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Energy and Quality Assessment in the Cooling of Crushed Bombino Nero Grapes with Indirect Heat Exchange System and Direct Heat Exchange System with CO_2

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Abstract: A study was conducted in a winery in Puglia on the effect of cooling crushed and destemmed Bombino Nero grapes, comparing two different systems: (1) traditional indirect heat exchange using a water-cooled with a tube-in-tube heat exchanger and (2) a direct refrigeration system with a CO_2 system. The must obtained from crushed grapes cooled with CO_2, compared to that treated with an exchanger, has a lower ethanol content, greater presence of sugars and higher color and tone; these qualitative advantages are due to much faster cooling and deoxygenation, which slowed down the development of indigenous yeasts present on the surface of the grapes and allowed for greater extraction of the anthocyanin components in the must. These qualitative advantages give added value to the wine, justifying higher energy costs. In fact, the test results highlighted limitations associated with higher energy costs for the direct cooling system with CO_2 compared to the traditional one with indirect heat exchange. Energy consumption in the winery is lower for the CO_2 system, but energy and costs for capture, liquefaction and stockage must also be considered. However, from an energy and functional point of view, the potential advantages related to the clarification phase should not be neglected: it could be carried out at higher temperatures than those currently adopted for musts treated with CO_2, limiting the amount of the required CO_2 and consequently the total energy consumption for the whole process.

Keywords: cooling of grapes; heat exchanger; CO_2 treatment of grapes; energy consumption; wine quality

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1. Introduction

Pre-fermentative cryomaceration involves placing the grapes in direct contact with a cryogen to achieve temperatures below 10 °C, effectively preventing the onset of alcoholic fermentation [1]. This technique has been widely applied in white wine production to enhance the contact between grape skins and juice, thereby maximizing the extraction of aromas and their precursors present in the skins [2–5].

Cryomaceration can also increase the phenolic compound content, particularly in white wine production. However, it must be carefully controlled as it can impact both the sensory profile and the stability of the final products [6,7]. For example, a 6 h pre-fermentative maceration at 10 °C improved the recovery of aroma-related compounds such as alcohols, terpenes, ethyl esters and acetate esters. While it also increased the phenolic compound concentrations, these changes were not sufficient to significantly alter the bitterness or astringency of the final wine [8,9].

In red wine production, pre-fermentative maceration of Cabernet Sauvignon grapes for 3–7 days at 5–8 °C resulted in changes to the volatile compound composition of the final wines, including reduced concentrations of C6 alcohols and fatty acids [10]. Similar studies using low-temperature maceration for the same grape variety produced more aromatic wines with a lower phenolic content [11], highlighting that maceration effects vary with grape variety, influencing both the phenolic levels and the formation of other compounds.

In general, low-temperature treatments of grape mash aim to selectively extract anthocyanins rather than tannins. However, wines from must subjected to pre-fermentative cooling do not always exhibit higher total anthocyanin levels or greater color intensity than control wines [12–16]. These outcomes may depend on complementary measures such as using inert gases to protect anthocyanins from enzymatic oxidation.

In this context, CO_2 has been employed both as an inert gas for anthocyanin protection and as a cryogenic agent, offering an alternative to traditional heat exchanger cooling systems. Studies suggest CO_2's advantages in color extraction, partly due to cell wall fragility during the rapid phase transition from liquid or solid to gaseous CO_2 [14–18].

For example, liquid CO_2 applied to the Italian white grape variety Greco reduced maceration temperatures to 2–4 °C over 24 h. The resulting wines exhibited more pronounced varietal character, a richer volatile fraction and higher phenolic content [19,20]. Similarly, pre-fermentative maceration of Sauvignon blanc with liquid CO_2 for 24 h increased the phenolic content, enhanced the antioxidant activity and preserved the varietal profile without inducing quinone formation, which is responsible for browning in white wines [21].

CO_2 has also been applied to whole grape clusters at 2–4 °C for 24 h. The resulting wines displayed higher aromatic compound concentrations compared to those produced via conventional cryomaceration or traditional winemaking methods [22].

Finally, a very recent review explores the effects of pre-fermentative cryomaceration on the aroma compounds of two white wines [23].

Despite the extensive focus on wine quality outcomes in the literature, comparative studies on the energy performance of common cooling techniques versus alternative solutions, such as CO_2-based methods, remain limited. This study aims to address this gap by conducting a real-scale experimental comparison of the energy consumption of two grape cooling systems for processing the same grape variety: a conventional heat exchanger-based system and one using CO_2 injection. In particular, we emphasize that assessing the environmental impact of different processes, such as wine production, becomes challenging when product quality is a contributing factor.

2. Materials and Methods

2.1. Experimental Trials

The grape cooling trials were conducted at the "Cantina di Ruvo di Puglia Soc. Coop. Agr." winery, located in Ruvo di Puglia (BA, Italy). Two cooling methods were tested on crushed grapes obtained from Bombino Nero grapes using a horizontal destemmer–crusher: 1. The first method utilized a concentric tube heat exchanger cooled by water (Figure 1a; Table 1), 2. The second method consisted of a pre-fermentative cryogenic treatment, in a protective atmosphere, by means of heat exchange through direct contact between the crushed grapes and liquid CO_2 (Figure 1b; Table 2).

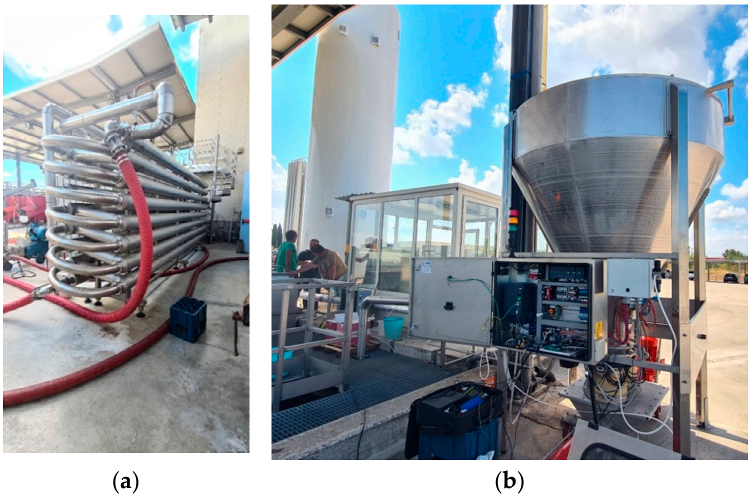
(**a**) (**b**)

Figure 1. Grape cooling systems used in the experimental trials: heat exchanger (**a**) and CO_2-based system (**b**).

Table 1. Key technical specifications of the heat exchanger (Figure 1a).

Parameter	Value
Nominal power (kW)	48
Flow rate (L/min)	1700
Product pipe diameter (mm)	76.1
Heat exchange fluid pipe diameter (mm)	101.6
Total product pipe length (mm)	7000
Pipe thickness (mm)	2
Number of pipes	16
Min/max allowable pressure (bar)	10
Total heat exchange surface (m^2)	26.72
Total achievable heat exchange (kW)	233.1

Table 2. Key technical specifications of the CO_2-based system (Figure 1b).

Parameter	Value
Installed power (kW)	12
Refrigerant fluid	CO_2
Gas CO_2 exhaust pipe diameter (mm)	300
Storage tank capacity (L)	1600/2500
Thermal exchange hopper capacity (L)	3500
Theoretical flow rate for 20 °C temperature drop (kg/h)	20,000

Figure 2 shows an outline of the two processes: the heat exchange process is obtained using the dashed lines, flux (1), while the CO_2 process is derived using the dotted lines, flux (2).

For the trials in series (1), the destemmed–crushed grapes were conveyed from the destemmer–crusher outlet to the heat exchanger using a single-screw pump (Table 3). After cooling, the must was transferred to a pneumatic press. Cold water, used as the thermal exchange fluid in the heat exchanger, was generated by a chiller (Table 4) and circulated by a centrifugal pump (power: 4.8 kW) at a flow rate of 1700 dm^3/min, at −2 °C and under a pressure of 1.5 bar. A total of 9000 kg of crushed grapes were cooled, achieving a temperature reduction of 10–12 °C over a total duration of 27 min.

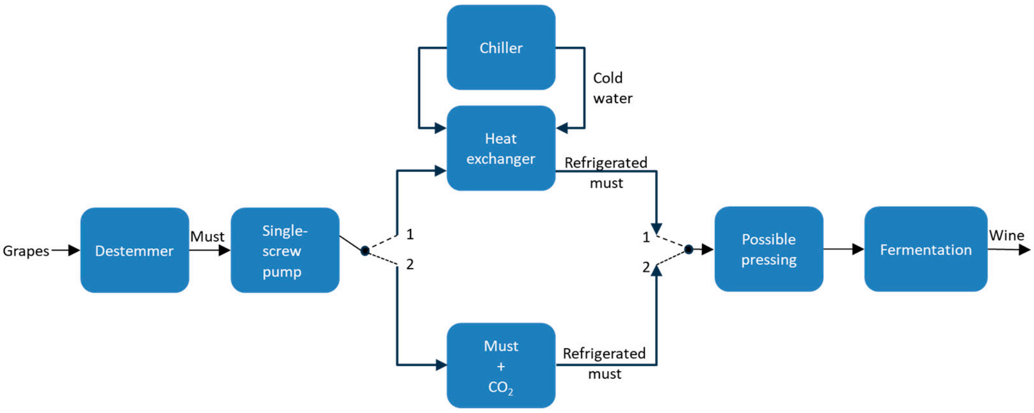

Figure 2. Outline of the two refrigeration processes: (1) heat exchanger, (2) CO_2.

Table 3. Key technical specifications of the single-screw pump used for grape mash transfer.

Parameter	Value
Flow rate (m^3/min)	0.33
Motor power (kW)	11.0
Head (m)	20–30
Pressure (bar)	2.0–3.0
Operating speed (rpm)	1475.0
Efficiency	91.4% to 100% of maximum power

Table 4. Key technical specifications of the water chiller.

Parameter	Value
Installed power (kW)	175.0
Refrigerant fluid	R 410 A
Nominal cooling capacity (kW)	455.1
Storage tank capacity (L)	1100
Water output temperature (°C)	Not lower than −5

For the trials in series (2), the crushed grapes were cooled through direct heat exchange with liquid CO_2 at −56 °C, coming from a cryogenic storage tank at the winery (Figure 1b). The grapes passed through a thermal exchange hopper (Figure 3), where they were mixed with liquid CO_2, which suddenly expanded into dry ice and gaseous CO_2. The cooled mash was saturated with CO_2 and reached the target temperature. The crushed grapes were fed into the hopper using the same single-screw pump connected to the destemmer–crusher (Table 3). After treatment, the mash was transferred to the pneumatic press using a second single-screw pump, integrated into the cryogenic system. A total of 15,000 kg of crushed grapes were processed, achieving a temperature reduction of 9–10 °C, with a CO_2 consumption of 800 kg, about half of the maximum CO_2 consumption found in various technical data sheets.

Figure 3. Grape mash mixing with CO_2 in the thermal exchange hopper.

2.2. Analytical Evaluations

The cooled mash was transferred to a pneumatic press to extract the must. These musts were clarified through overnight settling and subsequently analyzed prior to fermentation. Analytical measurements included sugar content (g/L), ethanol concentration (% v/v), volatile acidity (mg/L acetic acid), titratable acidity (g/L tartaric acid), pH, color intensity, hue and total polyphenols (mg/L). All parameters were assessed in triplicate using a Foss WineScan FT 120, following the manufacturer's protocol (Foss, Hillerød, Denmark).

2.3. Statistical Analysis

The study involved representative measurements from three trials for each system. Statistical analysis was performed using Statistics 12.0 software (StatSoft Inc., Tulsa, OK, USA). Analysis of variance (ANOVA) was conducted, and results were compared using Tukey's multiple comparison test at a significance level = 0.05.

2.4. Power Measurements

To measure the active electrical power absorbed by the machine motors, a Power Quality Meter & Analyzer with data logging functionality, YOKOGAWA CW12, Yokogawa Italia S.r.l. Nova Milanese – Italy (Figure 4), was used. This instrument measures the energy consumption of single-phase and three-phase loads, accounting for potential load imbalances across phases. Measurements were taken by inserting the analyzer connections into the electrical line between the control panel and the motor under analysis (Figures 1b and 4).

Global energy consumption was measured for the following systems:

- Heat exchanger system: the separate power consumption of the single-screw feed pump, the cooling water pump and the chiller were recorded (Figure 3).
- CO_2 system: total power consumption was recorded, coinciding with the power used by the discharge single-screw pump, excluding negligible control system consumption.

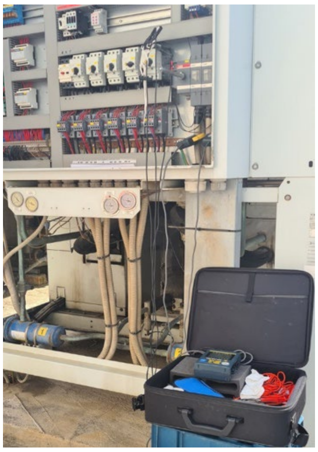

Figure 4. Power consumption measurement using the data logger connected to the water chiller's electrical panel.

3. Results and Discussion

3.1. Qualitative Aspects

As highlighted in Table 5, the resulting musts exhibit enological characteristics that are both comparable and suitable for high-quality winemaking. This aligns with the criteria outlined by Ribéreau-Gayon P. et al., 2005 [24].

Table 5. Analytical evaluations of the musts (mean ± SD).

Parameter	CO_2	Heat Exchanger
Ethanol (% vol.)	0.26 ± 0.08	0.96 ± 0.22
Sugar (g/L)	190.68 ± 12.2	164.58 ± 17.2
Volatile acidity (mg/L acetic acid)	0.01 ± 0.003	0.04 ± 0.004
Titratable acidity (g/L tartaric acid)	5.11 ± 0.11	4.99 ± 0.09
pH	3.48 ± 0.03	3.49 ± 0.04
Color intensity	1.41 ± 0.09	1.26 ± 0.07
Hue	0.71 ± 0.01	0.54 ± 0.015
Total polyphenols (mg/L)	662 ± 22	615 ± 19

A significant difference observed was the lower ethanol content in the must obtained from grapes cooled with CO_2 compared to that from grapes processed using the heat exchanger system. In the latter case, the static clarification phase (conducted at room temperature in this trial) initiated spontaneous fermentation, leading to the development of 0.96% vol. ethanol, compared to 0.26% vol. recorded with the direct CO_2 cooling system. This difference is likely due to the faster cooling and deoxygenation of the must achieved with CO_2, which slowed the activity of indigenous yeasts present on the grape surface that inoculate the must.

This result warrants further investigation, as the clarification phase plays a crucial role in the quality of the must and the resulting wine. In many cases, it is carried out via static decantation at low temperatures [25]. If the mildly inhibitory effect of CO_2 treatment is confirmed, it could allow for the use of slightly higher temperatures during clarification, potentially leading to energy savings due to the reduced amount of CO_2 required for grape cryo-cooling.

In line with the observed ethanol differences, must derived from the use of CO_2 contained a higher sugar concentration: 198.68 g/L compared to 168.58 g/L for the traditional system. Differences were also noted in the color and hue of the must, which were more pronounced with CO_2 cooling. The rapid cooling achieved with CO_2 facilitated greater extraction of anthocyanin compounds during the subsequent pressing phase.

This suggests that direct CO_2 cooling not only enhances heat exchange but also promotes the extraction of compounds of interest from the solid parts of the grapes. This characteristic points to broader potential applications for CO_2-based cooling, though further studies are needed to evaluate these effects in depth. Indeed, despite the higher overall energy consumption of CO_2-based cooling due to the energy required for CO_2 production, we observed a significantly improved quality of must obtained through this process, which may substantially impact the assessment of its environmental footprint.

3.2. Tests with Heat Exchanger

Figure 5 illustrates the trend over time of the active power associated with the cooling water pump. The short measurement duration is due to the pump operating cyclically at a constant flow rate with a power factor not lower than 0.94 and absorbed power ranging between 4.78 kW and 4.87 kW with an average value of 4.84 kW (Table 6). Figure 6 shows the trend of active power for the chiller, which has a power factor of 0.8, considered acceptable for a refrigeration unit serving multiple winery utilities. In this case, the measurement was stopped once steady-state conditions were reached, corresponding to an average absorbed active power of 62.8 kW (Table 6). The active power of the single-screw pump pushing the crushed grapes into the heat exchanger was 11.1 kW on average.

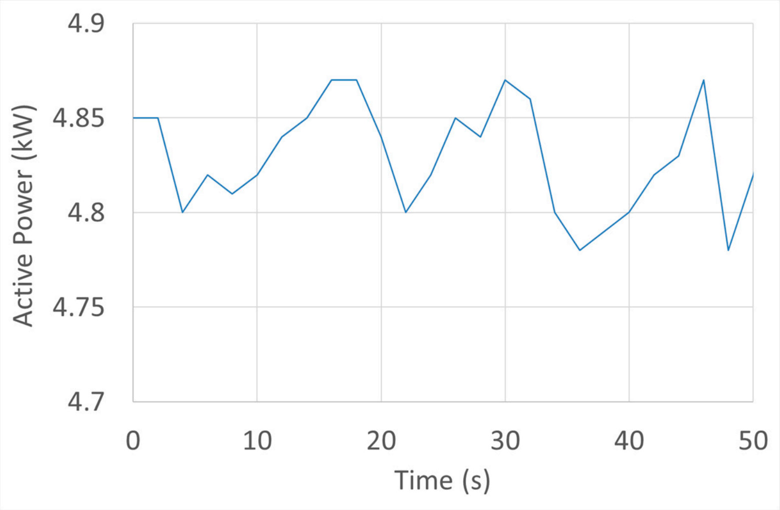

Figure 5. Active electric power consumption of the centrifugal pump supplying water to the heat exchanger.

Table 6. Energy and economic parameters of the cooling line equipped with the indirect heat exchange system with heat exchanger.

Parameter	**Water Chiller**	**Single-Screw Pump (Crushed Grapes)**	**Centrifugal Pump (Water)**	**Total Values**
Duration		27 min		
Average active power consumption	62.8 kW	11.1 kW	4.84 kW	78.74 kW
Power factor	0.8	0.99	0.94	-
Electricity consumption	28.3 kWh	5.0 kWh	2.2 kWh	35.5 kWh
Specific energy	11.3 kJ/kgmash	2.0 kJ/kgmash	0.9 kJ/kgmash	14.2 kJ/kgmash
Energy costs		0.2 EUR/kWh		
Economic costs	EUR 5.66	EUR 1.00	EUR 0.44	EUR 7.10

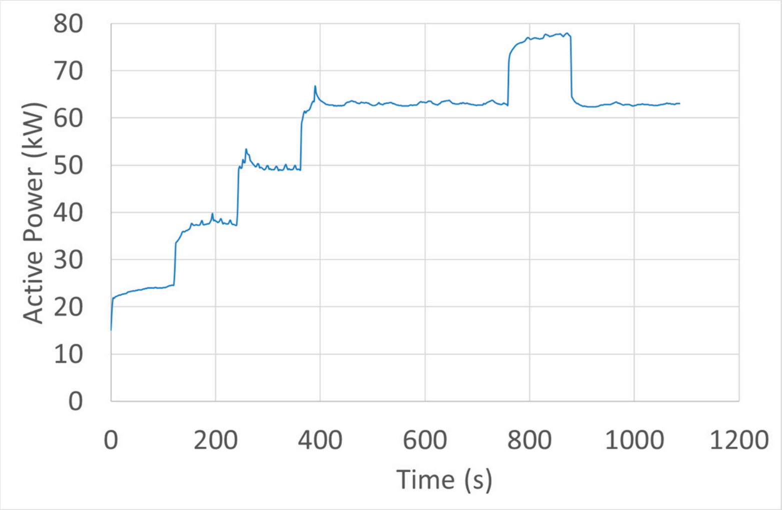

Figure 6. Active electric power consumption of the water chiller supplying the heat exchanger.

It is noted that the active power absorption of the whole crushed grapes cooling line with indirect heat exchange is mainly due to the water cooler (chiller); in this case, the relatively low power factor and the high active power absorption are certainly due to the use of the refrigeration unit in a very wide ambient temperature range, leading to a high condensation temperature. This is a typical limitation of the regions of Southern Italy, where the grape harvest takes place with a still warm climate, which causes the cooler compressor to operate with low efficiency and high electrical consumption.

In this case, energy calculations must consider only the steady-state condition over the entire trial duration of 27 min. Accordingly, the energy consumption amounts to 2.2 kWh for the refrigerated water pump, 5.0 kWh for the single-screw pump and 28.3 kWh for the water chiller, resulting in a total energy consumption of 35.5 kWh. Considering an average cost of 0.20 EUR/kWh, the energy cost for the trial is approximately EUR 7.10, which is negligible relative to the final wine's production cost. Finally, considering the processing of 9000 kg of crushed and destemmed grapes (mash), the specific energy consumption is calculated at 14.2 kJ/kgmash (Table 6).

3.3. Experiments with CO_2

Figure 7 illustrates the time-dependent behavior of the active power associated with the refrigeration system employing direct CO_2 injection. The electrical consumption is primarily attributable to the operation of the single-screw pump, which transfers the CO_2-cooled crushed grapes to the press. The remaining electrical load, approximately 78–82.0 W, is due to the instrumentation integrated into the system.

The single-screw pump operates intermittently, activating when the crushed grapes reach the maximum level in the loading hopper. This intermittent operation accounts for the periodic increases in active electrical power from 0.08 kW to 4.5 kW with an average power of 2.2 kW. Of course, also in this case, the active power of the single-screw pump pushing the crushed grapes into the CO_2 injection system was 11.1 kW on average.

The power factor remains nearly equal to 1 during the pump's operation and obviously drops to 0.25 during other intervals (Table 7). In this experiment, the measurements were concluded upon processing the entire quantity of crushed and destemmed grape mash (15,000 kg). In this case, the absorbed power does not depend on ambient conditions.

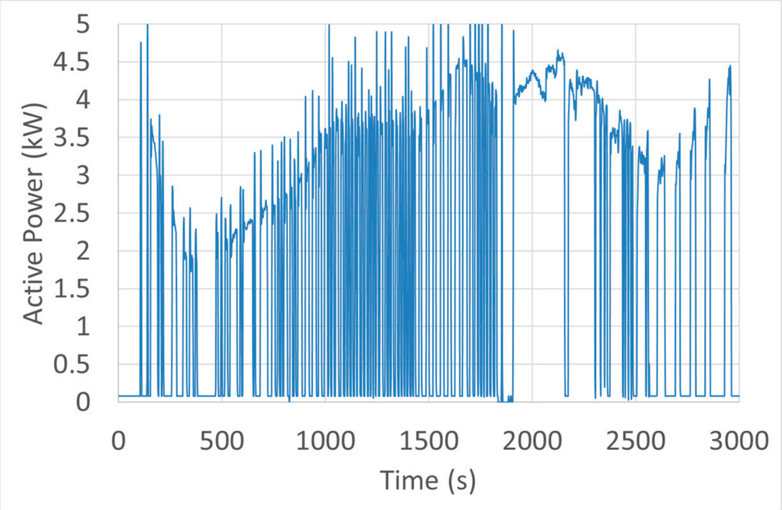

Figure 7. Active electric power consumption of the CO_2 cryogenic system.

Table 7. Energy and economic parameters of the cooling line employing the direct heat exchange system with CO_2.

Parameter	Screw Pump (Crushed Grapes)	Single-Screw Pump (Cooled Grapes)	Total Values
Duration		50 min	
Average active power consumption	11.1 kW	2.2 kW	13.3 kW
Power factor	0.99	0.99	-
Electricity consumption	9.3 kWh	1.8 kWh	11.1 kWh
Specific energy	2.23 kJ/kgmash	0.43 kJ/kgmash	2.66 kJ/kgmash
Energy costs		0.2 EUR/kWh	
Economic costs	EUR 1.86	EUR 0.36	EUR 2.22

The total energy consumption for the process was 11.1 kWh, with a corresponding energy cost of EUR 2.22 (Table 7). Moreover, it is important to note that both energy consumption and cost must account for producing CO_2 by an external supplier, which is then sold to the winery. The cost of bulk CO_2, including transportation and storage, ranges from 0.6 EUR/kgCO_2 to 0.75 EUR/kgCO_2, with temporary price spikes during shortages reaching up to 10 EUR/kgCO_2. Given that 800 kg of CO_2 was used, the CO_2 cost adds an average of 0.75 EUR/kgCO_2, amounting to a total cost of EUR 600. This corresponds to a unit cost of 0.04 EUR/kg of crushed and destemmed grapes (mash), resulting in a negligible increase in the final wine production cost. Therefore, from an economic standpoint, the impact on the final cost is minimal and the choice between the two systems cannot be based solely on economic considerations. As said in the previous paragraph, the quality of CO_2-refrigerated mash was much better than that obtained through the traditional heat exchanger refrigeration process, and this leads again to choosing the CO_2-refrigerated mash instead of the traditional one.

But, when using CO_2, the energy balance must account for the energy required to capture, liquefy and store the gas, which must also meet the purity standards necessary for food-grade applications. According to the literature, the energy consumption for capturing and purifying CO_2 is globally (sum of thermal and electric consumption) 2250 kJ/kgCO_2 according to Zheng, Y.; Gao, L., 2023 [26], 3900 kJ/kgCO_2 and 432 kJ/kgCO_2 (respectively, thermal and electric consumption) according to Haaf M. et al., 2020 [27]; the energy required for liquefaction and storage amounts to 288 kJ/kgCO_2 according to Chen, F.; Morosuk, T., 2021 [28]. Considering only the liquefaction process, when scaled to the unit mass of processed must, this corresponds to an energy consumption of 15.4 kJ/kg of crushed grapes, which is slightly over the energy consumption of the heat exchanger-based system. The capture process is of course about 10 times more energy-hungry.

4. Conclusions

Thermal control with direct contact with CO_2 during winemaking processes offers several advantages:

- Reducing the risk of undesired fermentation and aroma loss by cooling white grapes before pressing as it works in a protective atmosphere.
- Increasing the must concentration by cooling white grapes to approximately 0 °C immediately before pressing.
- Achieving rapid and uniform cooling of crushed and destemmed grapes (unattainable with conventional refrigeration systems) to facilitate cold skin maceration for white grapes and pre-fermentative maceration for red grapes.
- Enhancing aromatic extraction by cooling white grapes to around 0 °C, followed by a return to positive temperatures during pressing (cryo-extraction).

The findings of this study highlight a potential role for CO_2 in achieving technological advancements in wine production. Enhanced extraction of compounds responsible for the wine's organoleptic quality during maturation—for both red and white wines—could add value to the final product, potentially justifying higher energy costs.

However, the study also identified limitations, such as higher energy and environmental costs associated with direct cooling using CO_2 compared to traditional indirect heat exchange systems: this increase is due to the energy required to produce CO_2 itself. However, as mentioned above, the qualitative advantages observed, for example, during the clarification phase of musts treated with CO_2, allow the process to be carried out at higher temperatures than those currently adopted. This modified process could still lead to higher qualitative levels compared to the traditional system and result in significant energy savings in CO_2 treatment, making it competitive with the traditional system also in terms of environmental sustainability. This latter advantage would be particularly relevant in warm-climate regions, such as the one where this research was conducted, given the high energy consumption recorded for the refrigeration unit, which is due to the excessive temperature difference between the external environment and the evaporation temperature. In the enological sector, the ongoing need for innovative technologies to enhance wine quality underscores the necessity for further research. Evaluating the positive impacts of CO_2 use on wine characteristics and developing system designs that mitigate production costs, particularly from an energy and environmental perspective, will be critical for future advancements.

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References

1. Sanchez Palomo, E.; Perez-Coello, M.S.; Diaz-Maroto, M.C.; Gonzales Vinas, M.A.; Cabezuto, M.D. Contribution of free and glycosidically-bound volatile compounds to the aroma of Muscat "a petit grains" wines and effect of skin contact. *Food Chem.* **2006**, *95*, 279–289.
2. Salinas, M.S.; Garijo, J.; Pardo, F.; Zalacain, A.; Alonso, G.L. Color, polyphenol, and aroma compounds in rosé wines after prefermentative maceration and enzymatic treatments. *Am. J. Enol. Vitic.* **2003**, *54*, 195–202.
3. Salinas, M.R.; Garijo, J.; Pardo, F.; Zalacain, A.; Alonso, G.L. Influence of prefermentative maceration temperature on the colour and the phenolic and volatile composition of rosé wines. *J. Sci. Food Agric.* **2005**, *85*, 1527–1536.
4. Selli, S.; Cabaroglu, T.; Canbas, A.; Erten, H.; Nurgel, C. Effect of skin contact on the aroma composition of the musts of *Vitis vinifera* L. cv. Muscat of Bornova and Narince grown in Turkey. *Food Chem.* **2002**, *81*, 341–347.
5. Tamborra, P.; Piracci, A.; Coletta, A.; Esti, M. Ottimizzazione delle tecnologie di vinificazione per l'incremento dell'aroma del Fiano. *Food Sci. Technol.* **2009**, 56–67. Available online: https://www.aivv.it/download/atti/r026_0909_2010_tamborra.pdf (accessed on 3 March 2025).
6. Cheynier, V.; Souquet, J.M.; Moutounet, M. Glutathione content and glutathione to hydroxycinnamic acid ratio in *Vitis vinifera* grapes and musts. *Am. J. Enol. Vitic.* **1990**, *40*, 320–324.
7. Mattivi, F.; Poznanski, E.; Vrhovsek, U.; Carli, E.; Masuero, D. Il glutatione, dall'uva al vino. *OICCE Times* **2008**, *9*, 27–32.
8. Korenika, A.M.J.; Maslov, L.; Jakobović, S.; Palčić, I.; Jeromel, A. Comparative study of aromatic and polyphenolic profiles of Croatian white wines produced by cold maceration. *Czech J. Food Sci.* **2018**, *36*, 459–469.
9. Korenika, A.-M.J. Influence of Cold Maceration Treatment on Aromatic and Sensory Properties of Vugava Wine (*Vitis vinifera* L.). *J. Microbiol. Biotechnol. Food Sci.* **2020**, *10*, 49–53.
10. Luan, Y.; Zhang, B.Q.; Duan, C.Q.; Yan, G.L. Effects of different pre-fermentation cold maceration time on aroma compounds of *Saccharomyces cerevisiae* co-fermentation with *Hanseniaspora opuntiae* or *Pichia kudriavzevii*. *LWT* **2018**, *92*, 177–186.
11. Ruiz-Rodríguez, A.; Palma, M.; Barroso, C.G. Influence of temperature during pre-fermentative maceration and alcoholic fermentation on the phenolic composition of 'cabernet sauvignon' wines. *Foods* **2021**, *10*, 1053. [CrossRef]
12. Darriet, P.; Tominaga, T.; Lavigne, V.; Boidron, J.N.; Dubourdieu, D. Identification of a powerful aromatic component of *Vitis vinifera* L. var. Sauvignon wines: 4-marcapto-4-methylpentan- 2-one. *Flavour Fragr. J.* **1995**, *10*, 385–392.
13. Martínez-Lapuente, L.; Guadalupe, Z.; Higueras, M.; Ayestarán, B.; Pérez-Porras, P.; Bautista-Ortín, A.B.; Gómez-Plaza, E. Effect of Pre-fermentative Treatments on Polysaccharide Composition of White and Rosé Musts and Wines. *J. Agric. Food Chem.* **2023**, *72*, 1928–1937.
14. Piombino, P.; Genovese, A.; Gambuti, A.; Lamorte, S.A.; Lisanti, M.T.; Moio, L. Effects of off-vine bunches shading and cryomaceration on free and glycosilated flavours of Malvasia delle Lipari wine. *Int. J. Food Sci. Technol.* **2010**, *45*, 234–244. [CrossRef]
15. Roldán, A.M.; Sánchez-García, F.; Pérez-Rodríguez, L.; Palacios, V.M. Influence of different vinification techniques on volatile compounds and the aromatic profile of palomino fino wines. *Foods* **2021**, *10*, 453. [CrossRef]
16. Ruiz-Rodríguez, A.; Durán-Guerrero, E.; Natera, R.; Palma, M.; Barroso, C.G. Influence of two different cryoextraction procedures on the quality of wine produced from muscat grapes. *Foods* **2020**, *9*, 1529. [CrossRef]
17. Gordillo, B.; Lopez-infante, T.M.I.; Ramirez-Perez, P.; Gonzalez-Miret, M.L.; Heredia, F.J. Influence of Prefermentative Cold Maceration on the Color and Anthocyanic Copigmentation of Organic Tempranillo Wines Elaborated in a Warm Climate. *J. Agric. Food Chem.* **2010**, *58*, 6797–6803.
18. Parenti, A.; Spugnoli, P.; Calamai, L.; Gori, C. Effects of cold maceration on red wine qualityfrom Tuscan Sangiovese grape. *Eur. Food Res. Technol.* **2004**, *218*, 360–366.
19. Baiano, A.; Varva, G.; De Gianni, A.; Terracone, C.; Viggiani, I.; Del Nobile, M.A. Effects of different vinification technologies on physico-chemical properties and antioxidant activity of "Falanghina" and "Bombino bianco" wines. *Eur. Food Res. Technol.* **2013**, *237*, 831–842.
20. Baiano, A.; Mentana, A.; Varva, G.; Quinto, M. Effects of different vinification procedures and aging containers on phenolic and volatile composition of Greco white wines. *Eur. Food Res. Technol.* **2017**, *243*, 1667–1680.
21. Olejar, K.J.; Fedrizzi, B.; Kilmartin, P.A. Influence of harvesting technique and maceration process on aroma and phenolic attributes of Sauvignon blanc wine. *Food Chem.* **2015**, *183*, 181–189.
22. Pedrosa-López, M.C.; Aragón-García, F.; Ruíz-Rodríguez, A.; Piñeiro, Z.; Durán-Guerrero, E.; Palma, M. Effects from the Freezing of Either Whole or Crushed Grapes on the Volatile Compounds Contents in Muscat Wines. *Foods* **2022**, *11*, 1782. [CrossRef] [PubMed]
23. Van Breda, V.M.; van Jaarsveld, F.P.; vanWyk, J. Pre-Fermentative Cryogenic Treatments: The Effect on Aroma Compounds and Sensory Properties of Sauvignon Blanc and Chenin Blanc Wine—A Review. *Appl. Sci.* **2024**, *14*, 1483. [CrossRef]

24. Ribéreau-Gayon, P.; Dubourdieu, D.; Donèche, B.; Lonvaud, A. Other Winemaking Methods. In *Handbook of Enology: The Microbiology of Wine and Vinifications*, 1st ed.; Wiley: Hoboken, NJ, USA, 2005.
25. Jackson, R.S. *Wine Science*; Elsevier: Amsterdam, The Netherlands, 2020.
26. Zheng, Y.; Gao, L. Analysis of the mechanism of energy consumption for CO_2 capture in a power system. *Energy* **2023**, *262*, 125103.
27. Haafa, M.; Anantharamanb, R.; Roussanalyb, S.; Ströhlea, J.; Epplea, B. CO_2 capture from waste-to-energy plants: Techno-economic assessment of novel integration concepts of calcium looping technology. *Resour. Conserv. Recycl.* **2020**, *162*, 104.
28. Chen, F.; Morosuk, T. Exergetic and Economic Evaluation of CO_2 Liquefaction Processes. *Energies* **2021**, *14*, 7174. [CrossRef]