economic sign. A larger annual batch count can reduce the required effect, while a larger number of equipped vessels raises Csys(M), and larger batch volume can increase $L_k$. The pilot is used to identify economically relevant event types because temperature exposure, yeast strain, and juice handling were not matched across trials. A winery-level decision therefore requires class-specific baseline frequencies, direct losses, labour, vessel-capacity effects, quality outcomes, energy use, and total cost of ownership measured under comparable operating conditions.

**Comparison with other studies.** The proposed model extends existing fermentation-economic studies to the pre-investment stage. Giovenzana et al. [4] evaluated automated fermentation management using observed duration, labour, inputs, energy, and variable costs and showed that winery scale affected the economic result; the present model addresses the earlier decision point when enterprise data are still incomplete by expressing the break-even requirement as $q \geq \lambda$ and allowing system cost to vary with the number of equipped vessels. Nelson et al. [16], using 222 commercial red-wine fermentations, found no significant relationship between summary temperature measures and successful completion, which supports prospective estimation of $r_k$ instead of inference from the small Chardonnay pilot. Giovenzana et al. [17], Celorrio et al. [18], Yabo and Casenave [19], and Goelzer et al. [20] show that energy and tank-management effects are measurable but context-dependent. Cañete-Carmona et al. [15] and Winnie [14] demonstrate practical $CO_2$-based or modular monitoring options, while El Haloui et al. [23] and Perret and Corrieu [24] establish the historical precedent


e-ISSN: 2786-586X

for online $CO_2$-based kinetic monitoring. Against this literature, the present result is the economic linkage between defined fermentation outcomes, incremental cash-flow effects, scalable ownership cost, and the evidence required before adoption.

**Scientific novelty.** The scientific contribution is an application-specific extension of process-control economics to the preliminary evaluation of $CO_2$-based fermentation regulation under sparse technical evidence. Direct event losses are decomposed by mutually exclusive outcome classes, $A = N \times \Sigma p_{0k} r_k L_k$, while total cost of ownership is specified as Csys(M) with fixed and per-vessel capital and operating components. For a single outcome class, the model yields the feasibility condition $q \geq \lambda$, separating cases in which direct avoided losses can theoretically cover system cost from cases that require additional positive labour, capacity, quality, or energy effects. EVSI is incorporated as a criterion for deciding whether a controlled field validation is economically worth conducting before commercial adoption.

**Practical significance.** The model can be used by a winery as a staged pre-investment decision tool. Management first calculates the A-only feasibility boundary from observed frequencies of prespecified stuck or sluggish fermentation events, direct loss per event, and a credible annual total cost of ownership. Batch-level records can then quantify labour, vessel-capacity, quality, and energy effects without double counting; cooling-energy calculations should use actual electricity consumption or heat-removal data converted through measured chiller COP. EVSI can subsequently determine whether the expected value of a controlled validation study exceeds its cost and operational disruption. Commercial adoption is justified only when field data support a positive equivalent annual net benefit under sensitivity analysis for event frequency, loss size, vessel count, batch volume, system lifetime, discount rate, energy tariff, COP, downtime, and capacity utilisation.

## Conclusions

The documentary pilot shows that all six adaptive Chardonnay trials reached the report-defined dry endpoint, while the two non-feedback comparisons had adverse kinetics. Because thermal exposure, yeast strain, and juice handling were not matched, the pilot identifies economically relevant event types but does not estimate a treatment effect. The economic model separates direct event loss from labour, vessel capacity, quality, and energy, and allows annual total cost of ownership to contain fixed and per-vessel components. For one event class, the A-only rule $r^* = \lambda/q$ is feasible only when the expected annual event count q is at least as large as the cost-to-loss ratio λ.

Winery scale has no automatic sign. More annual batches can lower the break-even effect, but more equipped vessels raise system cost and larger tanks change the loss per event. The net scale effect must be calculated from N, M, batch volume, event probabilities, and incremental cash flows. A field validation should use prespecified outcome classes, laboratory residual-sugar endpoints, comparable thermal policies, batch-level labour and capacity records, metered cooling electricity with chiller COP, quality outcomes, and complete total-cost-of-ownership data. EVSI provides a decision rule for whether collecting those data is itself economically worthwhile. Further research should calibrate the model prospectively across wineries and vintages, estimate class-specific $p_{0k}$, $r_k$, and $L_k$, and test whether $CO_2$-based feedback adds value beyond monitoring alone under matched thermal exposure. With those data, the screening model can be extended to NPV, payback, after-tax cash flows, and probabilistic sensitivity analysis without changing the underlying incremental-cash-flow structure.

## Список використаних джерел

1. Вдовенко Н. М., Перегуда Ю. А., Коробова Н. М., Яцун А. Г. Вплив поведінкової та циркулярної економіки на розвиток системи управління винообними підприємствами


e-ISSN: 2786-586X

в умовах діджіталізації міжнародного бізнесу. Академічні візії. 2024. № 32. URL: https://academy-vision.org/index.php/av/article/view/1197.

2. Перегуда Ю. А., Вдовенко Н. М., Коробова Н. М. Теоретичні підходи до розвитку системи управління виноробними підприємствами в умовах діджіталізації міжнародного бізнесу й змін у компонентах конкурентоспроможності. Академічні візії. 2024. № 31. URL: https://www.academy-vision.org/index.php/av/article/view/1202.

3. Perehuda Y. Increasing the competitiveness of Ukrainian livestock products within the development of the post-industrial circular green economy model. Management and Entrepreneurship: Trends of Development. 2024. Vol. 1, No. 27. P. 19-31. DOI: https://doi.org/10.26661/2522-1566/2024-1/27-02.

4. Giovenzana V., Baroffio S., Beghi R., Casson A., Pampuri A., Tugnolo A., De Filippi D., Guidetti R. Technological innovation in the winery addressing oenology 4.0: testing of an automated system for the alcoholic fermentation management. Journal of Agricultural Engineering. 2021. Vol. 52, No. 4. DOI: https://doi.org/10.4081/jae.2021.1213.

5. Girotto F., Galeazzi A., Manenti F., Gueguen S., Piazza L. Water-food-energy nexus: Assessing challenges in the trend toward digitalization: The case study of an Italian winemaking industry. Environmental Progress & Sustainable Energy. 2022. Vol. 41, No. 6. e13893. DOI: https://doi.org/10.1002/ep.13893.

6. Bauer M., Craig I. K. Economic assessment of advanced process control - A survey and framework. Journal of Process Control. 2008. Vol. 18, No. 1. P. 2-18. DOI: https://doi.org/10.1016/j.jprocont.2007.05.007.

7. Craig I. K., Henning R. G. D. Evaluation of advanced industrial control projects: a framework for determining economic benefits. Control Engineering Practice. 2000. Vol. 8, No. 7. P. 769-780. DOI: https://doi.org/10.1016/S0967-0661(00)00007-1.

8. Howard R. A. Information Value Theory. IEEE Transactions on Systems Science and Cybernetics. 1966. Vol. 2, No. 1. P. 22-26. DOI: https://doi.org/10.1109/TSSC.1966.300074.

9. Braune E., Boncori A.-L., Dana L.-P. Digitalization's effect on everyday entrepreneurs in the French organic wine industry. Technological Forecasting and Social Change. 2025. Vol. 211. 123921. DOI: https://doi.org/10.1016/j.techfore.2024.123921.

10. Gallego-Martínez J. J., Cañete-Carmona E., Gersnoviez A., Brox M., Sánchez-Gil J. J., Martín-Fernández C., Moreno J. Devices for monitoring oenological processes: A review. Measurement. 2024. Vol. 235. 114922. DOI: https://doi.org/10.1016/j.measurement.2024.114922.

11. Boulton R., Nelson J., Knoesen A. A Review of Sensors for the Monitoring, Modeling, and Control of Commercial Wine Fermentations. Fermentation. 2025. Vol. 11, No. 6. 329. DOI: https://doi.org/10.3390/fermentation11060329.

12. Stroia N., Lodin A. Modeling of Must Fermentation Processes for Enabling $CO_2$ Rate-Based Control. Mathematics. 2025. Vol. 13, No. 10. 1653. DOI: https://doi.org/10.3390/math13101653.

13. Kontogiannis S., Tsoumani M., Kokkonis G., Pikridas C., Kotseridis Y. Proposed SmartBarrel System for Monitoring and Assessment of Wine Fermentation Processes Using IoT Nose and Tongue Devices. Sensors. 2025. Vol. 25, No. 13. 3877. DOI: https://doi.org/10.3390/s25133877.

14. Kovačević I., Aleksi I., Keser T., Matić T. Winnie: A Sensor-Based System for Real-Time Monitoring and Quality Tracking in Wine Fermentation. Applied Sciences. 2025. Vol. 15, No. 21. 11317. DOI: https://doi.org/10.3390/app152111317.

15. Cañete-Carmona E., Gallego-Martínez J.-J., Martín C., Brox M., Luna-Rodríguez J.-J., Moreno J. A Low-Cost IoT Device to Monitor in Real-Time Wine Alcoholic Fermentation Evolution Through $CO_2$ Emissions. IEEE Sensors Journal. 2020. Vol. 20, No. 12. P. 6692-6700. DOI: https://doi.org/10.1109/JSEN.2020.2975284.


e-ISSN: 2786-586X

16. Nelson J., Coleman R., Gravesen P., Silacci M., Velasquez A., Marinelli K., Boulton R. Analysis of a Commercial Red Wine Fermentation Dataset with a Wine Kinetic Model. Fermentation. 2025. Vol. 11, No. 1. 4. DOI: https://doi.org/10.3390/fermentation11010004.
17. Giovenzana V., Beghi R., Guidetti R., Luison M., Nardi T. Evaluation of energy savings in white winemaking: impact of temperature management combined with specific yeasts choice on required heat dissipation during industrial-scale fermentation. Journal of Agricultural Engineering. 2023. Vol. 54, No. 3. DOI: https://doi.org/10.4081/jae.2023.1523.
18. Celorrio R., Blanco J., Martínez E., Jiménez E., Saenz-Díez J. C. Determination of Energy Savings in Alcoholic Wine Fermentation According to the IPMVP Protocol. American Journal of Enology and Viticulture. 2016. Vol. 67, No. 1. P. 94-104. DOI: https://doi.org/10.5344/ajev.2015.14131.
19. Yabo A. G., Casenave C. Aroma synthesis and energy consumption in wine fermentation: a multiobjective optimization approach. IFAC-PapersOnLine. 2023. Vol. 56, No. 2. P. 6211-6216. DOI: https://doi.org/10.1016/j.ifacol.2023.10.743.
20. Goelzer A., Charnomordic B., Colombié S., Fromion V., Sablayrolles J.-M. Simulation and optimization software for alcoholic fermentation in winemaking conditions. Food Control. 2009. Vol. 20, No. 7. P. 635-642. DOI: https://doi.org/10.1016/j.foodcont.2008.09.016.
21. Bisson L. F. Stuck and Sluggish Fermentations. American Journal of Enology and Viticulture. 1999. Vol. 50, No. 1. P. 107-119.
22. Burdinskyi I. Feedback Control of White Wine Fermentation Kinetics: Experimental Development of an Adaptive $CO_2$-Based Real-Time Fermentation-Rate Control. Unpublished R&D report. 2025.
23. El Haloui N. E., Corrieu G., Cleran Y., Cheruy A. Method for on-line prediction of kinetics of alcoholic fermentation in wine making. Journal of Fermentation and Bioengineering. 1989. Vol. 68, No. 2. P. 131-135. DOI: https://doi.org/10.1016/0922-338X(89)90061-5.
24. Perret B., Corrieu G. Method for on-line prediction of the alcoholic fermentation rate in wine-making. Developments in Food Engineering. Boston: Springer, 1994. P. 564-566. DOI: https://doi.org/10.1007/978-1-4615-2674-2_181.
25. Butzke C. E., Park S. K. Impact of fermentation rate changes on potential hydrogen sulfide concentrations in wine. Journal of Microbiology and Biotechnology. 2011. Vol. 21, No. 5. P. 519-524. DOI: https://doi.org/10.4014/jmb.1010.10058.
26. International Organisation of Vine and Wine (OIV). International Standard for the Labelling of Wines, edition 2025. Type of wine: sugar-content definitions. URL: https://www.oiv.int/standards/international-standard-for-the-labelling-of-wines/part-iii-optional-information/optional-information/type-of-wine.

## References

1. Vdovenko, N. M., Perehuda, Y. A., Korobova, N. M., & Yatsun, A. H. (2024). The influence of behavioral and circular economy on the development of the management system of wine enterprises in the conditions of digitalization of international business. Akademichni Vizii, (32). https://academy-vision.org/index.php/av/article/view/1197
2. Perehuda, Y. A., Vdovenko, N. M., & Korobova, N. M. (2024). Theoretical approaches to the development of the management system of wine enterprises in the conditions of digitalization of international business and changes in competitiveness components. Akademichni Vizii, (31). https://www.academy-vision.org/index.php/av/article/view/1202
3. Perehuda, Y. (2024). Increasing the competitiveness of Ukrainian livestock products within the development of the post-industrial circular green economy model. Management and Entrepreneurship: Trends of Development, 1(27), 19-31. https://doi.org/10.26661/2522-1566/2024-1/27-02
4. Giovenzana, V., Baroffio, S., Beghi, R., Casson, A., Pampuri, A., Tugnolo, A., De Filippi, D., & Guidetti, R. (2021). Technological innovation in the winery addressing oenology 4.0: Testing of


e-ISSN: 2786-586X

an automated system for the alcoholic fermentation management. Journal of Agricultural Engineering, 52(4). https://doi.org/10.4081/jae.2021.1213
5. Girotto, F., Galeazzi, A., Manenti, F., Gueguen, S., & Piazza, L. (2022). Water-food-energy nexus: Assessing challenges in the trend toward digitalization: The case study of an Italian winemaking industry. Environmental Progress & Sustainable Energy, 41(6), e13893. https://doi.org/10.1002/ep.13893
6. Bauer, M., & Craig, I. K. (2008). Economic assessment of advanced process control - A survey and framework. Journal of Process Control, 18(1), 2-18. https://doi.org/10.1016/j.jprocont.2007.05.007
7. Craig, I. K., & Henning, R. G. D. (2000). Evaluation of advanced industrial control projects: A framework for determining economic benefits. Control Engineering Practice, 8(7), 769-780. https://doi.org/10.1016/S0967-0661(00)00007-1
8. Howard, R. A. (1966). Information value theory. IEEE Transactions on Systems Science and Cybernetics, 2(1), 22-26. https://doi.org/10.1109/TSSC.1966.300074
9. Braune, E., Boncori, A.-L., & Dana, L.-P. (2025). Digitalization's effect on everyday entrepreneurs in the French organic wine industry. Technological Forecasting and Social Change, 211, 123921. https://doi.org/10.1016/j.techfore.2024.123921
10. Gallego-Martínez, J. J., Cañete-Carmona, E., Gersnoviez, A., Brox, M., Sánchez-Gil, J. J., Martín-Fernández, C., & Moreno, J. (2024). Devices for monitoring oenological processes: A review. Measurement, 235, 114922. https://doi.org/10.1016/j.measurement.2024.114922
11. Boulton, R., Nelson, J., & Knoesen, A. (2025). A review of sensors for the monitoring, modeling, and control of commercial wine fermentations. Fermentation, 11(6), 329. https://doi.org/10.3390/fermentation11060329
12. Stroia, N., & Lodin, A. (2025). Modeling of must fermentation processes for enabling $CO_2$ rate-based control. Mathematics, 13(10), 1653. https://doi.org/10.3390/math13101653
13. Kontogiannis, S., Tsoumani, M., Kokkonis, G., Pikridas, C., & Kotseridis, Y. (2025). Proposed SmartBarrel system for monitoring and assessment of wine fermentation processes using IoT nose and tongue devices. Sensors, 25(13), 3877. https://doi.org/10.3390/s25133877
14. Kovačević, I., Aleksi, I., Keser, T., & Matić, T. (2025). Winnie: A sensor-based system for real-time monitoring and quality tracking in wine fermentation. Applied Sciences, 15(21), 11317. https://doi.org/10.3390/app152111317
15. Cañete-Carmona, E., Gallego-Martínez, J.-J., Martín, C., Brox, M., Luna-Rodríguez, J.-J., & Moreno, J. (2020). A low-cost IoT device to monitor in real-time wine alcoholic fermentation evolution through $CO_2$ emissions. IEEE Sensors Journal, 20(12), 6692-6700. https://doi.org/10.1109/JSEN.2020.2975284
16. Nelson, J., Coleman, R., Gravesen, P., Silacci, M., Velasquez, A., Marinelli, K., & Boulton, R. (2025). Analysis of a commercial red wine fermentation dataset with a wine kinetic model. Fermentation, 11(1), 4. https://doi.org/10.3390/fermentation11010004
17. Giovenzana, V., Beghi, R., Guidetti, R., Luison, M., & Nardi, T. (2023). Evaluation of energy savings in white winemaking: Impact of temperature management combined with specific yeasts choice on required heat dissipation during industrial-scale fermentation. Journal of Agricultural Engineering, 54(3). https://doi.org/10.4081/jae.2023.1523
18. Celorrio, R., Blanco, J., Martínez, E., Jiménez, E., & Saenz-Díez, J. C. (2016). Determination of energy savings in alcoholic wine fermentation according to the IPMVP protocol. American Journal of Enology and Viticulture, 67(1), 94-104. https://doi.org/10.5344/ajev.2015.14131
19. Yabo, A. G., & Casenave, C. (2023). Aroma synthesis and energy consumption in wine fermentation: A multiobjective optimization approach. IFAC-PapersOnLine, 56(2), 6211-6216. https://doi.org/10.1016/j.ifacol.2023.10.743
20. Goelzer, A., Charnomordic, B., Colombié, S., Fromion, V., & Sablayrolles, J.-M. (2009). Simulation and optimization software for alcoholic fermentation in winemaking conditions. Food Control, 20(7), 635-642. https://doi.org/10.1016/j.foodcont.2008.09.016


e-ISSN: 2786-586X

21. Bisson, L. F. (1999). Stuck and sluggish fermentations. American Journal of Enology and Viticulture, 50(1), 107-119.
22. Burdinskyi, I. (2025). Feedback control of white wine fermentation kinetics: Experimental development of an adaptive $CO_2$-based real-time fermentation-rate control [Unpublished R&D report].
23. El Haloui, N. E., Corrieu, G., Cleran, Y., & Cheruy, A. (1989). Method for on-line prediction of kinetics of alcoholic fermentation in wine making. Journal of Fermentation and Bioengineering, 68(2), 131-135. https://doi.org/10.1016/0922-338X(89)90061-5
24. Perret, B., & Corrieu, G. (1994). Method for on-line prediction of the alcoholic fermentation rate in wine-making. In Developments in Food Engineering (pp. 564-566). Springer. https://doi.org/10.1007/978-1-4615-2674-2_181
25. Butzke, C. E., & Park, S. K. (2011). Impact of fermentation rate changes on potential hydrogen sulfide concentrations in wine. Journal of Microbiology and Biotechnology, 21(5), 519-524. https://doi.org/10.4014/jmb.1010.10058
26. International Organisation of Vine and Wine. (2025). International Standard for the Labelling of Wines: Type of wine - sugar-content definitions. https://www.oiv.int/standards/international-standard-for-the-labelling-of-wines/part-iii-optional-information/optional-information/type-of-wine


e-ISSN: 2786-586X