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# Hygrothermal conditions for the biological aging of sherry wine

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ABSTRACT

The present work analyzed the hygrothermal environment of several prestigious warehouses where sherry wines of “Fino” and “Manzanilla” type are made. Through descriptive statistics, frequency histograms and psychrometric diagrams of temperature and relative humidity variations have been obtained. In addition, other factors such as the stability and uniformity of the interior environment have been quantified. The results showed significant temperature variations throughout the year (limit values of 5 °C and 31 °C), with a more stable relative humidity (between 60% and 90% for most of the year). Indoor conditions varied much more rapidly than in wineries for the aging of red wine, as a result of constant ventilation. Therefore, the annual average stability was 2.0 ± 0.8 °C per day and 0.14 ± 0.12 °C per hour. Vertical uniformity decreased in spring and summer, with stratification values close to 0.5 °C/m and 3% r.h./m. The monitored indoor environment is outside the comfort ranges described in the literature for extended periods of time (in the most extreme case, 96% of the time outside the recommended interval). For that reason, a reference psychrometric comfort diagram was proposed.

*Industrial relevance:* For the first time, the hygrothermal behavior of several wineries producing high quality wines (very high scores in the oenological guides) was extensively analyzed. The results of the study, which include monthly comfort intervals, should be a very useful tool for the sherry wine industry, in order to control and ensure optimal development of the flor yeast film. It should also be taken into account for the correct design of new wineries or the rehabilitation of abandoned warehouses.

## 1. Introduction

The process for the elaboration of biologically aged white wines through the so-called “criaderas” system can be considered as the most important contribution of the South of Spain to the enology field worldwide (Moreno-Garcia, Raposo, & Moreno, 2013). The “flor yeast film” is a biological film composed of a mixture of microorganisms, mainly yeasts of the genus *Saccharomyces* (David-Vaizant & Alexandre, 2018; Zara, Gross, Zara, Budroni, & Bakalinsky, 2010), which form a velum on the surface (film), which can reach 1-cm thick (Marin-Menguiano, Romero-Sanchez, Barrales, & Ibeas, 2017), which protects it from the oxidative action of air. In this way, the evolution or aging of the wine does not occur in an oxidative but biological way. The continued action of this flor yeast film is manifested in the appearance of different and peculiar organoleptic characters (Suárez Lepe & Íñigo Leal, 2004).

Flor yeast or flor velum yeasts can grow at the surface of different wines. These flor yeasts can be found in very specific wine processes known as biological aging practiced in Spain (Andalusia), Italy (Sardinia), Hungary and France (Jura) to produce Xeres, Vernaccia di Oristano, Szamorodni, and Vin Jaune wines, respectively (David-Vaizant & Alexandre, 2018).

In Jerez, sherry wines of biological aging known as “Finos” and “Manzanillas” are made from completely fermented musts where the content of reducing sugars does not exceed 5 g per liter (BOJA, 2013), unlike other sweet liquor wines, partially fermented or to which sugar has been added.

Once fermented, a certain amount of alcohol is added to them, in order to slightly increase their alcohol content in a process known as “fortification” or “heading”. With this technique, the risk of subsequent infections is reduced and, therefore, its biological stability is favored. Alcoholic graduation can reach 15.5 or 16 GL (Gay-Lussac degrees: measure that expresses the alcohol content in a liquid in relation to its percentage in 100 units of it) without inhibiting this phenomenon (Bravo Abad, 1995). In warm climates, wines with low alcohol content are at great risk of acetification (Suárez Lepe & Íñigo Leal, 2004).

When sugar is depleted and yeast growth depends on access to

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oxygen, changes in the composition of the cell wall occur, increasing its hydrophobic surface, reducing its density, and ascending to the surface in search of oxygen (Zara et al., 2005), allowing them to grow thanks to their oxidative metabolism, not dependent on alcoholic fermentation (Alexandre, 2013).

During this phase, flor yeasts use glycerol, ethyl acetate and ethanol as the primary source of carbon and produce mainly acetaldehyde and other compounds (Alexandre, 2013; Dos Santos, Feuillat, & Charpentier, 2000; Marin-Menguiano et al., 2017; Zara et al., 2010). This phase consumes a large amount of oxygen which preserves the wine in a reduced state that gives it its characteristic pale color (Marin-Menguiano et al., 2017; Suárez Lepe & Íñigo Leal, 2004).

Even when the flor yeast film remains on the surface of the wine throughout the year, the busiest times are in spring and autumn, when there are better conditions in the environment; this seasonal resurgence is called "flowering" (Domecq, 2011).

Another of the great historical contributions to the world wine industry of sherry wines was the aging system in American oak barrels called "Criaderas and Soleras". This dynamic system of periodic mixtures is intended to give uniformity and continuity to production, avoiding seasonal variations, and maintaining constant quality over the years (Domecq, 2011).

The system of "criaderas" and "soleras" consists of several levels or scales, each consisting of a certain number of barrels. The oldest is located on the floor of the cellar, which is why it is called "solera" (floor). On this the different scales are placed that follow it in less old age, which are called "criaderas" (tiers) and are listed according to their order of seniority with respect to the solera. The solera supplies the wine intended for consumption. Periodically a certain proportion of the wine contained in each of the barrels that make up the solera is extracted, producing a partial vacuum in them. This operation is called "saca" (tirage). The vacuum produced in the solera is completed with the set of barrels that comes from the scale that follows in age, or 1st tier, and so on until the scale or younger tier is completed with wine from the vintage. The operation of completing the vacuum originated on a scale is called "rocío" (refilling). The operation of tirages and refilling is called "run scales" (Domecq, 2011). This system favors biological aging under a flor yeast film, providing new nutrients from the younger scales.

There have been numerous scientific studies conducted in recent years on the biological aging under flor yeasts, which gives an idea of the interest that the scientific world devotes to this biological process. However, most research papers published to date focus on the characterization of the yeasts involved in the formation of the "flor yeast film", evolution of wine compounds, and darkening phenomena. Thus, for example, Esteve-Zarzoso, Peris-Toran, Garcia-Maiquez, Uruburu, and Querol (2001), Naumov (2017), Marin-Menguiano et al. (2017) and David-Vaizant and Alexandre (2018) studied the characterization of flor yeast film-forming yeast populations; Zara et al. (2010), Alexandre (2013) and Moreno-Garcia et al. (2013) analyzed the adaptation mechanisms that allow the flor yeast strains to survive in the wine after fermentation is over; Villamiel, Carmen Polo, and Victoria Moreno-Arribas (2008) and Dos Santos et al. (2000) studied changes in compounds during biological aging; Palma, Barroso, and Perez-Bustamante (2000), Ortega, Lopez-Toledano, Mayen, Merida, and Medina (2003), Lopez-Toledano, Mayen, Merida, and Medina (2006) and Merida, Lopez-Toledano, and Medina (2007) carried out studies on the darkening of sherry wines subjected to oxidative aging and the ability of flor yeasts to retain this phenomenon.

Although the film requires very sensitive and limiting environmental conditions for its development, references to the environmental conditions in which it should be performed are scarce, mostly exclusively of temperature, of an annual nature and without experimental basis. There are only two precedents where the environmental conditions of Jerez wineries were monitored (García del Barrio, 1984; Lozano & Perdigones, 1989). These studies supposed a first approach to the analysis of the hygrothermal conditions in the wineries, although with very limited means, focused on the behavior of the building and providing little information on the hygrothermal conditions of the aging. Given the existing gap, the present work analyzes the hygrothermal environment of several aging warehouses where prestigious sherry wines Fino and Manzanilla types are elaborated, delimiting comfort zones that ensure a good aging of the wine.

The study is part of a project of the Spanish national R&D plan entitled "Bioclimatic design strategies in wine cellars as nearly zero-energy buildings models". The ultimate objective of this project is to determine the effectiveness of the constructions to provide adequate hygrothermal conditions for the aging of the wine.

## 2. Hygrothermal conditions during the biological aging of sherry wine

Biological aging has the peculiarity that it requires an abundant presence of oxygen for the development of the flor yeast film, which implies a constant ventilation of the cellars (García del Barrio, 1984). In addition, the environmental conditions that are required for the development of flor yeast are very sensitive and limiting. Thus, Marcilla, Alas, and Feduchy (1936) pointed out as limit temperatures between 10 and 25 °C, with an optimum of 15 to 17 °C; Cruess (1946) in the tests carried out in a laboratory in California on twelve strains of flor yeasts concluded, that at the temperature of 68–70 °F (20–21.1 °C) all the cultures formed film properly; however, in general, these could not maintain its activity with temperatures above 80 °F (26.7 °C); Fernández de Bobadilla (1943) postulated that the temperature must be kept within the limits of between 15 and 20 °C; García del Barrio (1984) made microclimatic recommendations inside the wineries, with a maximum value of 25 °C and a minimum of 12 °C, since above or below these temperatures the activity stops microbial. He also included that "the environmental humidity of the winery, that is, the relative humidity of the air is its interior, should be as high as possible and also as constant as possible throughout the day, night and year"; Lozano and Perdigones (1989) followed up on a series of wineries in the Puerto de Santa María aimed at establishing the possible relationships between the behavior of the flor yeast in the barrels and the evolution in environmental conditions, concluding that with an ambient temperature of 18–20 °C, within the aging cellar, the aging process will be optimal; Barbadillo (1993) recommended a temperature between 16 and 18 °C. However, Bravo Abad (1995) postulated that in the biological aging cellars the temperature must be as stable as possible, being the ideal value of 15 °C, without ever exceeding 25 °C; the relative humidity as much high possible and constant abundant aeration. Yravedra-Soriano (2003) postulated that the optimum temperature range should be between 18 and 22 °C and provide an adequate humidity range of between 70 and 75%. Meanwhile, Suárez Lepe and Íñigo Leal (2004) stated that the most convenient temperatures for the flor yeast are those between 15 and 18 °C. Over 25 °C, and below 13 °C, the yeast paralyzes its action and the film is detached in fragments, disappearing completely from the surface of the wine. Twice a year the microorganism goes up to give aging to the wine because the temperature of the winery coincides with the optimum for the development of the flor yeast phase, being the most active times in the months of April to May and from September to October. Although in the area of Sanlúcar de Barrameda the film remains on the wine throughout the year (Hidalgo Togores, 2011).

## 3. Material and methods

### 3.1. Monitored warehouses

After contacting dozens of wineries, six warehouses have been selected where the aging of sherry wines of recognized prestige is carried out, belonging to the Barbadillo, Delgado Zuleta and Hidalgo la Gitana wineries. Wineries have been selected in which both "Manzanilla" and "Fino" are aged, located in Sanlúcar de Barrameda. Its wines are among the most prestigious and best valued of their kind, reaching scores between 92 and 94 (out of 100) according to Parker, and between 92 and 95 (out of 100) according to Peñín. The selection includes both modern warehouses (20th century) and traditional wineries from the 19th century, known as cathedral warehouses (Fig. 1).

The monitoring was carried out using Hobo® brand temperature and humidity recorders and sensors. The accuracy of the sensors is greater than ±0.3 °C and ± 3% r.h., with a resolution of 0.03 °C and 0.03% r.h.

To characterize the interior hygrothermal behavior throughout the year, a total of 72 temperature and 24 humidity sensors were distributed in the different warehouses, located between 0 and 4 m high (Fig. 2), space where the aging barrels are located. Taking into account that a measurement interval of 15 min was set, the results of the study are based on >3 million data.

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

### 3.2. Characterization of the indoor hygrothermal environment

The hygrothermal behavior of the set of warehouses has been synthesized in psychrometric diagrams and frequency histograms, through

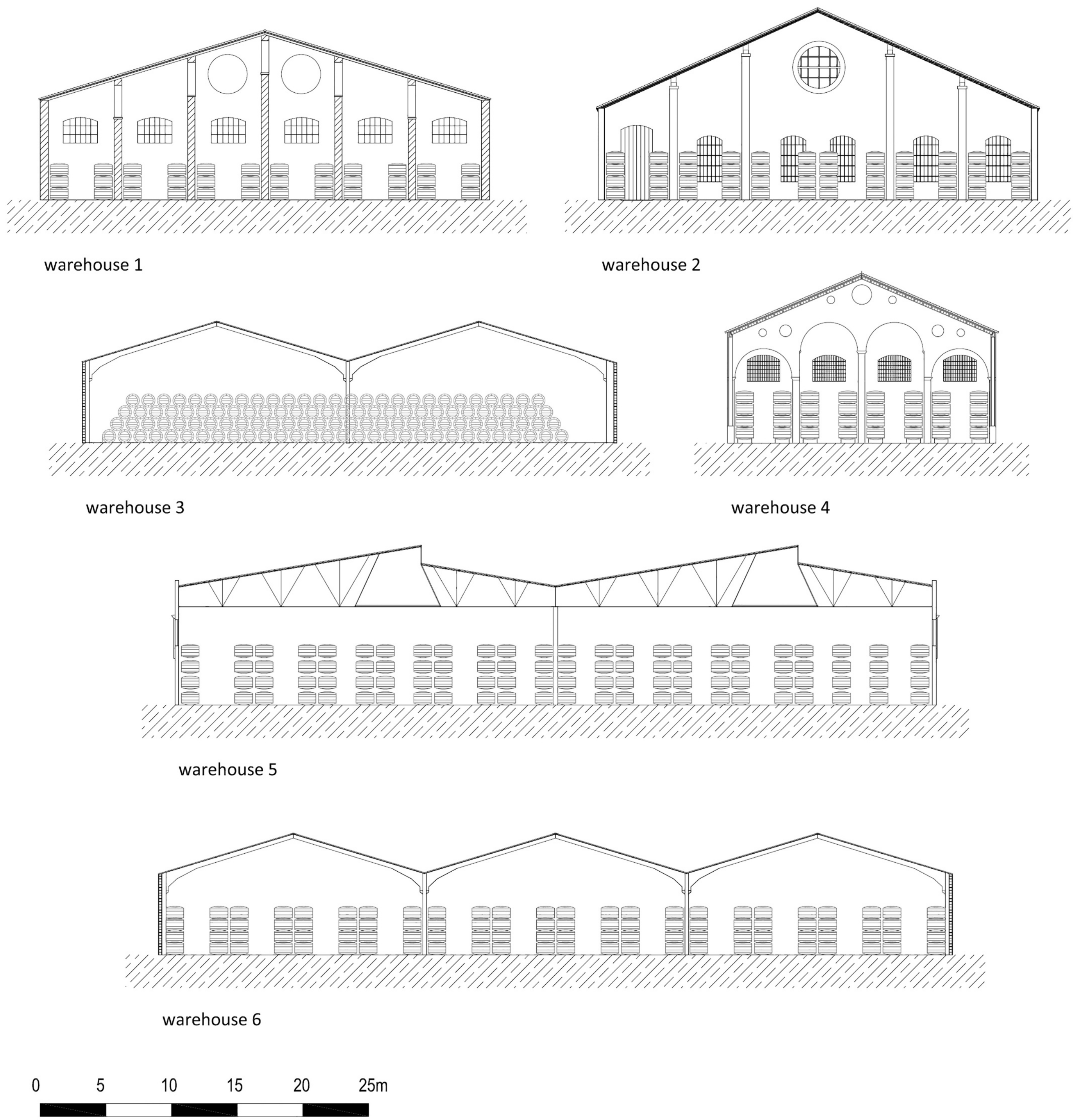


**Fig. 1.** Elevations of the six monitored warehouses.

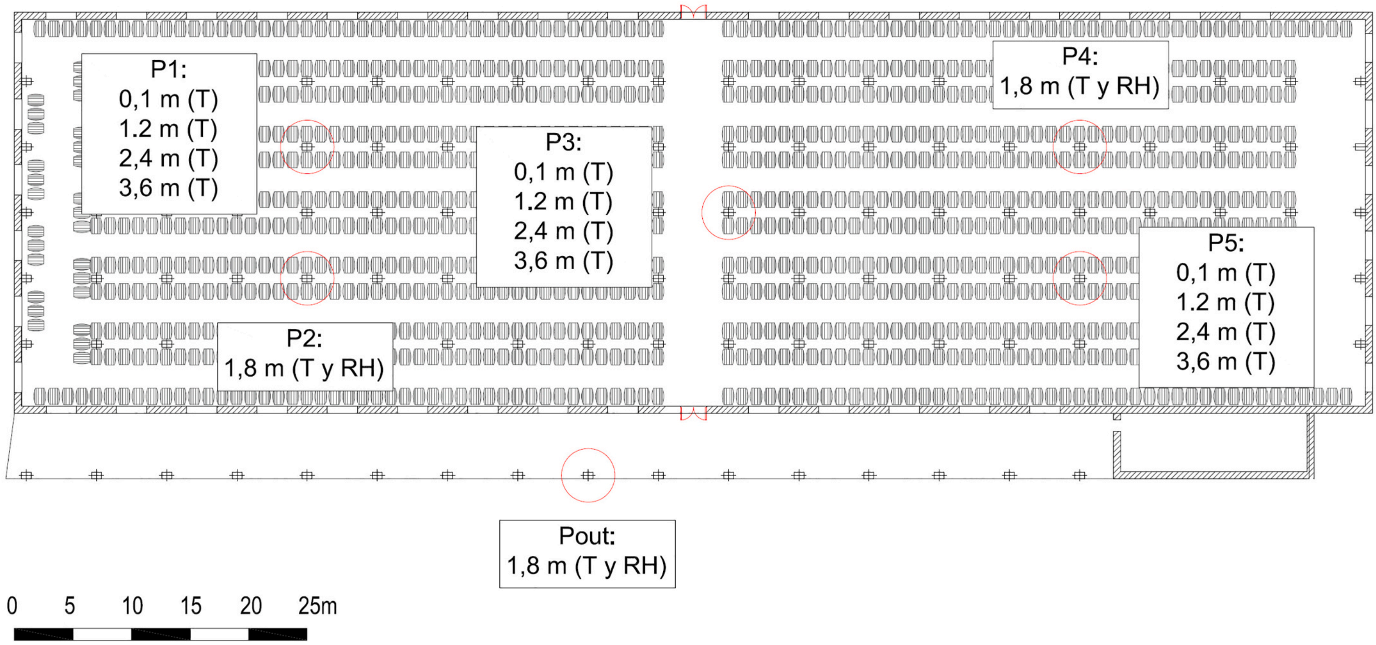


**Fig. 2.** Example of sensor distribution installed in one of the warehouses.

descriptive statistics of the set of sensors installed in the area occupied by the aging barrels.

In addition, other aspects that could affect aging have been analyzed, such as the stability and uniformity of the previous environment. Stability is the speed at which the temperature and relative humidity vary at each of the monitoring points (°C/h, °C/day, etc.). Stability is directly related to existing ventilation in aging warehouses. Uniformity refers to the differences in temperature and relative humidity between the sensors inside the warehouse at a given time. Vertical uniformity (stratification in a specific position) and horizontal uniformity (differences between sensors at the same height) were analyzed.

### 3.3. Comfort intervals

After the characterization of the hygrothermal environment, the percentage of time within the comfort intervals described by different authors for the aging of the sherry wine has been quantified (Table 1). It is necessary to clarify that the bibliography referring to the hygrothermal conditions of aging of sherry wine is scarce. In addition, in most cases, it is limited to annual temperature ranges. On the other hand, the majority of authors specify an optimal range, and there are few who deal with range limits for the development of the flor yeast film.

**Table 1**
Hygothermal comfort intervals recommended by different authors for the aging of Sherry wine.

| Author | Limit range | Optimal range |
|---|---|---|
| Marcilla et al. (1936) | 10–25 °C | 15–17 °C |
| Cruess (1946) | ? - 26.6 °C | ? - 20 °C |
| Fernández de Bobadilla (1943) | – | 15–20 °C |
| García del Barrio (1984) | 12–25 °C | – |
| Lozano and Perdigones (1989) | – | 18–20 °C |
| Barbadillo (1993) | – | 16–18 °C |
| Bravo Abad (1995) | ? - 25 °C | 15 °C |
| Yravedra-Soriano (2003) | – | 18–22 °C; 70–75%r.h. |
| Suárez Lepe and Íñigo Leal (2004) | 13–25 °C | 15–18 °C |

## 4. Results and discussions

### 4.1. Hygrothermal environment

The frequency histogram showed important temperature variations throughout the year. During the summer, the indoor temperature was maintained between 21 °C and 31 °C; most of winter between 6 °C and 16 °C (Fig. 3). During these seasons, the monthly dispersion was lower than during the rest of the year. The temperature was concentrated around values reaching frequencies close to 30–35%: 11 °C $\leq T <$ 12 °C in January, 12 °C $\leq T <$ 13 °C in February, 24 °C $\leq T <$ 25 °C in August, etc. On the contrary, spring and fall were transition periods, with a greater dispersion and lower maximum frequencies.

The differences in relative humidity between months were much smaller than in the case of temperature (Fig. 4). Eighty-four percent of the year the relative humidity was maintained between 60% r.h. and 90% r.h., which seems to be a consequence of the external relative humidity and the effectiveness of the irrigation of the ground floor.

During the summer months, the relative humidity was lower than the rest of the year, with values below 85% r.h. and with a maximum frequency close to 70% r.h.. The rest of the months of the year, the humidity ranged between 50% r.h. and 100% r.h., with a maximum frequency that was usually between 75% r.h. and 85% r.h.

The monthly dispersion was much higher than in the case of temperature. Every month, the difference between the maximum and minimum recorded values exceeded 50% r.h.. The monthly interval with the highest frequency barely accounted for 10% of the total values.

The psychrometric diagram summarizes the joint evolution of indoor temperature and relative humidity (Fig. 5). It revealed the real hygrothermal environment and the extreme changes to which the biological aging of wine is subjected: inter-monthly and intra-monthly variations, limits reached, etc.

July and August seemed to be the months of greatest risk for evaporation losses, combining many days of high temperatures and low relative humidity. During these months, evaporative cooling by irrigation can be an interesting practice to reduce wine losses and control the increase in temperature. In contrast, the winter months combined the lowest temperatures of the year with high values of relative humidity.

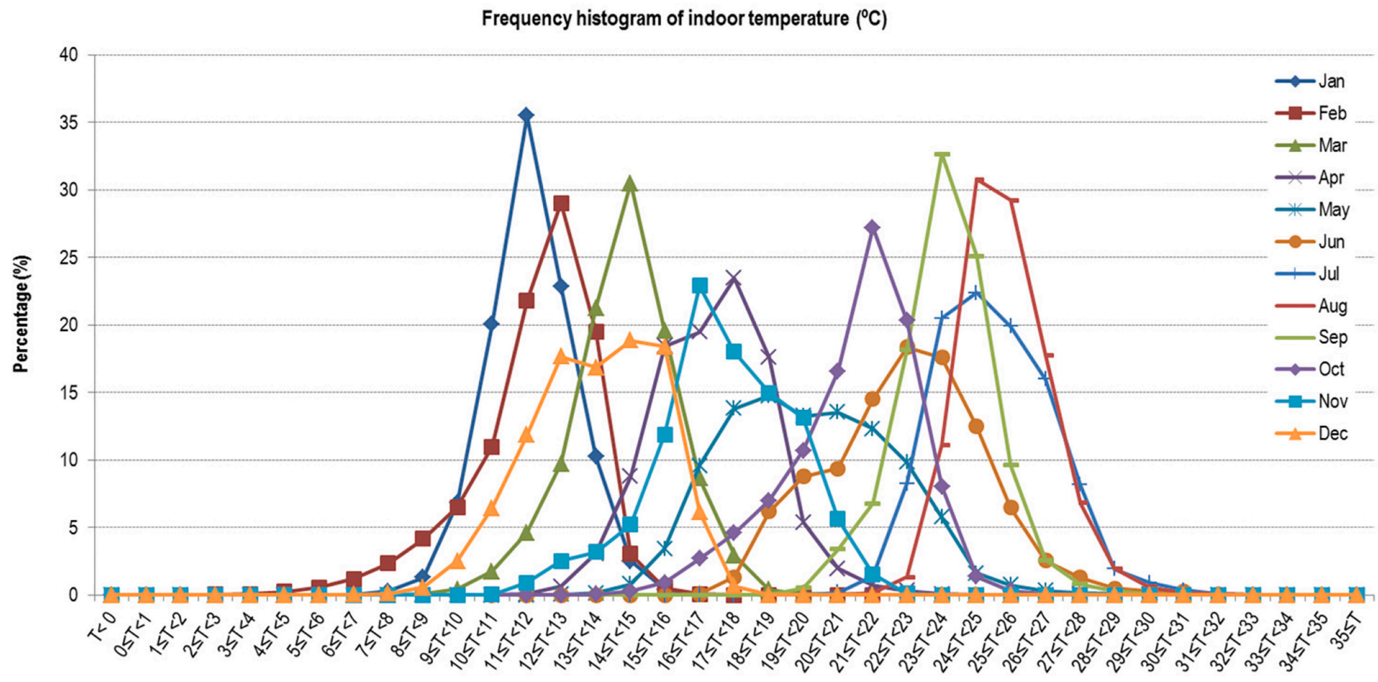


**Fig. 3.** Frequency histogram of the indoor air temperature in the volume occupied by the barrels.

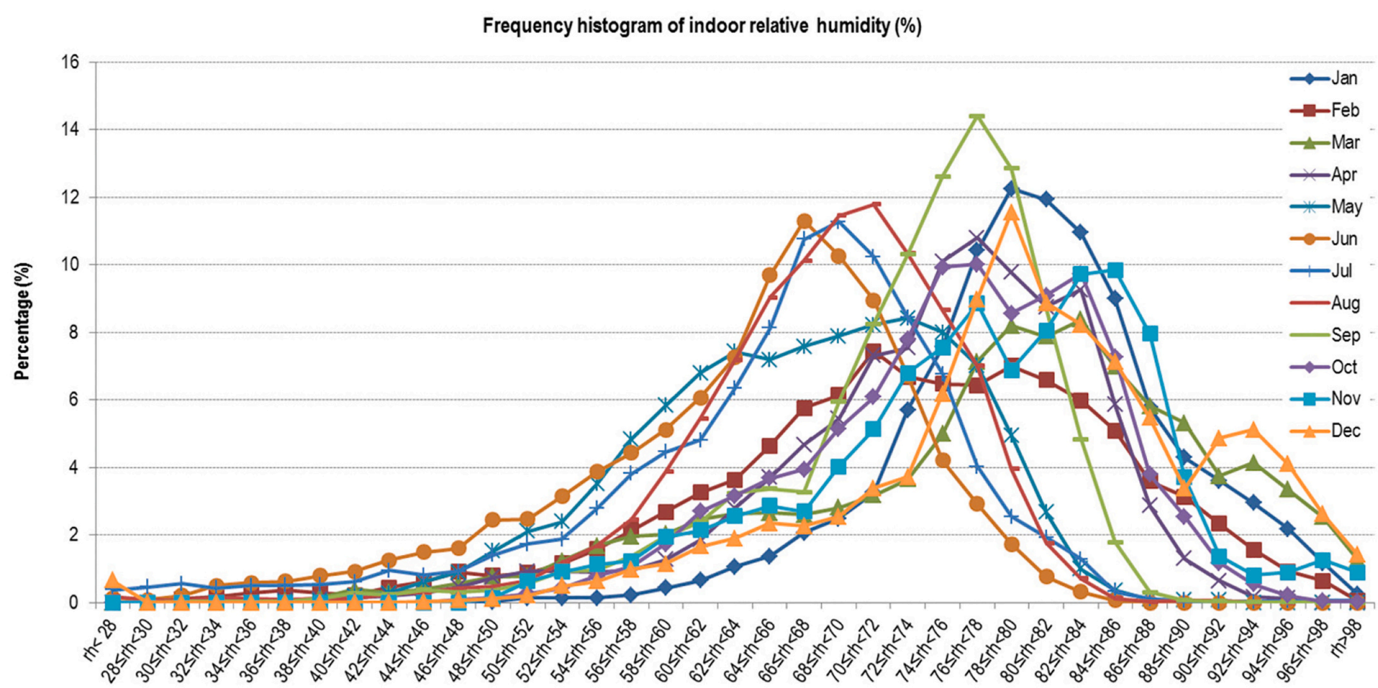


**Fig. 4.** Frequency histogram of the indoor air relative humidity in the volume occupied by the barrels.

### *4.2. Stability*

The stability study (how quickly conditions vary at the same point) showed similar temperature variations throughout the year, with an annual average of 2.0 ± 0.8 °C per day (Fig. 6) and 0.14 ± 0.12 °C per hour. The months with the highest external temperature were those with the lowest internal stability, with variations >2 °C, following the trend of external variation.

Although the peculiarities of the construction make it ineffective in reducing annual temperature variations, it manages to maintain a much more stable environment on a daily and hourly scale. The interior stability was much greater than the exterior, where average daily variations of almost 10 °C were reached in summer. The large volume of air inside, as well as the thermal inertia of the barrels, could explain this behavior. Therefore, the flor yeast film was not subjected to sudden exterior changes, but evolved in a more stable environment with progressive changes.

Biological aging occurs in a less stable environment than oxidative aging of red wine. The indoor conditions vary more quickly than in wineries for red wine, where the average daily variation ranges from

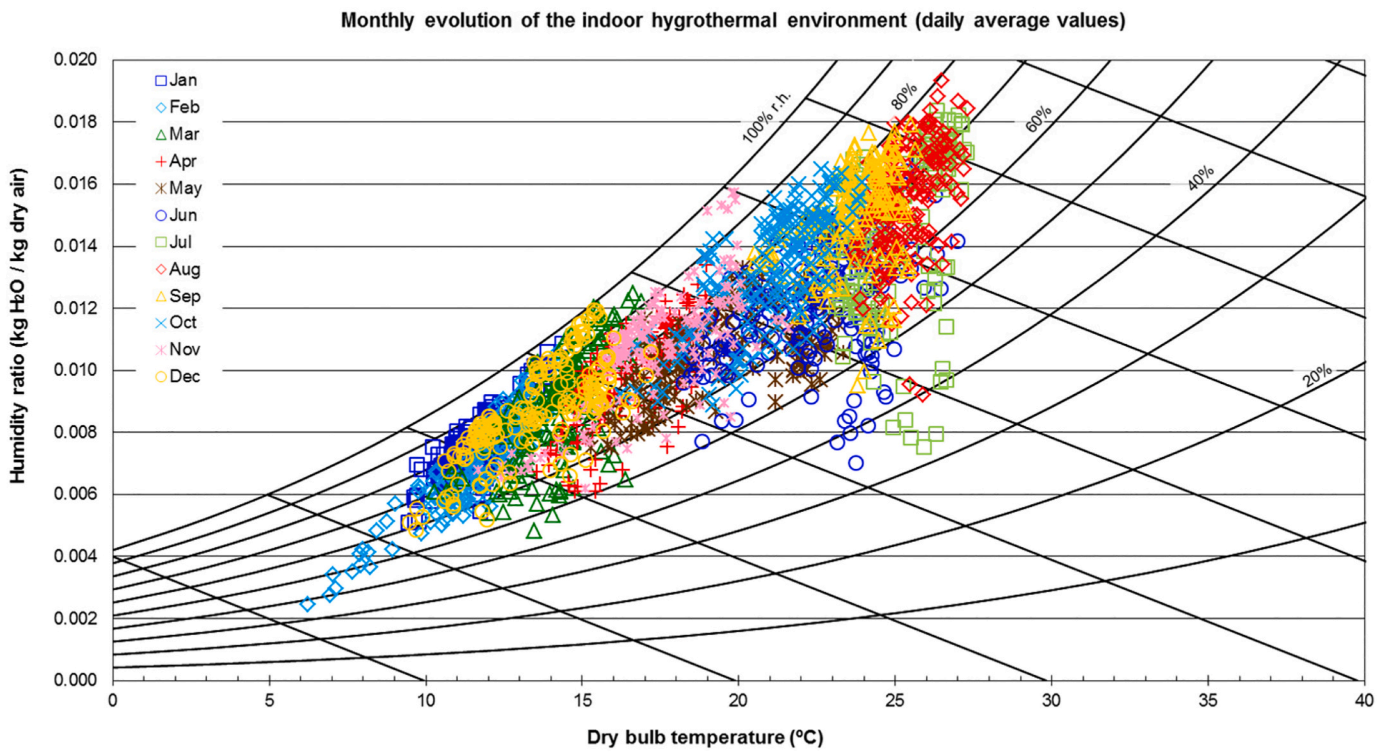


**Fig. 5.** Monthly evolution of the indoor hygrothermal environment in the set of warehouses (daily averages of the T-r.h. sensors in the barrel area).

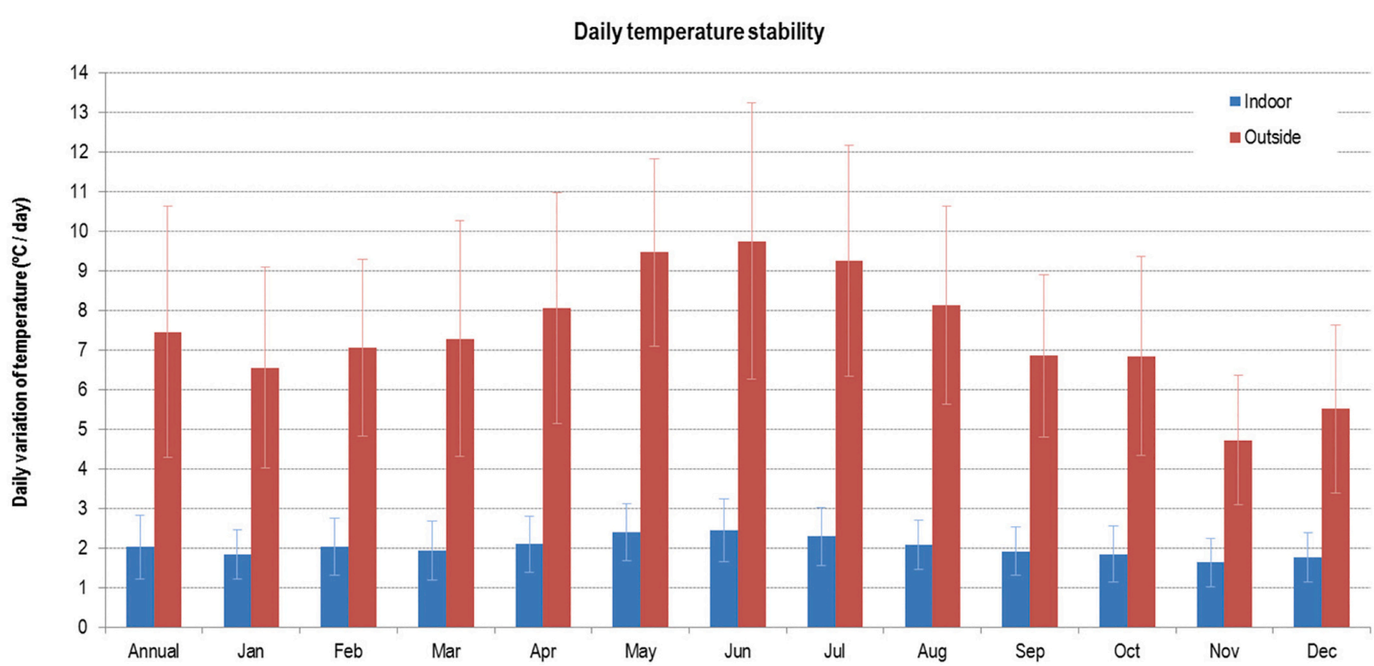


**Fig. 6.** Monthly average of daily temperature variation ($^{0}$C/day) in the area occupied by the barrels and outdoor.

0.1 °C / day in underground cellars and basements up to 1 °C / day in aboveground with air-conditioning warehouses (Mazarron, Cid-Falceto, & Canas, 2012).

The relative humidity stability had greater differences than the temperature, with an annual average of 11 ± 7% r.h. per day (Fig. 7) and 1.0 ± 1.1% r.h. per hour. In general, the greatest variations in relative humidity occurred in the summer months. Sudden variations in relative humidity do not appear to be a factor that penalizes the development of the flower veil in biological aging. However, daily variations were three times less than those outside, highlighting the effectiveness of warehouses in providing a more stable environment for biological aging.

### 4.3. Uniformity

The uniformity analysis (differences throughout the winery at the same time) showed that the height differences were much greater than those found in a horizontal plane. In the case of temperature uniformity, the annual average in the vertical plane was almost twice as high as in

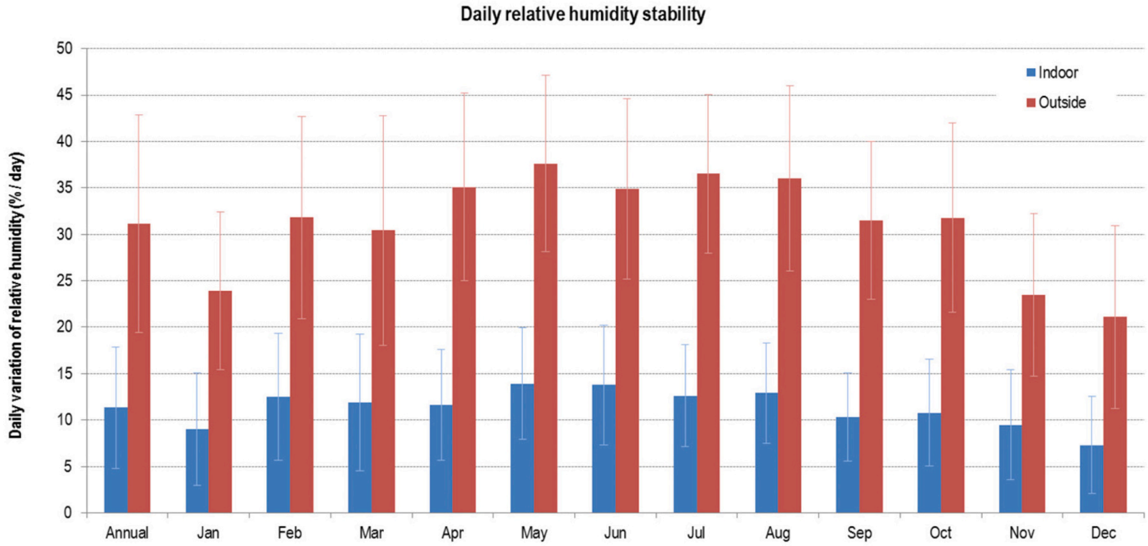


**Fig. 7.** Monthly average of daily variation of relative humidity (% r.h./day) in the area occupied by the barrels and outdoor.

the horizontal plane, with a much larger standard deviation (Fig. 8). In relative humidity, the differences were even greater (Fig. 9). In the summer months, these differences increased, being three times higher in the case of temperature and four times higher in relative humidity. Therefore, the placement of the barrels in the vertical plane seems to be a more important factor in decision-making than their location in the horizontal plane of the winery.

The warehouses were quite uniform in a horizontal plane, considering the same height. The differences in temperature between the different sensors placed in them were usually of a few tenths of a degree, the average of the difference between the point being at a higher and lower temperature of 0.6 °C, only twice the accuracy of the sensors used. Equivalently, the average of the maximum relative humidity difference between two sensors in the warehouse was around 3% r.h., close to the accuracy of the sensors used.

On the contrary, the vertical stratification was remarkable in spring and summer, with values close to 2 °C (0.5 °C/m) and 12% r.h. (3% r.h./m) of monthly average between the floor and the upper height of the barrels. The area near the floor always remained at a lower temperature and higher relative humidity than the upper zone.

This average difference was increased when considering the evolution throughout each day, with stratification peaks in the afternoon that can exceed 1 °C/m monthly average in the hottest months (Fig. 10). 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. These differences justify the usefulness of the traditional system of "criaderas" and "soleras", where the wine of greater antiquity and value is located at the lower level, subjected to lower temperature and higher relative humidity.

As the outside temperature decreases, the stratification was reduced due to the cooling of the air in the upper zone in contact with the roof. Therefore, considering each day, the lowest stratification occurred

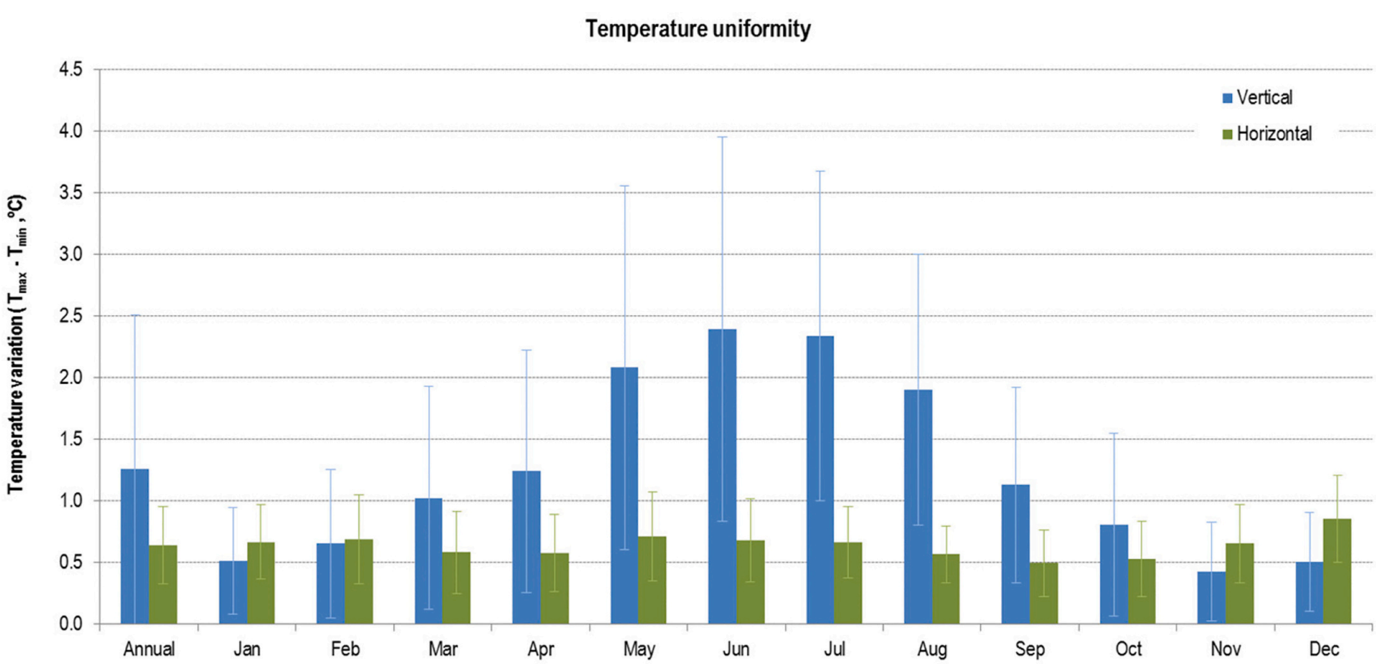


**Fig. 8.** Monthly average of temperature uniformity (vertical and horizontal).

 

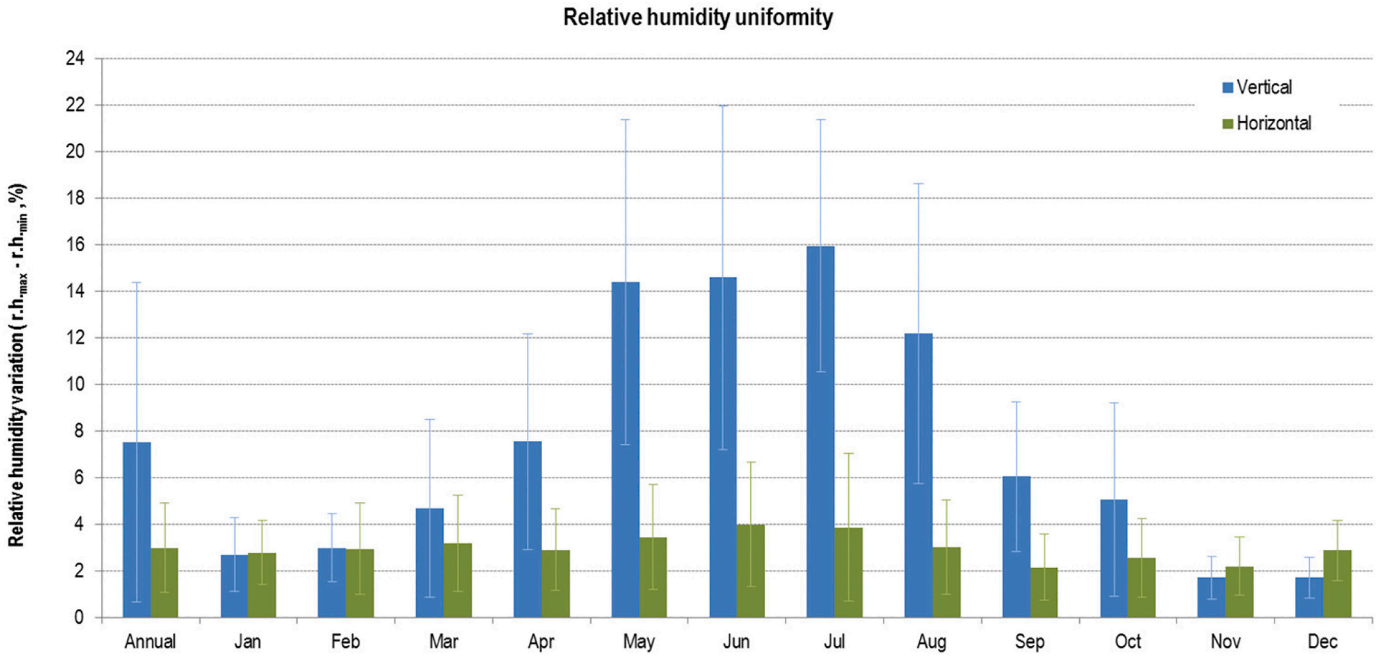


**Fig. 9.** Monthly average of relative humidity uniformity (vertical and horizontal).

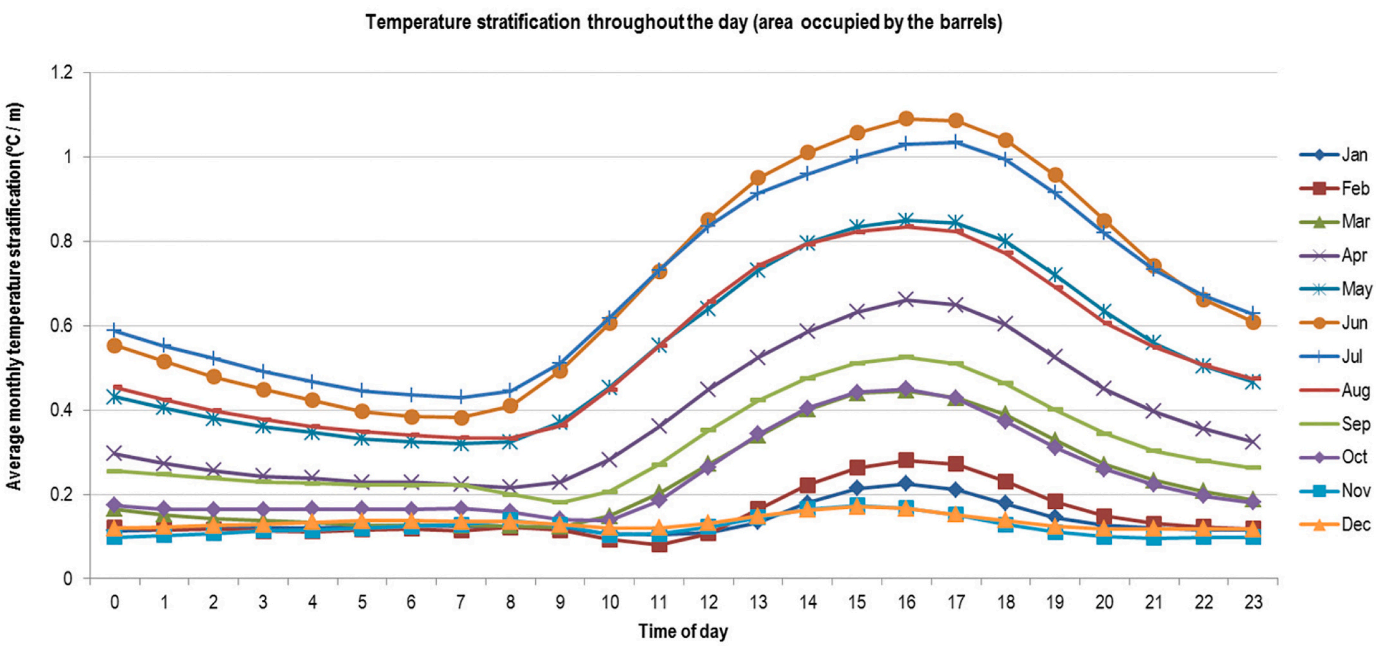


**Fig. 10.** Average stratification (°C per meter) throughout the day in the area occupied by barrels.

during the late hours of the evening (Fig. 10). Throughout the year, the lowest stratification occurred in winter, with monthly average values of 0.5 °C (Fig. 8) and 2% r.h (Fig. 9). Therefore, in the winter months, the height of the barrels should not be a factor to be taken into account in the aging process.

### 4.4. Comfort intervals

The indoor environment was usually not maintained within the optimal aging ranges mentioned by different authors (Fig. 11). In summer, the temperature recorded in the warehouses far exceeded the recommended optimum values. The greatest similarity to reality occurred in the spring and autumn months, although in most cases it did not reach 50% of the time. Therefore, the annual percentage within the range described by most authors was $<30\%$.

On the contrary, there was a lot of proximity to reality when it comes to limit ranges. The percentage increased significantly, with an annual average between 70% and 99%. The intervals cited in the bibliography do reflect the reality of the most active times of veil development, reaching 100% in April, May, October and November. However, most authors are too restrictive in the summer and winter months, leaving the actual values outside the limits (Fig. 12).

Taking into account the differences found between the existing bibliography and reality, a reference psychrometric diagram was

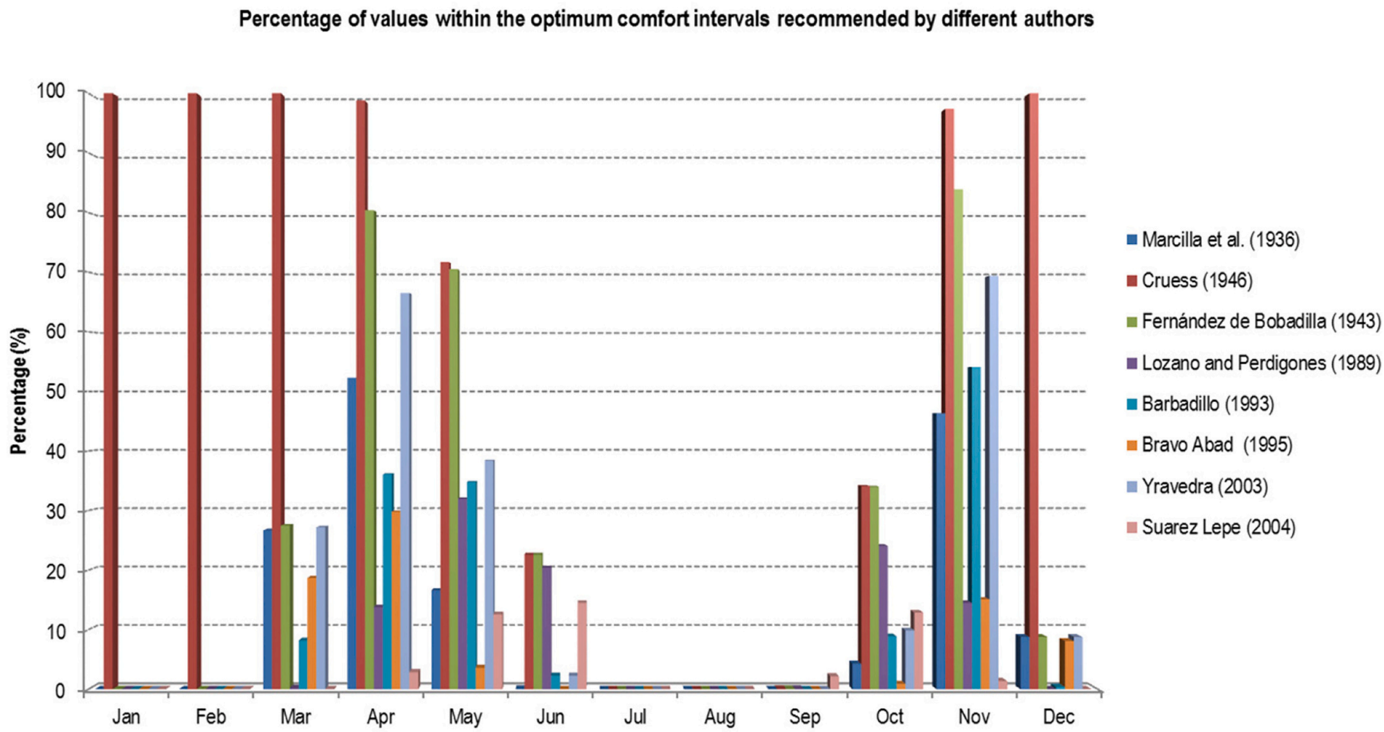


**Fig. 11.** Percentage of values monitored within the optimum comfort intervals described by different authors.

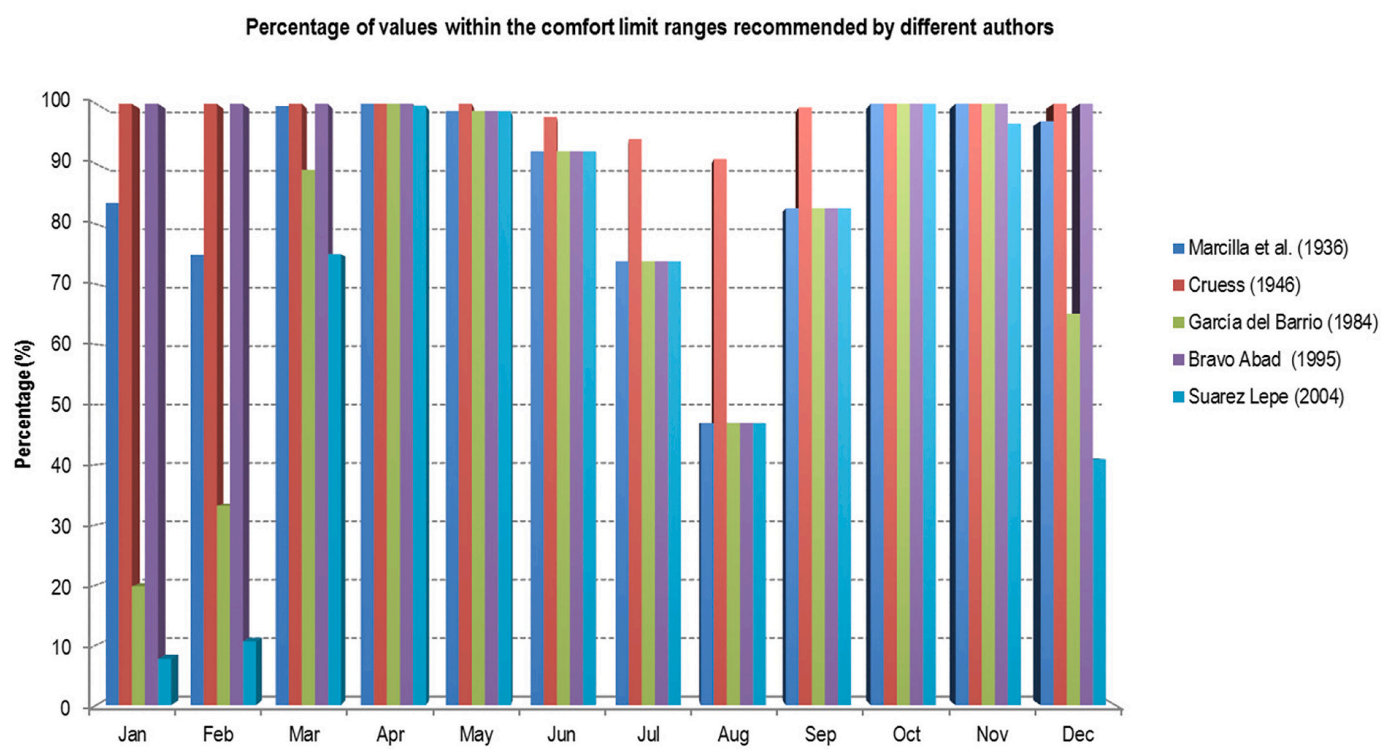


**Fig. 12.** Percentage of values monitored within the comfort limits described by different authors.

proposed (Fig. 13). The diagram showed the monthly evolution of the hygrothermal environment that ensures a good development of the flor yeast film. The diagram refers to the daily average values of the barrel area. Comfort zones would be wider if existing variations within warehouses for uniformity and stability were considered. The diagram only reflects contrasted areas of sherry wine aging based on the actual values of wineries of great prestige, not implying that outside these areas the aging cannot be carried out.

For the calculation of the recommended monthly limits, it was decided to eliminate the extreme values, using data between the 5th and the 95th percentile. Table 2 summarizes the limits for each period.

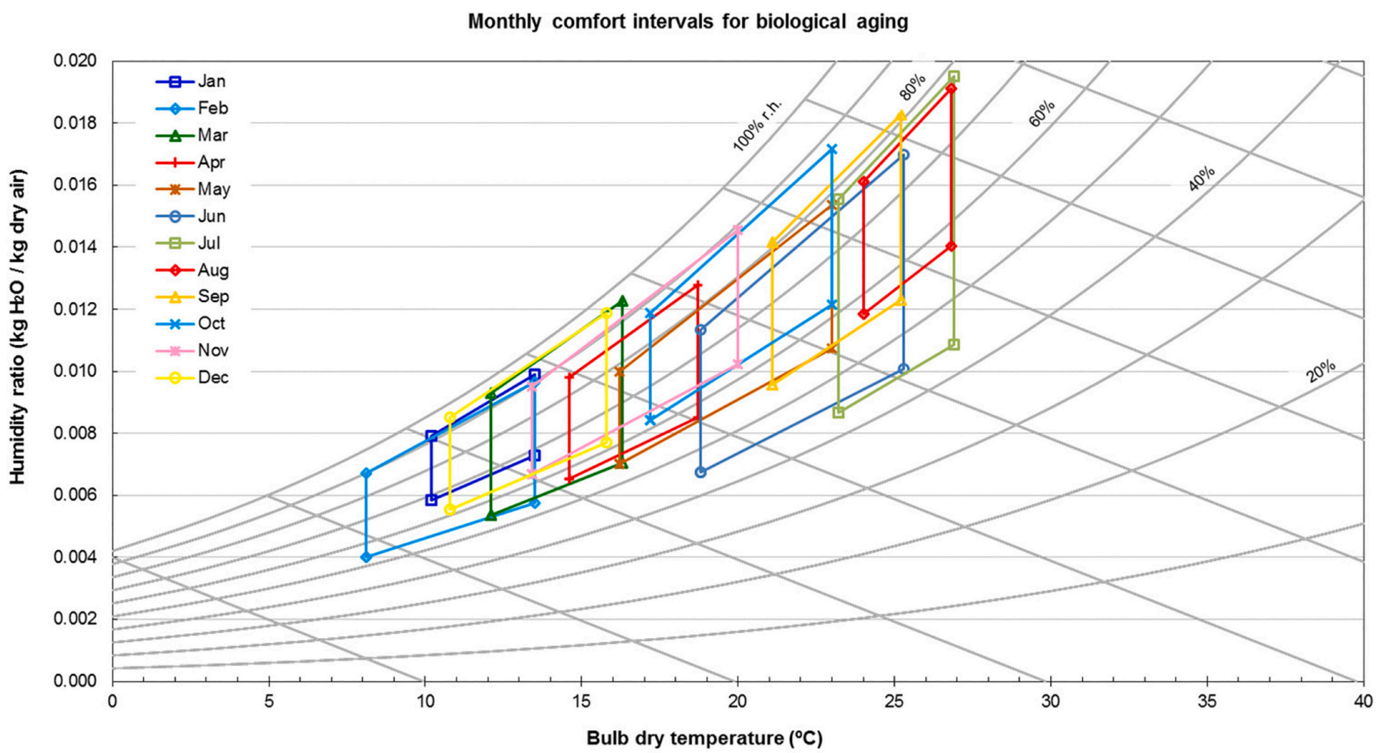


**Fig. 13.** Contrasted monthly comfort zones that ensure proper aging of sherry wine.

**Table 2**
Contrasted monthly comfort intervals that ensure proper aging of sherry wine.

| — | Temperature (°C) | | Relative humidity (%r.h.) | |
|---|---|---|---|---|
| | Lower limit | Upper limit | Lower limit | Upper limit |
| Jan | 10.2 | 13.5 | 68 | 92 |
| Feb | 8.1 | 13.5 | 54 | 90 |
| Mar | 12.1 | 16.3 | 55 | 95 |
| Apr | 14.6 | 18.7 | 57 | 85 |
| May | 16.2 | 23.0 | 55 | 78 |
| Jun | 18.8 | 25.3 | 45 | 75 |
| Jul | 23.2 | 26.9 | 44 | 78 |
| Aug | 24.0 | 26.8 | 57 | 77 |
| Sep | 21.1 | 25.2 | 55 | 81 |
| Oct | 17.2 | 23.0 | 62 | 87 |
| Nov | 13.4 | 20.0 | 63 | 89 |
| Dec | 10.8 | 15.8 | 62 | 95 |

## 5. Conclusions

The present study has carried out the first exhaustive characterization of the hygrothermal environment in which the biological aging of sherry wine takes place. The data and results obtained should serve as a reference for oenological treatises.

The results highlighted the peculiarities of biological aging and the differences with red wine aging: significant temperature variations throughout the year (limit values of 5 °C and 31 °C); relative humidity usually maintained between 60% and 90%; lower stability due to high ventilation (annual average of 2.0 ± 0.8 °C and 11 ± 7% r.h. per day); high vertical stratification in spring and summer (0.5 °C/m and 3% r.h./m) that justify the usefulness of the traditional system of "criaderas" and "soleras"; etc.

The paper also highlighted the differences between the comfort intervals recommended in the bibliography (annual ranges, generally only temperature) and the actual measured environment. For that reason, hygrothermal monthly comfort intervals have been provided that ensure a good development of the flor yeast film. The psychrometric diagram summarizing the comfort intervals should be a useful tool for the wine industry, in order to control and improve the biological aging of sherry wines.

## CRediT authorship contribution statement

**Ignacio Cañas :** Project administration, Funding acquisition, Conceptualization. **Eduardo G. Navia-Osorio :** Investigation, Formal analysis, Visualization. **César Porras-Amores :** Investigation, Validation, Writing – review & editing. **Fernando R. Mazarrón :** Supervision, Methodology, Formal analysis, Writing – original draft.

## 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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