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Hygrothermal conditions for the aging of red wine from experimental data

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ABSTRACT

Despite the importance of the aging process, there is great disparity in the hygrothermal conditions in which to carry it out. The aim of this work is to propose contrasted data, based on successful cases and millions of experimental data, which can be taken as a reference for the climate control of aging rooms. For this purpose, the hygrothermal environment of 19 red wine aging rooms with multiple construction designs was monitored and statistically characterized. The results showed a great variability in the hygrothermal environment. Frequency histograms and psychometric diagrams revealed the true hygrothermal environment of red wine aging rooms. There were large differences in stability and uniformity depending on the construction design (up to four times). The indoor hygrothermal environment was not kept within the comfort ranges mentioned by a wide list of authors (2–65% of time out of range). A contrasted psychometric diagram establishing monthly comfort intervals and other useful data (stability, uniformity …) were proposed, based on the hygrothermal environment of wineries with quality wines. The results should be a valuable tool for the wine sector, in order to control the evolution of aging, set the programming of air conditioning equipment and simulate the behavior of new wineries.

1. Introduction

In the winemaking process, the aging is the longest and sometimes the most decisive stage during which the wine's sensorial characteristics change, becoming more complex and stable. The objective of wine aging is to improve its quality by modifying its sensory characteristics, such as flavor, color, and fragrance (Mazarron, Cid-Falceto, & Canas-Guerrero, 2012). Although oenologists decide the optimum amount of cask storage time for each wine, in some countries there are laws that regulate the minimum aging time (Garde-Cerdan & Ancin-Azpilicueta, 2006). For example, in the case of Spain, the law 24/2003 (law of the vineyard and wine), establishes that to be a "Crianza", the minimum aging period must be 24 months, of which at least 6 months must have been in oak barrels, etc. These periods may be extended by the appellations of origin depending on the characteristics of their wines.

Given the importance and duration of aging, there are numerous previous papers focused on the hygrothermal environment of the aging rooms of red wine. Most of them analyzed the behavior and/or effectiveness of specific construction designs (Arredondo-Ruiz, Canas, Mazarron, & Manjarrez-Dominguez, 2020). Thus, Barbaresi, Dallacasa, Torreggiani, and Tassinari (2017) tested the effectiveness of different retrofit interventions for thermal behavior improvement in unconditioned above-ground farm buildings; Torreggiani, Barbaresi, Dallacasa, and Tassinari (2018) analyzed the effectiveness of different architectural elements in improving the thermal behavior of unconditioned above-ground building; Mazarron, Cid-Falceto, and Canas-Guerrero (2012) studied the hygrothermal behavior of an above-ground warehouse, carrying out an energy simulation in different locations; Mazarron and Canas (2009) studied the annual thermal behavior of traditional underground wine cellars; Barbaresi, Torreggiani, Benni, and Tassinari (2014) defined a method to assess reliability in energy simulations for underground cellar modelling, as a reliable tool for energy-efficiency-oriented building and system design; Mazarrón el al. (2013) evaluated the possibility of using the basement of agro-industrial buildings as a way to age and preserve wine.

Several works analyzed the effect that other factors have on the indoor hygrothermal environment, such as ventilation (Mazarron, Porras-Amores, & Canas-Guerrero, 2015; Porras-Amores, Mazarron, Canas, & Villoria, 2019; Santolini, Barbaresi, Torreggiani, & Tassinari, 2019).

Few precedents have analyzed the hygrothermal environment of different construction designs. The works of Benni, Torreggiani, Barbaresi, and Tassinari (2013) and Mazarron, Cid-Falceto, and Canas (2012) compared different construction designs, from above-ground

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warehouses to underground constructions.

However, none of these works questioned the comfort intervals described in many oenological treatments. Nor did they go into statistical analysis of a large number of aging rooms, which would serve as a reference for the sector.

For decades, oenology treatises have included references to the most suitable temperature and humidity conditions for the aging of wine. Muñoz Ochoa (1955) recommended that the temperature be kept constant between 8 and 12 °C with relative humidity between 45 and 80%; Marescalchi (1965) between 4 °C and 12 °C; Cortés (1968) a low and constant temperature between 8 and 11 °C, with average indoor relative humidity between 65% and 80%; Soroa Pineda (1969) from 4 to 12 °C; Troost (1985) from 12 to 15 °C, and relative humidity between 86% and 98%; De Rosa (1988) between 15 and 18 °C; Ough (1996) between 10 and 15 °C; Rankine (1999) recommended for California temperatures of 13–18 °C; Plasencia and Villalón (1999) between 10 °C and 14 °C; Hidalgo Togores (2003) stated that relative humidity values above 80% considerably reduce the wine loss by up to 2–3% a year, though they also deem positive relative humidity values between 70% and 80% so as to rule out mold appearing, and constant temperatures from 12 to 15 °C; Foulonneau (2004) opted for a fresh and constant temperature (11–14 °C).

Another matter many studies deal with is the limit temperature values and the harmful effects caused by them. According to Troost (1985) cask cellars reaching temperatures of 18–20 °C are not suitable for wine. De Rosa (1988) reported that temperatures above 20 °C accelerate the formation of esters and reduce the wine's final smoothness at the end of the aging as these temperatures accelerate the process excessively. Yravedra (2003) recommended that the aging process should be slow; therefore avoiding a high temperature of 20 °C which would accelerate the process, at 5 °C would be inviable. At 18 °C, there is the risk of bacterial activity and at a constant 12 °C, the wine would not age, either.

Frequent temperature changes are also harmful (Troost, 1985). Vogt (1971) argued that the annual temperature oscillation should not exceed the limit of 5–6 °C: significant thermal oscillations must be avoided. Plasencia and Villalón (1999) pointed out that temperature changes are normally harmful, and may compromise the wine's longevity. Hidalgo Togores (2003) said that the temperature must be constant, to prevent the cask wood from expanding and contracting. This would lead to greater wine loss and to leaks through the joints.

Although some authors declared that low humidity is a hindrance to the wine's maturing (Troost, 1985), most of the references to this matter associated low humidity with wine loss due to evaporation. Levels of wine loss are currently high enough in many cases to produce a considerable financial impact (de Adana, Lopez, & Sala, 2005). Favorable indoor temperatures and relative humidity guarantee good development of the wine while avoiding excessive wine losses due to diffusion through the oak and evaporation into the air (Martin & Canas, 2006). de Adana et al. (2005) reported the loss of wine stored for one year to vary from 1 to 9%, depending on the temperature, relative humidity and air velocity over the casks.

Faced with the lack of scientific literature on the subject, the aim of this work is to reveal the interior environment in which red wine aging actually takes place, proposing contrasted comfort intervals and other useful data based on successful cases.

2. Material and methods

2.1. Selected aging rooms

The present work culminates a research line initiated more than 15 years ago, in which more than 90 aging rooms have been monitored, obtaining more than 120 million temperature and relative humidity data. However, for the present study, only 19 representative aging rooms from the 40 monitored in the last Spanish national R&D&I plan project have been selected. These aging rooms include multiple constructive designs, with different conditions of contour and location within Spain (Table 1). All wineries that did not have several years of wine ratings in the oenological guides have been discarded. This is intended to provide an indicator of the minimum quality of the wines that can be obtained during aging under specific hygrothermal conditions. In some of the selected wineries with the highest score, the average price of their prestigious wines exceeds 80 €. In addition, the wineries monitored in previous projects, mostly small and for private production, have also been discarded.

Table 1
Main characteristics of the monitored aging rooms: construction design, climate control systems and maximum rating of their wines.

Wine cellar	Type	Air conditioning	Humidifiers	Max. Wine Score
W1	Aerial	Yes	Yes	94.6
W2	Basement	Yes	Yes	94.5
W3	Basement	No	Yes	92.8
W4	Underground	No	No	92.5
W5	Aerial	Yes	Yes	92.0
W6	Buried	No	No	92.0
W7	Basement	No	No	91.5
W8	Basement	No	No	91.5
W9	Underground	No	No	91.0
W10	Aerial	Yes	No	90.9
W11	Buried	No	No	90.5
W12	Basement	Yes	No	90.1
W13	Semi-basement	No	No	90.0
W14	Aerial	Yes	Yes	89.3
W15	Aerial	Yes	Yes	88.8
W16	Basement	No	Yes	88.8
W17	Underground	No	No	88.8
W18	Basement	No	No	87.3
W19	Aerial	Yes	No	86.6

In the selected aging rooms, wines with similar starting material were aged; in particular, wines based on the "tempranillo" variety, the majority grape in Spain for red wine vinification. Almost all wineries produce monovarietal wines (100%), except in four of them where blends with a high percentage of tempranillo are made: 80% (W24), 85% (W17), 92% (W10) and 93% (W9).

The monitored aging rooms belong to the "Aalto", "Campo Viejo", "Castillejo", "Cillar de Silos", "Emina Ribera", "Fariña", "Gormaz", "Legaris", "Martínez Lacuesta", "Mauro", "Murua", "Peñafiel", "Puelles", "Resalte de Peñafiel", "Valduero", "Valsotillo", "Viña Olabarri" and "Viña Vilano" wineries.

The existing literature showed differences in hygrothermal performance depending on the constructive design and its thermal inertia. For this reason, many of the analyses carried out will be performed by grouping the aging rooms into three major groups. Group 1: aboveground; Group 2, basement and semi-basement; Group 3: underground and buried.

2.2. Monitoring system

The monitoring was carried out using Hobo® U23 Pro v2 data-loggers (Accuracy ≥ ±0.25 °C and ±2.5% r. h.; resolution 0.03 °C and 0.03% r. h.) and Omega OM-92 data-loggers (Accuracy ≥ ±0.3 °C and ±3.0% r. h.; resolution 0.01 °C and 0.01% r. h.).

The long experience (more than fifteen years) of the research team in the monitoring of warehouses (Martin & Canas, 2006; Mazarron & Canas, 2009; Mazarron et al., 2012, 2013, 2015) has shown that the interior environment of the warehouses is very uniform on the horizontal plane, with marked differences in the vertical, with a strong stratification in the summer months (Porras-Amores, Mazarron, & Canas, 2014). Therefore, in each warehouse, sensors were installed at various heights at a central point of the barrel room, calculating the average temperature to which the barrels are subjected. The monitoring period was one year, using a measurement interval of 15 min.

2.3. Characterization of the indoor hygrothermal environment

The indoor environment characterization was based on the analysis of millions of temperature and relative humidity data obtained in the monitoring process. For this purpose, an application based on Microsoft Excel and Visual Basic for Application (VBA) was developed. The tool performs statistical analysis of the set of sensors installed in the volume occupied by the barrels, with the objective of characterizing and synthesizing the following aspects:

- Representative values for each of the aging rooms: descriptive statistics of the annual hygrothermal behavior. It allows identification of differences between specific aging rooms. The following statistical indicators were calculated using Microsoft Excel functions from all the quarter-hourly data recorded throughout the year by the sensors: Mean, Median, Mode, Standard Deviation, Variance, Kurtosis, Skewness coefficient, Range, Minimum, Maximum, Percentiles (1, 3, 5, 7 and 9).
- Monthly evolution of the hygrothermal environment: monthly frequency histograms, which show the most frequent temperature and relative humidity values for each group and the existing dispersion. Detailed data for comparison between groups and with other wineries, but analyzing temperature and relative humidity separately. For this purpose, each quarter-hourly data that falls within a certain interval (for example, 17 °C ≤ T < 18 °C) was counted; then, the frequency was calculated against the total values of the month.
- Hygrothermal behavior combining temperature and humidity simultaneously: psychrometric diagrams showing the monthly average for each of the rooms. Wine aging could be different with the same temperature range but different relative humidity and vice versa. For this purpose, monthly averages for each winery were calculated from all available data on the volume occupied by the barrels. They were then displayed on a psychrometric diagram developed with VBA programming.
- Stability and uniformity: other aspects that could affect aging have been analyzed. Stability is the rate at which temperature and relative humidity vary at each of the monitoring points (°C/h, °C/day, etc.). The maximum and minimum values recorded by each sensor in each period (hour, day.) were determined; the stability was calculated as the difference between both values, according to the set interval. The monthly and annual averages of the calculated stability values were finally calculated. Uniformity refers to the differences in temperature and relative humidity between the sensors inside the warehouse at a given moment. As previously mentioned, vertical stratification is usually the greatest source of variability of uniformity within the aging room. Therefore, it will be used as a representative value. It was calculated in a manner equivalent to stability, being the difference between the values recorded at each moment by all sensors.

2.4. Checking comfort intervals of oenological bibliography

Following the characterization of the hygrothermal environment, it was intended to quantify the percentage of time that the comfort intervals described by different authors for the aging of the red wine are met. Several references have been selected trying to cover the largest number of different ranges, in particular: 8 °C ≤ T ≤ 12 °C and 45% ≤ r. h ≤ 80% (Muñoz Ochoa, 1955); 4 °C ≤ T ≤ 12 °C (Marescalchi, 1965); 8 °C ≤ T ≤ 11 °C and 65% ≤ r. h ≤ 80% (Cortés, 1968); 4 °C ≤ T ≤ 12 °C (Soroa Pineda, 1969); 12 °C ≤ T ≤ 15 °C and 86% ≤ r. h ≤ 98% (Troost, 1985); 15 °C ≤ T ≤ 18 °C (De Rosa, 1988); 10 °C ≤ T ≤ 15 °C (Ough, 1996); 13 °C ≤ T ≤ 18 °C (Rankine, 1999); 10 °C ≤ T ≤ 14 °C (Plasencia & Villalón, 1999); 12 °C ≤ T ≤ 15 °C and 70% ≤ r. h ≤ 80% (Hidalgo Togores, 2003); 11 °C ≤ T ≤ 14 °C (Foulonneau, 2004).

By means of VBA programming, the developed application performed a quarter-hourly check in each aging room of the constructive group. Each data that fell within a certain interval (for example, 8 °C ≤ T < 12 °C and 45% ≤ r. h. < 80%) was counted; then, the global percentage for each month was calculated based on the total number of data involved.

2.5. Reference monthly comfort intervals

The specialized literature lacks monthly data based on a large number of wineries. In addition, the disparity of the annual ranges proposed in the oenological treatises could be due to unrealistic or non-representative data. It is therefore necessary to establish realistic monthly comfort intervals that serve as a reference for the wine sector, in order to control the aging process, set the programming of the air conditioning equipment, simulate the hygrothermal behavior of new designs, etc. To ensure that the proposed ranges are appropriate, only the wineries with the highest scoring wines were selected.

It is assumed that there are many variables that may affect the final quality of the wine (grape quality, transport, fermentation, etc.), although there are adequate hygrothermal conditions. This makes it difficult to identify inappropriate aging conditions, forcing the study to focus on recommended conditions based on verified data from successful experiences.

The score provided should be interpreted as an approximation of the quality that can be achieved. Considering that many other factors influence the final quality, the wine with the highest average score of the winery has been selected as representative of the potential of the aging room. In this way, taking care of the rest of the factors, it can be ensured that under certain hygrothermal conditions wines of the aforementioned score can be made.

Wines that have a barrel aging time of at least one year have been chosen, being affected by all variations of the year in both temperature and humidity. The qualification of the wines has been made on the basis of expert assessment, in particular, the average of Peñin's appraisals of the wines of Spain (mainly national) and Robert Parker (considered by some to be the most influential wine critic in the world). Various sources consider the Peñin and Parker guides as the two most followed specialized guides in Spain. A further 59 sources have been ruled out due to the lack of evaluations of the wines of all the wineries analyzed.

To avoid vintages of atypical quality, the average of assessments of the last 10 years (vintages from 2008 to 2017) of each of the experts has been considered, verified that the vintages are subsequent to the construction of the barrel warehouse. The final valuation of the winery has been calculated as the arithmetic mean of the two sources mentioned (Table 1).

After calculating the scores, the proposed diagram was based on the top six aging rooms on the list with a score above 92. The proposed diagrams show the monthly evolution of the daily average hygrothermal environment of the barrel area that ensures a good development of the aging. The diagrams reflect contrasted red wine aging areas based on the actual values of wineries with high quality wines, not implying that outside these areas the aging cannot be carried out. For the calculation of the recommended monthly limits, it has been chosen to eliminate extreme values, using data between the 5th and 95th percentiles.

3. Results and discussions

Considering the differences in hygrothermal behavior depending on the constructive design described in the literature, most of the results were synthesized by grouping the aging rooms into three groups. In this way, other wineries will be able to have a more defined framework for comparison based on their specific design.

Table 2
Representative values of the internal temperature (°C) and relative humidity (% r.h.) in each of the monitored aging rooms.

		Mean	Median	Mode	Stand. deviation	Variance	Kurtosis	Skewness coeff.	Range	Minimum	Maximum	Percentile 1	Percentile 3	Percentile 5	Percentile 7	Percentile 9	Stability (/h)	Stability (/day)
Temperature (°C)	WH1	12.4	12.6	14.8	2.1	4.3	−1.3	−0.09	7.9	8.6	16.5	9.5	11.1	12.6	13.7	15.2	0.01	0.18
	WH2	14.2	14.4	13.7	1.3	1.6	−1.0	−0.24	6.5	10.8	17.3	12.3	13.4	14.4	15.0	15.7	0.01	0.17
	WH3	13.2	12.5	10.4	3.1	9.7	−1.5	0.19	9.6	8.7	18.3	9.3	10.6	12.5	16.0	17.5	0.00	0.09
	WH4	10.3	10.3	10.7	0.8	0.6	−0.9	0.07	3.9	8.5	12.4	9.2	9.8	10.3	10.7	11.4	0.02	0.16
	WH5	13.5	14.0	15.3	2.0	4.0	−1.2	−0.20	9.7	9.5	19.2	10.6	11.9	14.0	14.9	15.8	0.06	0.75
	WH6	12.6	12.5	14.7	1.7	2.8	−1.4	0.08	7.4	8.3	15.7	10.4	11.2	12.5	13.9	14.9	0.04	0.31
	WH7	12.9	12.6	10.4	3.0	8.8	−1.3	0.12	11.5	7.1	18.6	9.2	10.5	12.6	15.2	16.9	0.01	0.17
	WH8	13.0	12.3	9.8	3.0	9.3	−1.1	0.53	10.7	9.0	19.6	9.7	10.4	12.3	15.0	17.7	0.01	0.14
	WH9	12.0	12.0	12.6	0.6	0.4	−1.2	0.02	2.9	10.8	13.7	11.2	11.6	12.0	12.5	12.8	0.01	0.06
	WH10	14.5	14.2	17.0	3.2	10.2	−1.3	0.01	14.5	6.2	20.7	10.3	12.1	14.2	16.9	18.7	0.05	0.72
	WH11	14.4	14.1	11.8	2.4	5.8	−1.4	0.14	9.4	10.1	19.4	11.3	12.5	14.1	16.3	17.7	0.01	0.12
	WH12	17.1	17.0	16.6	0.9	0.8	−0.1	0.42	4.9	15.1	20.0	16.0	16.6	17.0	17.6	18.3	0.01	0.18
	WH13	13.0	12.4	9.7	3.2	10.3	−1.3	0.32	11.2	8.3	19.5	9.2	10.5	12.4	14.9	17.6	0.01	0.10
	WH14	14.2	13.6	12.8	1.8	3.2	−0.9	0.23	9.5	10.0	19.5	11.9	13.0	13.6	15.5	16.6	0.12	0.95
	WH15	12.6	12.5	14.7	1.7	2.8	−1.4	0.08	7.4	8.3	15.7	10.4	11.2	12.5	13.9	14.9	0.02	0.33
	WH16	16.1	16.0	18.3	1.7	2.9	−1.4	0.10	5.9	13.2	19.1	13.8	14.7	16.0	17.4	18.4	0.01	0.07
	WH17	11.6	11.4	10.6	2.1	4.4	−1.2	0.04	8.9	6.9	15.8	9.0	10.1	11.4	13.2	14.4	0.01	0.11
	WH18	14.8	14.6	11.3	3.5	12.4	−1.4	0.14	11.5	9.4	20.9	10.3	12.0	14.6	17.8	19.5	0.01	0.11
	WH19	17.1	16.5	22.0	4.0	15.9	−1.1	0.27	15.6	10.3	25.9	11.7	14.6	16.5	19.4	22.9	0.02	0.43
Relative humidity (%)	WH1	81	80	77	4	14	1.6	0.05	40	55	95	77	78	80	82	86	0.2	3.2
	WH2	81	80	88	6	37	−1.1	0.19	36	61	96	74	77	80	87	90	0.3	2.6
	WH3	76	75	89	8	60	−0.7	−0.15	43	47	90	66	71	75	81	86	0.2	3.6
	WH4	97	100	100	6	30	4.0	−2.06	31	69	100	89	99	100	100	100	0.2	1.4
	WH5	73	72	71	4	18	3.0	0.65	47	53	100	69	71	72	74	78	0.7	5.7
	WH6	74	75	79	13	182	−0.8	−0.32	63	37	100	55	66	75	83	91	0.7	6.9
	WH7	80	81	82	6	39	0.4	−0.75	35	58	93	72	78	81	84	88	0.4	4.7
	WH8	73	73	70	10	99	−0.2	0.05	58	43	100	60	68	73	78	86	0.8	7.6
	WH9	90	92	97	7	48	−0.2	−0.84	31	67	98	80	86	92	95	97	0.3	2.0
	WH10	74	74	73	6	41	0.6	−0.20	54	36	91	66	71	74	77	82	0.5	5.9
	WH11	87	87	91	5	22	−0.6	−0.34	34	63	97	81	84	87	91	93	0.2	1.9
	WH12	70	73	74	12	139	0.4	−0.72	73	27	100	54	65	73	77	85	0.3	4.0
	WH13	84	84	85	6	31	−0.4	−0.40	35	60	95	76	81	84	87	91	0.2	2.1
	WH14	77	80	80	8	57	0.6	−1.17	45	49	95	64	77	80	82	84	1.3	9.1
	WH15	74	75	79	13	182	−0.8	−0.32	63	37	100	55	66	75	83	91	0.3	2.9
	WH16	82	83	93	10	93	−0.9	−0.28	55	45	100	69	76	83	90	94	0.3	3.3
	WH17	95	96	100	5	20	1.2	−1.10	27	73	100	88	93	96	97	100	0.1	1.1
	WH18	73	73	84	9	78	−0.7	−0.03	51	46	98	62	67	73	78	84	0.2	4.3
	WH19	75	78	80	9	87	0.5	−0.89	63	29	92	61	72	78	81	85	0.4	5.9

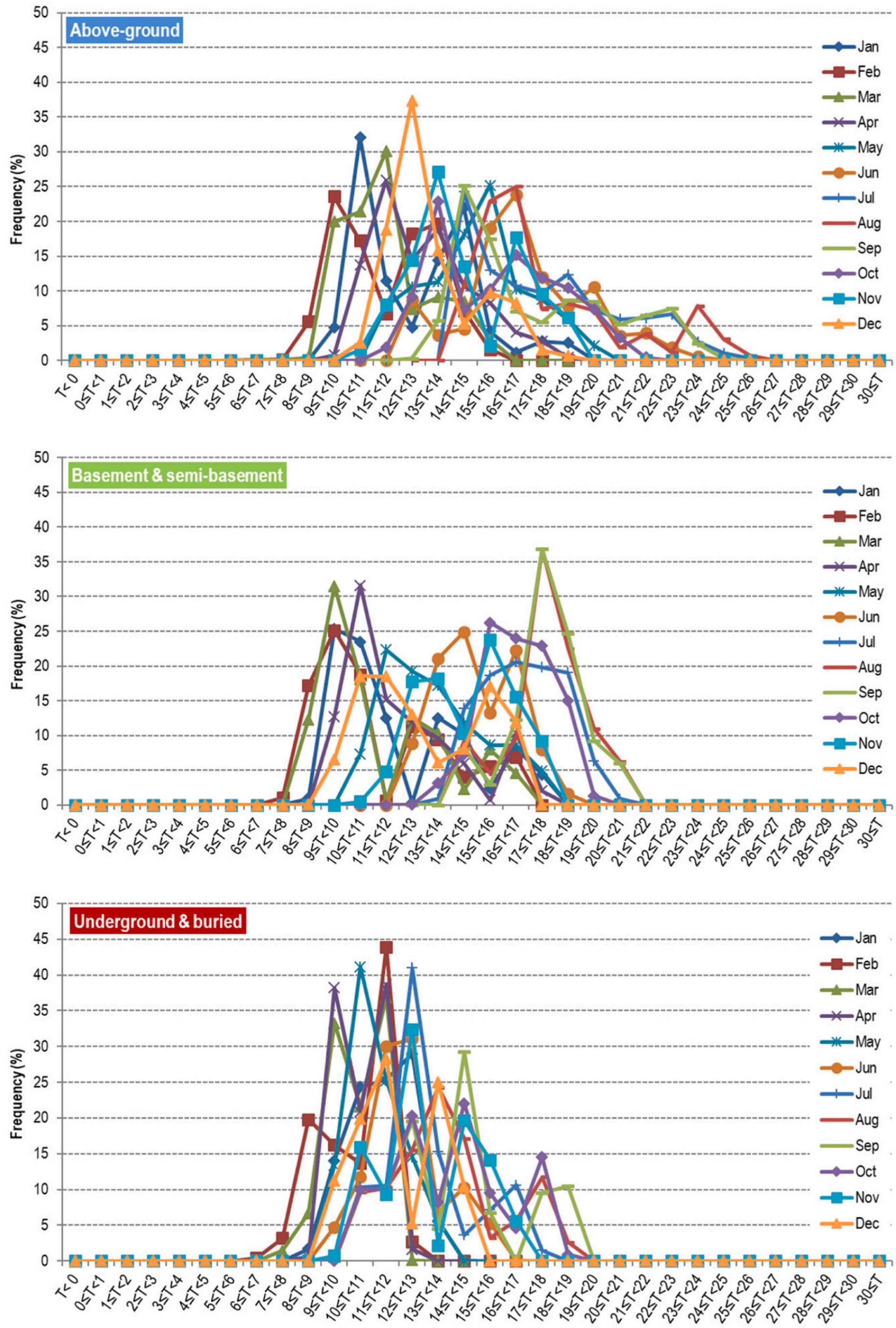

Fig. 1. Monthly frequency histograms (%) of the air temperature inside the volume occupied by the barrels according to the construction design.

3.1. Representative values of the annual hygrothermal environment

The evolution of the indoor temperature recorded in the different aging rooms presented a great variability (Table 2). Thus, for example, the average annual temperature varied between 10.3 °C and 17.1 °C, with a standard deviation between 0.6 °C and 4 °C; the maximum annual temperature between 12.4 °C and 25.9 °C; the minimum annual between 6.2 °C and 15.1 °C; the range of annual variation between 2.9 °C and 15.6 °C; the average internal stability between 0.06 °C/day and 0.95 °C/day; etc.

Most wineries exceeded the maximum annual range recommended by some authors (5-6 °C). Many wineries exceeded the maximum temperature of 18 °C recommended by some authors. However, only the winery with the lowest score (WH19) far exceeded the limit value of 20 °C recommended by several other authors.

Equivalently, the evolution of the internal relative humidity recorded in the different warehouses also presented a great variability (Table 2). The average annual relative humidity varied between 70% and 97%, with a standard deviation between 4% and 13%; the maximum annual relative humidity between 90% and 100%; the minimum annual between 27% and 73%; the annual variation range between 27% and 73%; the average internal stability between 1.1%/day and 9.1%/day; etc.

The representative values showed that there is no single solution for red wine aging. Quality wine can be obtained in very different environments. Even in wineries with similar constructive design, the differences that can be found are remarkable.

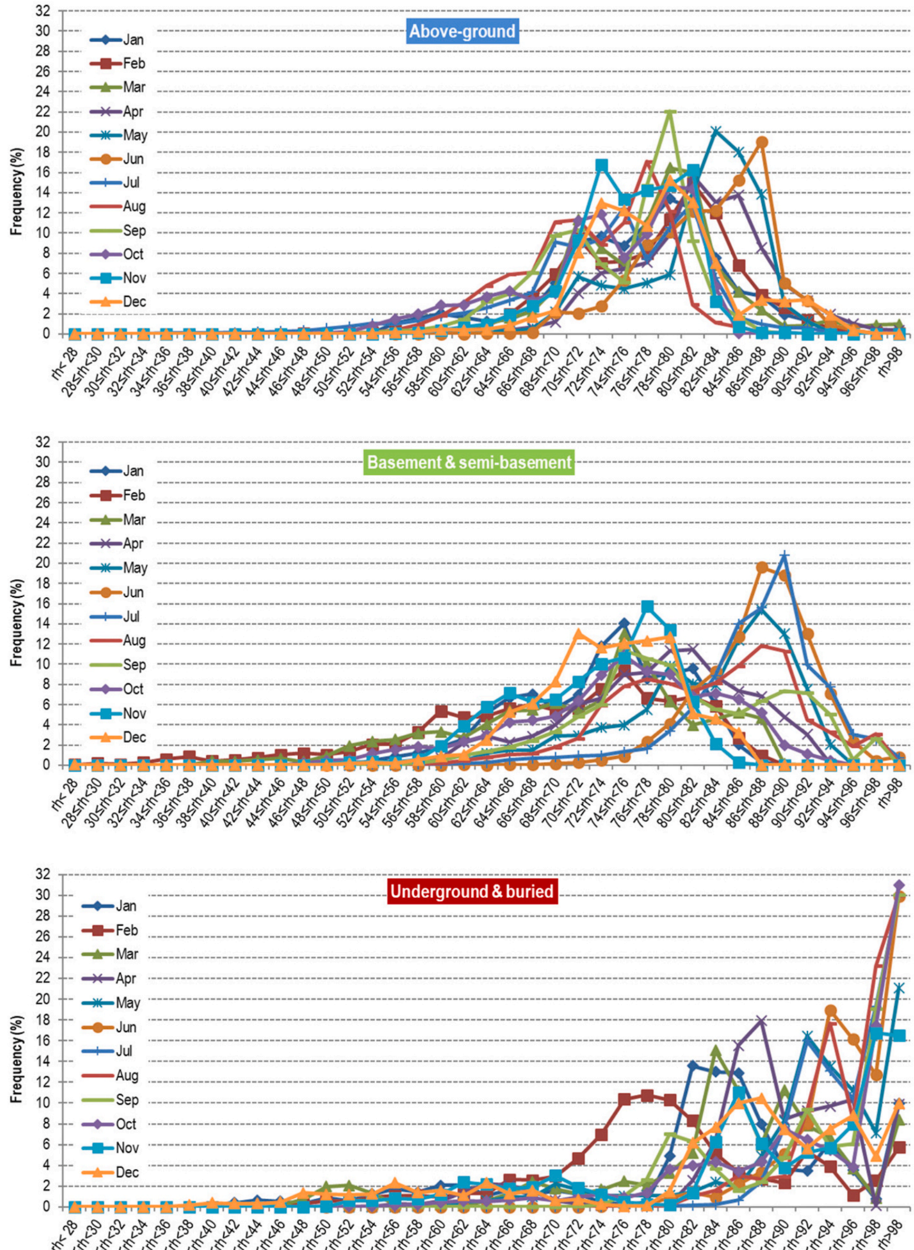

Fig. 2. Monthly frequency histograms (%) of the air relative humidity inside the volume occupied by the barrels according to the construction design.

3.2. Monthly evolution of the hygrothermal environment

Frequency histograms showed significant temperature variations throughout the year, especially between the summer months. There were also huge differences between the three groups in which the warehouses have been divided according to their constructive design (Fig. 1). Above-ground rooms showed the greatest dispersion, a consequence of the air-conditioning systems. In the opposite case were underground and buried cellars, with a high concentration of values around a few degrees.

During the summer, the most frequent temperatures occurred between 11 °C and 15 °C in group 3 (underground and buried), increasing between 15 °C and 19 °C in group 2 (basement and semi-basement). The air conditioning equipment allowed the above-ground aging rooms (group 1) to be positioned between the other two groups, with values between 14 °C and 17 °C. However, the maximum frequency reached was lower than in the other designs (less than 25%). Energy expenditure and the set point temperature of the air conditioning system were the probable causes. In no case the temperature was above 20 °C in group 3, values above 18 °C were rare; in group 2, values of 22 °C were reached, although infrequent above 20 °C; in group 1, values of 26 °C were reached, with a non-negligible frequency above 20 °C.

Temperatures were more similar in winter. There were no differences in the minimum temperature reached, close to 6 °C in the 3 groups. The recommendations of the oenological treatments not to fall below 5 °C were complied with.

Differences between groups were more pronounced in relative humidity (Fig. 2). The underground and buried aging rooms had much higher relative humidity values than the rest, especially in the summer months, with the most frequent value above 98% r. h. Some wineries with high wine scores maintained a very high relative humidity, questioning the claims of many authors about humidity.

The above-ground aging rooms showed a high degree of homogeneity, with the most frequent values between 74% r. h. and 90% r. h. for

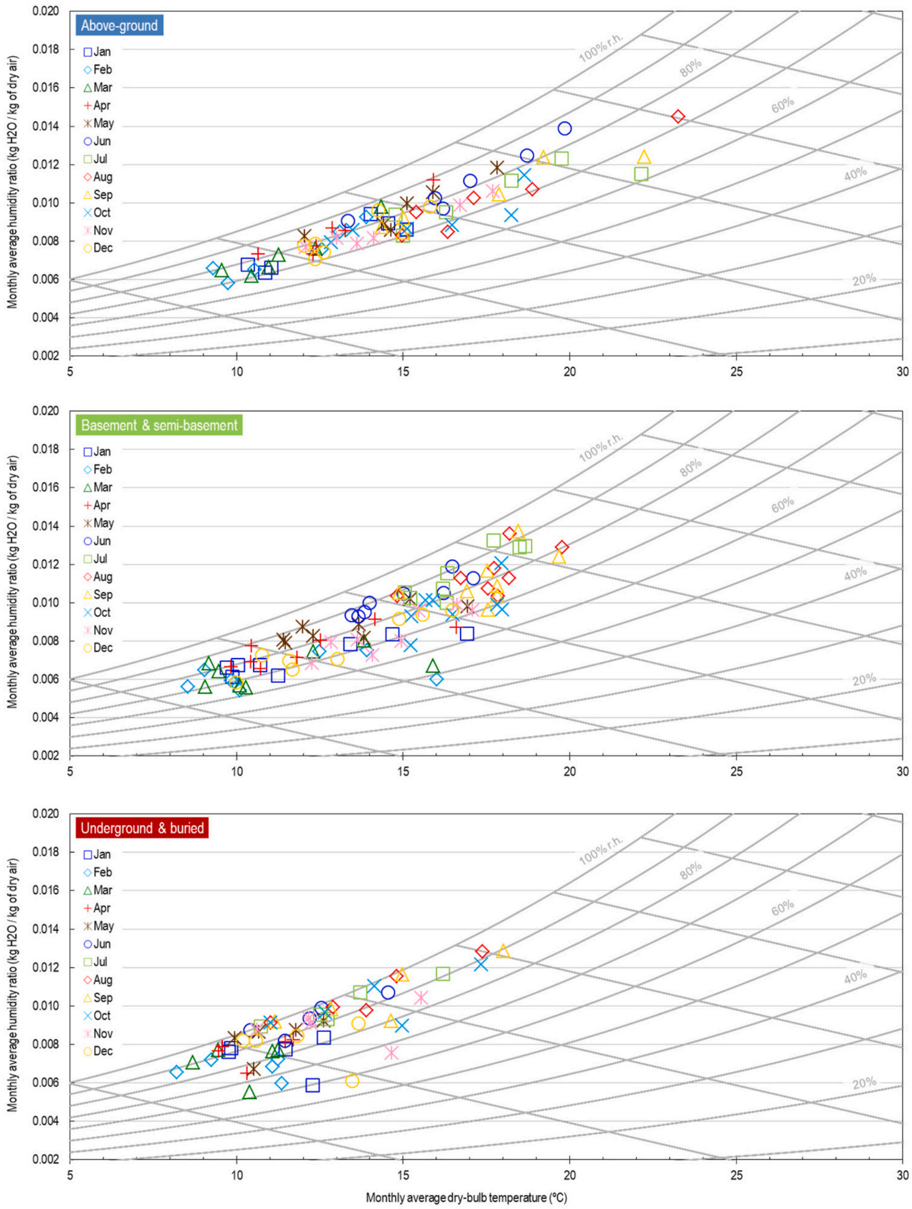

Fig. 3. Monthly average of the interior hygrothermal environment in the barrel area of each of the analyzed warehouses.

all months. The relative humidity differences between months were much smaller than in the case of temperature, since the relative humidity showed greater oscillations throughout each month.

Basement and semi-basement rooms showed an intermediate behavior among the other groups, with frequent values around 90% in the summer months, without reaching 98%.

3.3. Psychometric diagrams

The psychometric diagrams summarize the joint evolution of the temperature and relative humidity inside, showing monthly average values of each warehouse separately (Fig. 3). They provide valuable complementary information to the histograms, for example, for evaporative wine losses in the barrels.

The dispersion of values was very evident in group 1 (above-ground), especially in terms of temperature. The air conditioning programming was remarkable in this group's warehouses. Monthly average temperature differences could reach several degrees. Monthly average relative humidity was usually between 70% and 90%. The most severe case was that of the WH19 winery, which during the summer months combined very high average temperatures with very low relative humidity.

During the summer months, where the combination of a higher temperature and lower relative humidity implies an increase in evaporative losses, the group 3 maintained better conditions for reducing losses. On the other hand, most basement aging rooms combined the highest temperatures of the year (between 15 °C and 19 °C) with relative humidity between 70% and 90%.

3.4. Stability and uniformity

The study of the speed with which the temperature varies at the same point showed large differences in thermal stability depending on the construction design. Underground and buried rooms had a much higher thermal stability than other designs. Thus, the annual average was 0.56 ± 0.36 °C/day in group 1, 0.80 ± 0.28 °C/day in group 2 and 0.15 ± 0.13 °C/day in group 3 (Fig. 4).

In all cases, hourly stability was high, with an annual average of less than 0.05 °C/h in the three groups. In this way, there is a concordance

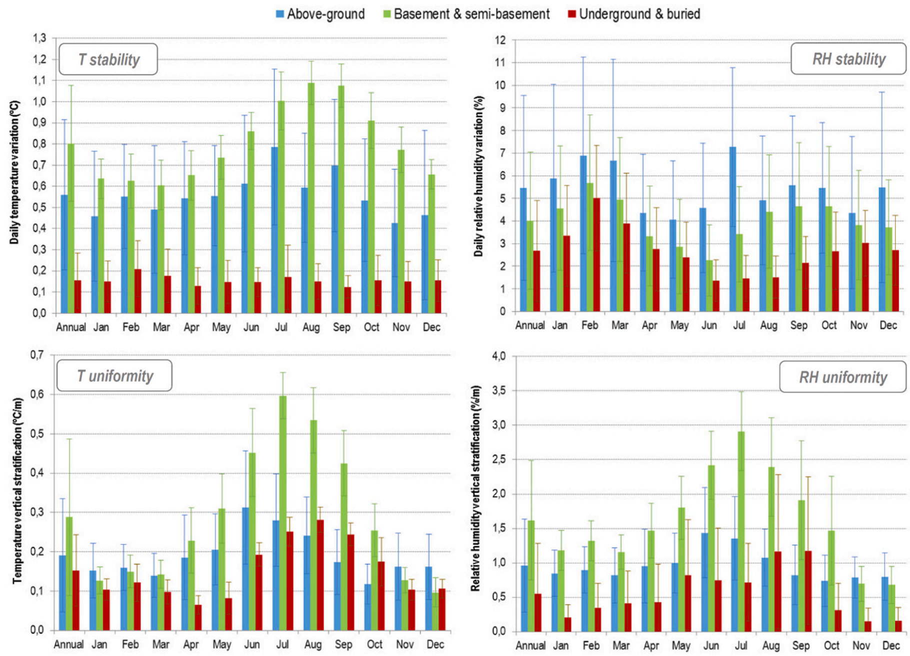

Fig. 4. Average stability (°C/day and %r.h./day) and vertical uniformity (°C/m and % r. h./m) in the area occupied by barrels.

between the statements of the oenology treatises and the reality of the wineries, relative to the fact that temperature changes are normally harmful, and may compromise the wine's longevity.

The aging rooms were less stable in relative humidity, with an annual average of 5.5 ± 4.1% r. h. per day in group 1, 4.0 ± 3.0% r. h. in group 2 and 2.7 ± 2.2% r. h. in the group 3 (Fig. 4). Hourly variations in relative humidity had a value of 0.6 ± 0.8% r. h. in group 1, 0.4 ± 0.5% r. h. in group 2 and 0.3 ± 0.5% r. h. in the group 3.

The analysis of vertical uniformity showed a not insignificant thermal stratification, especially in the case of basements during the summer (Fig. 4). The increase in temperature from the ground level could reach monthly average values of 0.5 °C per meter, which must be taken into account if there are several barrel levels. In above-ground aging rooms, the air-conditioning systems located at the top helped to reduce stratification, reaching values close to those of underground constructions.

Annual mean values were lower, due to less stratification in the winter months. Thus, the annual average was 0.19 ± 0.14 °C/m in group 1, 0.29 ± 0.20 °C/m in group 2 and 0.15 ± 0.09 °C/m in group 3 (Fig. 4).

Equivalently, the relative humidity decrease with height could exceed a monthly average value of 2% per meter during summer in basement rooms. The annual average was 1.0 ± 0.7 %r.h./m in group 1, 1.6 ± 0.9 %r.h./m in group 2 and 0.6 ± 0.7 %r.h./m in group 3 (Fig. 4).

3.5. Checking oenological bibliography

The actual indoor hygrothermal environment was not kept within the comfort ranges of temperature and relative humidity mentioned by different authors to carry out the aging, at least for several months a year (Fig. 5). The percentage of hours per year within the described intervals ranged from 4% to 54% depending on the author in group 1, from 7% to 56% in group 2, and from 2% to 65% in group 3.

The differences between what happens in reality and the recommendations in the literature were especially striking in summer, with an average of 13% of the time within the comfort intervals in group 1 and group 2, and 30% in group 3.

3.6. Reference monthly comfort intervals

Taking into account the differences found between the literature and reality, it was necessary to establish monthly comfort intervals that serve as a reference for the wine sector. Therefore, a diagram based on wineries where prestigious wines are aged was proposed (Fig. 6). Specifically, the proposed diagram was based on the top six aging rooms on the list with a score above 92. The selected aging rooms are representative of the main constructive designs.

The proposed diagram showed the monthly evolution of the daily average hygrothermal environment of the barrel area that ensures a good development of the aging. The diagrams reflect contrasted red wine aging areas based on the actual values of wineries with high quality wines, not implying that outside these areas the aging cannot be carried out.

4. Conclusions

The monitoring of 19 wineries showed a great variability in the hygrothermal environment in which the aging of red wine is carried out. There is no single solution for red wine aging. Quality wine can be obtained in very different environments. Even in wineries with similar constructive design, the differences that can be found are remarkable.

Frequency histograms revealed what actually happens inside the aging rooms. They showed significant temperature and relative humidity variations, especially during summer months. There were also huge differences between the three groups in which the warehouses have been divided according to their constructive design. Frequency histograms provide a monthly reference to compare the temperature and relative humidity of other aging rooms and ensure that these are usual values.

The psychometric diagrams provided complementary information, combining temperature and relative humidity simultaneously. It is a valuable tool for aspects such as evaporation losses. Thus, during the summer months, underground cellars offered better conditions to reduce losses. On the other hand, most basement aging rooms combined the highest temperatures of the year with relative humidity between 70% and 90%. Dispersion was very evident in above-ground aging rooms, especially in terms of temperature, due to air conditioning

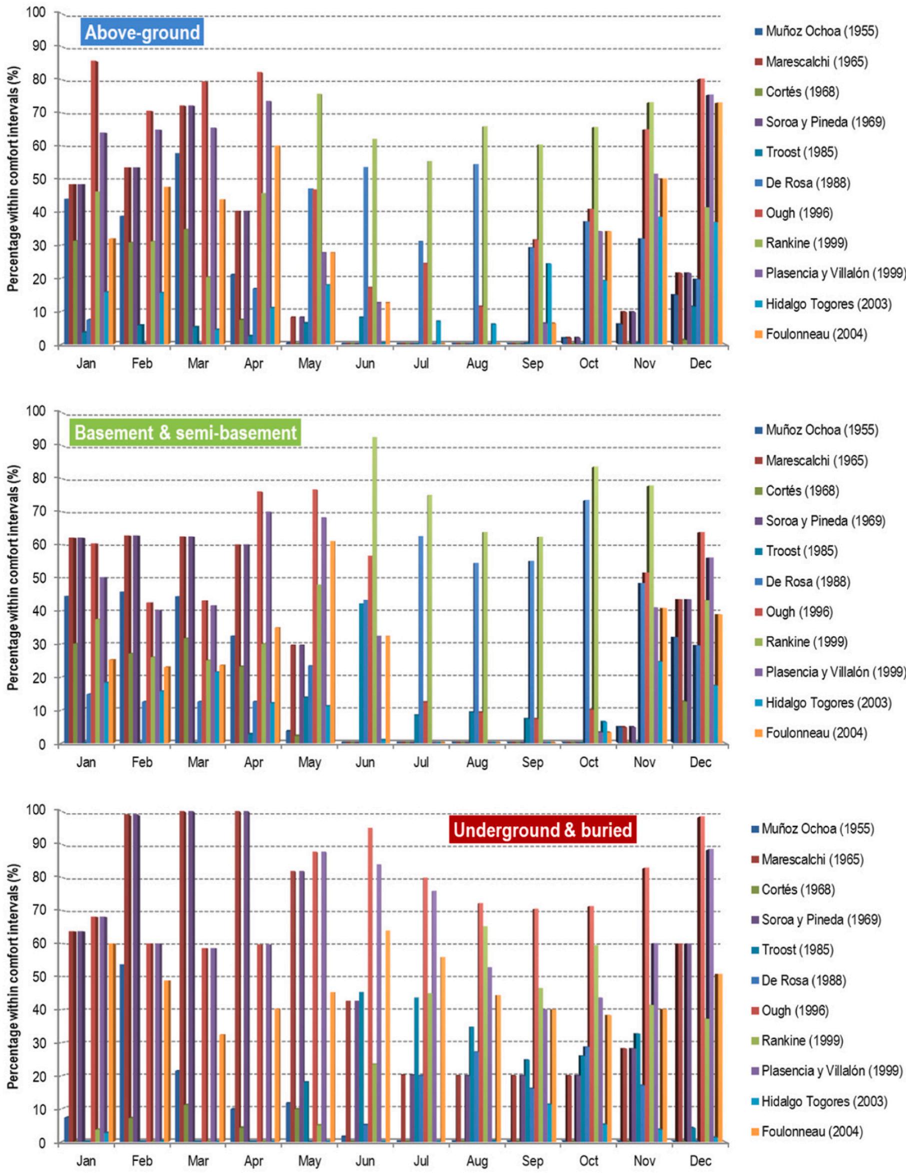

Fig. 5. Percentage of values monitored within the comfort ranges described by different authors.

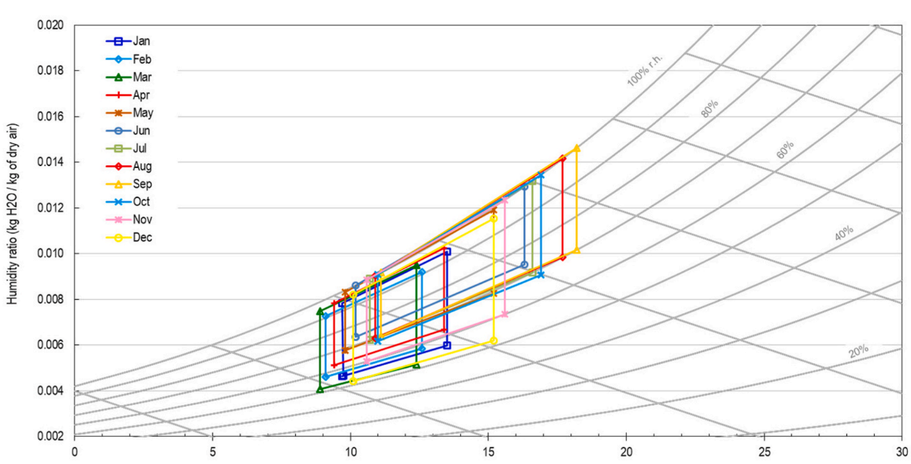

Fig. 6. Contrasted zones of monthly comfort that ensure correct aging of red wine. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

programming.

The results showed large differences in thermal stability depending on the constructive design: underground were the most stable. The aging rooms were less stable in relative humidity, with significant daily variations in all groups. The analysis of vertical uniformity revealed a not insignificant thermal stratification, especially in the case of basements during the summer. Monthly averages exceeded 0.5 °C and 2%r.h. per meter. As a result, barrels of higher levels were subjected to higher temperature and lower relative humidity than those of the lower level for several months a year, which could lead to greater losses and a different evolution of the wine.

Comparison of the experimental data with the comfort intervals proposed by several authors revealed that these do not reflect reality. The indoor hygrothermal environment was not kept within the temperature and relative humidity comfort ranges mentioned by a wide list of authors, at least for several months a year.

In addition, the specialized literature lacks monthly reference ranges obtained statistically. For this reason, a diagram based on wineries where prestigious wines are aged was proposed. The selected aging rooms are representative of the main constructive designs. Although this is a proposal with limitations, it represents a considerable advance over the existing bibliography. It should be clarified that the diagram does not imply that quality aging cannot be carried out outside the proposed areas.

The results of this work should be a useful tool for the winemaking sector. For example, to serve as a reference for the control of the aging process in other wineries, design of new aging rooms by means of simulations, set the programming of air conditioning equipment, etc.

Future research should be directed to analyze more temperature and humidity profiles of other wineries with poor quality wines to explore different perspectives on the comfort range obtained in this research.

CRediT authorship contribution statement

Fernando R. Mazarrón: Conceptualization, Methodology, Investigation, Data curation, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Ignacio Cañas:** Conceptualization, Methodology, Formal analysis, Supervision, Project administration, Funding acquisition, Writing – review & editing.

Declaration of competing interest

None.

All authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work (employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

Data availability

The authors do not have permission to share data.

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References

de Adana, M. R., Lopez, L. M., & Sala, J. M. (2005). A Fickian model for calculating wine losses from oak casks depending on conditions in ageing facilities. *Applied Thermal Engineering, 25*(5–6), 709–718.

Arredondo-Ruiz, F., Canas, I., Mazarron, F. R., & Manjarrez-Dominguez, C. B. (2020). Designs for energy-efficient wine cellars (ageing rooms): A review. *Australian Journal of Grape and Wine Research, 26*(1), 9–28. https://doi.org/10.1111/ajgw.12416

Barbaresi, A., Dallacasa, F., Torreggiani, D., & Tassinari, P. (2017). Retrofit interventions in non-conditioned rooms: Calibration of an assessment method on a farm winery. *Journal of Building Performance Simulation, 10*(1), 91–104. https://doi.org/10.1080/19401493.2016.1141994

Barbaresi, A., Torreggiani, D., Benni, S., & Tassinari, P. (2014). Underground cellar thermal simulation: Definition of a method for modelling performance assessment based on experimental calibration. *Energy and Buildings, 76*, 363–372. https://doi.org/10.1016/j.enbuild.2014.03.008

Benni, S., Torreggiani, D., Barbaresi, A., & Tassinari, P. (2013). Thermal performance assessment for energy-efficient design of farm wineries. *Transactions of the Asabe, 56*(6), 1483–1491.

Cortés, I. M. (1968). *Enología*. Madrid: Alhambra.

De Rosa, T. (1988). *Tecnología del vino tinto*. Madrid: Mundi-Prensa.

Foulonneau, C. (2004). *Guía práctica de La vinificación. (Con La ley de La viña Y del vino)*. Madrid: A. Madrid Vicente.

Garde-Cerdan, T., & Ancin-Azpilicueta, C. (2006). Review of quality factors on wine ageing in oak barrels. [Article]. *Trends in Food Science & Technology, 17*(8), 438–447. https://doi.org/10.1016/j.tifs.2006.01.008

Hidalgo Togores, J. (2003). *Tratado de enología*. Madrid: Mundi-Prensa.

Marescalchi, C. (1965). *Manuale dell'enologo. Casale monferrato: Fratelli Marescalchi*.

Martin, S., & Canas, I. (2006). A comparison between underground wine cellars and aboveground storage for the aging of Spanish wines. *Transactions of the Asabe, 49*(5), 1471–1478.

Mazarron, F. R., & Canas, I. (2009). Seasonal analysis of the thermal behaviour of traditional underground wine cellars in Spain. *Renewable Energy, 34*(11), 2484–2492. https://doi.org/10.1016/j.renene.2009.03.002

Mazarron, F. R., Cid-Falceto, J., & Canas, I. (2012). Ground thermal inertia for energy efficient building design: A case study on food industry. *Energies, 5*(2), 227–242. https://doi.org/10.3390/en5020227

Mazarron, F. R., Cid-Falceto, J., & Canas-Guerrero, I. (2012). Assessment of aboveground winery buildings for the aging and conservation of wine. *Applied Engineering in Agriculture, 28*(6), 903–910.

Mazarron, F. R., Lopez-Ocon, E., Garcimartin, M. A., & Canas, I. (2013). Assessment of basement constructions in the winery industry. *Tunnelling and Underground Space Technology, 35*, 200–206. https://doi.org/10.1016/j.tust.2012.07.007

Mazarron, F. R., Porras-Amores, C., & Canas-Guerrero, I. (2015). Annual evolution of the natural ventilation in an underground construction: Influence of the access tunnel and the ventilation chimney. *Tunnelling and Underground Space Technology, 49*, 188–198. https://doi.org/10.1016/j.tust.2015.04.015

Muñoz Ochoa, P. (1955). *Prácticas de vinificación. Publicaciones monográficas de la revista vinícola y de agricultura, 2nd*. Zaragoza: La Académica.

Ough, C. S. (1996). *Tratado básico de enología*. Zaragoza: Acribia.

Plasencia, P., & Villalón, T. (1999). *Manual de los vinos de España*. León: Editorial Everest.

Porras-Amores, C., Mazarron, F. R., & Canas, I. (2014). Study of the vertical distribution of air temperature in warehouses. *Energies, 7*(3), 1193–1206. https://doi.org/10.3390/en7031193

Porras-Amores, C., Mazarron, F. R., Canas, I., & Villoria Saez, P. (2019). Natural ventilation analysis in an underground construction: CFD simulation and experimental validation. *Tunnelling and Underground Space Technology, 90*, 162–173. https://doi.org/10.1016/j.tust.2019.04.023

Rankine, B. (1999). *Manual práctico de enología*. Zaragoza: Acribia.

Santolini, E., Barbaresi, A., Torreggiani, D., & Tassinari, P. (2019). Numerical simulations for the optimisation of ventilation system designed for wine cellars. *Journal of Agricultural Engineering, 50*(4), 180–190. https://doi.org/10.4081/jae.2019.952

Soroa Pineda, J. M. (1969). *Compendio de enología* (Vol. 2ª). Madrid: Dossat.

Torreggiani, D., Barbaresi, A., Dallacasa, F., & Tassinari, P. (2018). Effects of different architectural solutions on the thermal behaviour in an unconditioned rural building. The case of an Italian winery. *Journal of Agricultural Engineering, 49*(1), 52–63. doi:779 10.4081/jae.2018.779.

Troost, G. (1985). *Tecnología del vino*. Barcelona: Omega.

Vogt, E. (1971). *Fabricación de vinos*. Zaragoza: Acribia.

Yravedra, M. J. (2003). *Arquitectura y cultura del vino. Andalucía, Cataluña, La Rioja y otras regiones*. Madrid: Munilla-Lería.