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Comparison of *Eucalyptus* spp. wood quality in solar and conventional drying

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Abstract. The aim of the study was to compare the quality of sawn *Eucalyptus* spp. wood under solar and conventional drying, focusing on parameters such as drying rate, moisture gradient, drying stresses, and wood defects. For this purpose, a comparison was made between samples dried in a solar kiln and a conventional drying chamber. As a preliminary analysis, the specific gravity and initial moisture content of the wood were evaluated, and the quality and drying parameters of the wood were assessed both before and after the drying process. It was observed that the drying rate in the conventional chamber was twice as high above the fiber saturation point and four times higher in the diffusion phase compared to solar drying. Regarding the moisture gradient and defect index, there was no statistical difference between the two processes. However, the percentage of pieces with defects was significantly higher in conventional drying, as well as demonstrating higher drying stresses, which may hinder mechanical processing after water removal. Therefore, it can be concluded that solar drying presents a quality similar to conventional drying and can be a good alternative for drying processes.

Keywords: Solar Kiln, Drying Defect Index. Drying Parameters. Wood. Dry.

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Comparação da qualidade da madeira de *Eucalyptus* spp. entre a secagem solar e convencional

Resumo. O objetivo do estudo foi comparar a qualidade da madeira serrada de *Eucalyptus* spp. sob secagem solar e convencional, focando em parâmetros como taxa de secagem, gradiente de umidade, tensões de secagem e defeitos da madeira. Para isto, foi realizado a comparação entre amostras secas em uma estufa solar e uma câmara de secagem convencional. Como análise preliminar da madeira, foi avaliada a massa específica aparente e o teor de umidade inicial, sendo antes e após o processo de secagem avaliados os parâmetros de qualidade e de secagem da madeira. Observou-se que a taxa de secagem na câmara convencional foi duas vezes maior acima do ponto de saturação das fibras e quatro vezes maior na fase de difusão quando comparada a secagem solar. Com relação ao gradiente de umidade e índice de defeitos, não houve diferença estatística entre os dois processos. Contudo, a porcentagem de peças que apresentaram defeitos foi significativamente maior na secagem convencional, bem como, demonstraram maiores tensões de secagem, o que pode prejudicar o beneficiamento mecânico após a

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remoção de água. Desta forma, pode-se concluir que a secagem solar apresenta uma qualidade similar a secagem convencional e pode ser uma boa alternativa para processos de secagem.

Palavras-chave: Secador Solar. Índice de Defeitos na Secagem. Parâmetros de Secagem. Madeira. Seco.

Comparación de la calidad de la madera de *Eucalyptus* spp. entre el secado solar y convencional

Resumen. El objetivo del estudio fue comparar la calidad de la madera aserrada de *Eucalyptus* spp. bajo secado solar y convencional, centrándose en parámetros como la tasa de secado, el gradiente de humedad, las tensiones de secado y los defectos de la madera. Para ello, se compararon muestras secadas en un secador solar y en una cámara de secado convencional. Como análisis preliminar de la madera, se evaluaron la densidad aparente y el contenido inicial de humedad, y antes y después del proceso de secado se evaluaron los parámetros de calidad y de secado de la madera. Se observó que la tasa de secado en la cámara convencional fue el doble de alta por encima del punto de saturación de las fibras y cuatro veces mayor en la fase de difusión en comparación con el secado solar. En relación con el gradiente de humedad y el índice de defectos, no hubo diferencia estadística entre los dos procesos. Sin embargo, el porcentaje de piezas con defectos fue significativamente mayor en el secado convencional, así como las tensiones de secado, lo que puede perjudicar el procesamiento mecánico posterior a la eliminación de agua. De esta forma, se puede concluir que el secado solar presenta una calidad similar al secado convencional y puede ser una buena alternativa para los procesos de secado.

Palabras clave: Secador Solar. Índice de Defectos en el Secado. Parámetros de Secado. Madera. Seco.

INTRODUCTION

Wood drying is a crucial stage in the production chain of the wood industry, as it directly influences the mechanical, physical, and aesthetic properties of the final product. Proper removal of moisture from wood can prevent defects such as cracks, warping, and collapse, ensuring the quality and durability of the final products. Additionally, dried wood is more resistant to fungal and insect attacks, which increases its lifespan and commercial value.

Among the common methods of wood drying, conventional drying and air drying are the most widely used worldwide; however, the former requires a high initial and maintenance investment, as well as high energy costs, making its use on smaller scales difficult, while the latter requires a long drying period, the final moisture content rarely reaches the equilibrium moisture content of the environment, and there is also no control over environmental variables.

Solar dryers can be an intermediate alternative to these two processes, without a high implementation cost, and can provide good quality final drying in a time frame reduced compared to air drying. They can also be applied in small businesses and rural areas. Solar drying is considered sustainable and clean, recommended for species known as refractory, which have low permeability and ease of developing defects during drying.

Drying parameters, such as moisture gradient, internal tensions, and drying rate, are fundamental aspects that affect the final quality of dried wood. Drying defects such as warping, twisting, cracks, and collapse can compromise the quality and usability of the wood. These problems occur when the drying process is not properly controlled, causing internal tensions and undesirable deformations. Therefore, it is essential to establish an effective drying process that minimizes these defects, ensuring the production of high-quality wood.

Within this perspective, the study's objective is to compare the quality of sawn *Eucalyptus* spp. wood in solar and conventional drying, particularly focusing on the drying rate, moisture gradient, drying tensions, and wood defects.

THEORETICAL FRAMEWORK

Wood Drying

Proper drying is the most critical intermediate phase in the transformation of wood into products, as it adds significant value to the final product (Jankowsky, 1995; Santos, 2002). According to Martins (1988), it is the process of reducing moisture content to achieve a specific level with minimal defects while remaining economically feasible for the intended use.

As wood loses moisture, its physical and mechanical properties change (Madsen, 1992). Dried wood exhibits increased mechanical properties, thermal, electrical, and acoustic insulation, better surface workability, and improved paint and varnish application. It also favors bonding and the use of nails and screws. Dried wood offers greater dimensional stability, higher resistance to decay caused by fungi, and protection against some wood-boring insects (Kollman; Côté Junior, 1968). This reduction in defects lowers process costs (Stangerlin, 2009).

Due to certain physiological and anatomical characteristics, *Eucalyptus* wood requires a more meticulous drying process. It tends to experience high levels of stress, which can lead to a large percentage of defects and low yield (Rocha, 2000). Vermaas (1995) notes that wood of this genus typically dries slowly and can exhibit intrinsic defects such as collapse, moisture gradients, cracked surfaces, and significant growth stresses, resulting in substantial wood loss. A major issue with *Eucalyptus* wood is its high growth stress levels (Waugh, 1998).

The types of water in wood can be classified into two categories: capillary water (free water), which occupies cell cavities and vessel lumens, and impregnation water (hygroscopic water), found in polymolecular layers and submicroscopic spaces of the cell wall, bound by electrical forces known as hydrogen bonds (Brown *et al.*, 1952; Kollmann, 1959; Kollmann; Côté Junior, 1968; Bramhall; Wellwood, 1976; Cech; Pfaff, 1977; Santini, 1981; Simpson, 1984; Severo, 1989).

The evaporation of free water (absorbed water) and impregnation water (adsorbed water) is defined as desorption. The mechanism of moisture movement in the cellular structure during drying is complex and requires a detailed study of the physics of water and wood (Cech; Pfaff, 1977). There are two types of water movement in wood: capillarity, which occurs above the fiber saturation point (FSP), and diffusion, which occurs below this point (Santini, 1981).

Wood Drying Methods

The known drying methods are: air drying, low-temperature drying, including pre-dryers and dehumidifiers, conventional drying, high-temperature drying, vacuum drying, high-frequency drying, press drying, and chemical drying. However, the most commonly used methods are air drying and conventional drying (Oliveira, Skaar; Wengert, 1982).

Solar kiln drying has been recommended by several authors (Santini, 1981; Haque, 2002; Bauer, 2003; Stangerlin, 2009; Cremonez, 2016; Cremonez, 2020; Cremonez, 2023) as an alternative to methods with high investment costs, maintenance, and energy consumption.

Solar kilns rely on the selective transmission properties of transparent materials, which allow the passage of short-wave solar radiation (the main component of solar energy) through their surface while blocking long-wave radiation of lower temperatures reflected by the usual collectors or the dry material inside (Hanson, 1963).

Despite the varied climatic characteristics across Brazil, the annual average global irradiation remains relatively uniform, with relatively high annual averages nationwide. The maximum global irradiation value of 6.5 kWh/m² occurs in the northern part of Bahia, near the border with Piauí (Bandeira, 2012).

Germany is one of the countries that effectively applies photovoltaic technology to generate electricity. Therefore, it is possible to compare the energy potential between this country and Brazil. In this comparison, the area with the lowest solar potential in Brazil is 4.5 kWh/m², while Germany's maximum is only 1.3 kWh/m². This indicates that all regions in Brazil have sufficient solar energy potential for solar power generation (Freire, 2013).

Conventional or artificial drying is the most widely used drying process worldwide, operating at temperatures ranging from 50°C to 100°C. It is conducted in environments where temperature, relative humidity, and air speed can be controlled. This type of equipment includes an air humidification system, a set of dampers that allows air exchange between the dryer interior and the external environment, and a ventilation system that promotes air circulation between the drying wood boards (Jankowsky, 1995).

Drying Rate

The drying rate is the amount of water evaporated within a certain time period and can also be related to the evaporation area of the wood piece. It allows for estimating the drying time of a given species from green wood condition to a target moisture content at a specified temperature and equilibrium humidity (Muniz, 1993; Severo, 2000; Batista; Klitzke, 2010).

The drying rate depends on both environmental factors and intrinsic wood properties. According to studies conducted by Santini (1980), increasing the temperature significantly reduces the drying time, equilibrium moisture content, and energy consumption.

Drying Defects

A drying defect is any change in the structure of wood that complicates its processing at a later stage (Brandão, 1989). Drying defects not only decrease the market value of the product but also discourage the use of refractory species (Martins, 1988).

In general, such species must be dried slowly, avoiding severe environmental conditions during the drying process, as they can present various defects such as cracks, warping, and collapse, among others, which often complicate their use (Oliveira, 1997).

Warping refers to any distortion or deformation of a piece of wood relative to the original planes of its surfaces, causing curvature along its axes (Galvão; Jankowsky, 1985). Warping can result from differences in contraction (radial, tangential, and longitudinal) within the same piece or from growth stresses. These can be exacerbated by the presence of irregular or twisted grain and abnormalities in the wood, such as juvenile wood and reaction wood (Simpson, 1991). Pratt (1974) classifies warping into five types: bowing, crooking, warping, complex bending, and twisting. Warping can be reduced or avoided through proper stacking, mechanical restraint, and steaming during drying (Vermaas, 1998).

Cracks appear as a result of growth stresses in the wood and differences in moisture between contiguous regions of a piece during the drying process (Galvão; Jankowsky, 1985). In other words, according to Santini (1992), cracks are separations of the wood's constituent elements along the longitudinal grain.

During the drying process, three types of cracks may occur: surface, end, and internal cracks. Surface and end cracks occur in the early stages due to moisture gradients (Denig *et al.*, 2000), while internal cracks manifest at the end of the process, often as an extension of surface cracks (Santos, 2002).

Collapse is one of the main issues affecting the timber industry, especially with *Eucalyptus*. Alongside high growth stresses, which exacerbate splitting, careful drying of this species is necessary. Collapse occurs above the fiber saturation point (FSP), typically at the beginning of drying (Keey, Langrish; Walker, 2000). It is a distortion, flattening, or crushing of the wood, and in extreme cases, it presents as wrinkling (Simpson, 1991; Melo, 1999). It is characterized by a noticeable alteration of the wood cells, which instead of having a polygonal shape, appear crushed (Melo, 1999).

As Simpson (1991) explains, collapse can be caused by compressive drying stresses within the interior parts of the boards that exceed the wood's compressive strength or capillary forces in the cell cavities that are completely filled with water. It occurs when capillary stress exceeds the resistance to compression perpendicular to the grain of the cell wall. Cavalcante (1991) and Severo (2000) assert that steaming treatment allows recovery of collapsed wood.

METHODOLOGY

Materials

The material used in this study comprised commercial boards of *Eucalyptus* spp., a mix of *Eucalyptus grandis* and *Eucalyptus* saligna, provided by Mademape Madeiras in Campina Grande do Sul, Paraná, from trees around 15 years old.

The logs were sourced from the state of Paraná, from the company Klabin, and processed at Mademape using an initial vertical bandsaw and then a resaw, resulting in boards of 2.5x10x250 cm (thickness x width x length), totaling approximately 1 m^3 of wood for drying.

A total of 93 boards were selected for their phytosanitary condition, with 63 used for solar drying and 30 (yielding 60 samples) for conventional drying. The material was sent to the wood machining laboratory at the Federal University of Paraná for sample preparation.

Construction of Solar Kiln

For solar drying, a greenhouse-style solar kiln was constructed (Figure 1) in the yard adjacent to the Centro de Ciências Florestais da Madeira (CIFLOMA) at the Universidade Federal do Paraná, Curitiba, Paraná (Cremonez, 2016; Cremonez *et al.*, 2020; 2023).

Figure 1 - Solar kiln.

Source: the authors (2024).

Drying

The 63 boards selected for solar drying were resized to 2.5 x 10 x 205 cm, with a sample measuring 2.5 x 10 x 2.5 cm removed from each end of the boards for initial moisture content measurement, resulting in a solar drying sample size of 2.5 x 10 x 200 cm.

The complete cycle stacking consisted of seven rows and nine columns of boards, centered perpendicularly to the kiln and allowing air passage perpendicular to the fibers, as shown in Figure 2. Three concrete blocks were used as mechanical restraint on the pieces, weighing 50 kg/m².

Figure 2 - Stacking arrangement in solar drying.

Source: The authors (2024).

The samples for conventional drying were resized to 2.5 x 10 x 70 cm from the original boards, with a sample of 2.5 x 10 x 2.5 cm taken from each end of the boards for initial moisture content measurement, resulting in samples measuring 2.5 x 10 x 65 cm, totaling 60 boards for drying.

A pilot drying chamber was used for conventional drying, with nominal internal dimensions of 0.80 x 0.80 x 4.00 m (width x height x length), totaling an approximate capacity of 1 m³ of sawn timber.

Heating was achieved using an electric system, consisting of three shielded resistors (heat exchangers) of 9 kW (46000 BTU) each and equipped with forced air circulation via an axial fan with 8 blades, a 60 cm diameter, producing 3600 m³/h, powered by a 4-pole, 1.5 HP motor running at 1750 rpm. The stacking arrangement for conventional drying and sensor pins as shown in Figure 3.

Figure 3 – Stacking arrangement for conventional drying and sensor pins.

Source: The authors (2024).

The moisture measurement of the woods was conducted using eight pairs of sensor pins (eight long and eight short), which operate based on resistive principles. The pins were inserted into the wood at 1/2 and 1/4 of the board thickness, perpendicularly to the grain and spaced 25 mm apart, aiming to measure the moisture gradient during the drying process. Each board with sensor pins had one pair inserted at 1/2 of the thickness (long pin) and another pair of sensor pins inserted at 1/4 (short pin) of the board thickness.

Drying Program

The drying program used is shown in Table 1, with an intermediate steaming phase using saturated steam (100°C and 100% relative humidity) in phase 7 for collapse recovery (Bluhm; Kauman, 1965; Severo, 2000).

Table 1 - Drying program used for *Eucalyptus* spp. wood with a thickness of 2.5 cm.

Phase	Moisture content (%)	DBT (ºC)	WBT (ºC)	RH (%)	EMC (%)	DP
HTG	5 hours	40	40	100	-	-
1	42	40	38	88	18	2.4
2	37	42	39	83	16	2.2
3	32	45	42	84	16	2.2
4	28	48	44	79	14	2.1

5	24	50	44	70	12	2.1
6	21	53	46	66	10	2.1
7	17	100	100	100	19	-
8	14	58	46	51	8	2.1
9	12	60	46	44	6	2.1
10	10	63	42	30	4	2.1
CND	8 hours	69	51	64	10	-

Note: DBT: Dry bulb thermometer; WBT: Wet bulb thermometer; RH: Relative humidity of the air; EMC: Equilibrium moisture content of wood; DP: Drying potential; HTG: Heating; CND: Conditioning.
Source: Batista (2009) modified by the authors (2024).

A circulation speed of 2.5 m/s was used for drying in the conventional chamber, as described in various wood drying manuals such as Hildebrand (1970), Siau (1984), Simpson (1991). To achieve this, through empirical testing and with the aid of an anemometer, 85% of the fan's rotation was adopted. The parameters of the dried wood and drying process are described in table 2.

Table 2 - Specific gravity, initial moisture content, final moisture content, and drying time.

Method	SG12% (g/cm³)	IMC (%)	FMC (%)	Time (hours)
Solar drying	0.60 (0.11)	80.97 (27.04)	11.88 (1.28)	744
Conventional drying	0.60 (0.11)	66.43 (17.41)	9.92 (2.43)	179

Note: IMC: Initial moisture content; FMC: Final moisture content; SG12%: Specific gravity at 12% moisture content. Values in parentheses correspond to standard deviation and coefficient of variation (%).
Source: The authors (2024).

Drying Rate

The drying rate was determined for both drying methods by adopting Severo's (2000) methodology using Equation 1. While time in days is more appropriate for solar drying and time in hours for conventional drying, both times were calculated for both methods for comparison purposes. Thirty random repetitions were evaluated per drying cycle.

$$DR = \frac{TUi - TUf}{t} \qquad (1)$$

Note:

DR – Drying rate (%MC/hour);
IMC – Initial moisture content;
FMC – Final moisture content;

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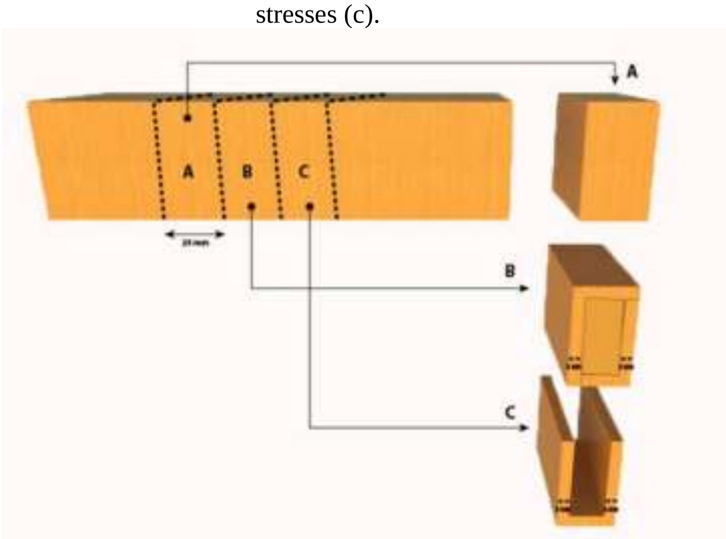
T – Time (hours).

The drying rate was quantified for the loss of capillary water (above the FSP down to 32%), hygroscopic water (32% down to 10%), and total water (above the FSP down to 10%).

Final Moisture Content, Moisture Gradient, and Drying Stresses

To evaluate final moisture content, moisture gradient, and drying stresses, the methodology suggested by Simpson (1991) was used, as illustrated in Figure 4 and 5. For each variable (final moisture content, moisture gradient, and drying stresses), 30 samples were used, totaling 90 repetitions per drying method.

Figure 4 - Sample preparation method for drying evaluation; Final moisture content (a), Moisture gradient (b), And drying stresses (c).



Source: modified from Jankowsky (1985).

Figure 5 - Procedure adopted for classification of drying stresses

Source: modified from Jankowsky (1985).

Wood Shrinkage

The evaluation of shrinkage in width and thickness was carried out with measurements of the dimensions of the pieces before and after drying according to Equation 2, without considering longitudinal shrinkage. A total of 30 repetitions were performed per drying cycle.

$$\text{Wood shrinkage} = \frac{\text{Du}-\text{Ds}}{Du}.100 \qquad (2)$$

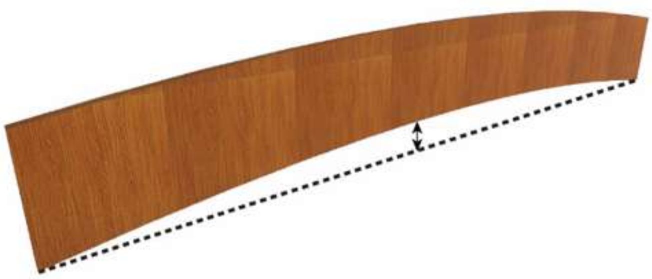
Note:

Du = dimension or wet volume (mm or mm³);
Ds = dimension or dry volume (mm or mm³).

Incidence of Defects

The bows of warps (bow, crook, and cup) and the sum of cracks along the board and end cracks were measured according to the IBDF Standard for Hardwood Classification - Classification by the Worst Face (Brasil, 1983) of 30 repetitions in each drying cycle. The measurement of defects before drying was carried out to verify whether they increased after the pieces underwent the drying process. After the drying cycles, warps and cracks were measured again. Measurements of bow were conducted as shown in Figure 6, using Equation 3.

Figure 6 - Demonstration of bow measurement



Source: The authors (2024)

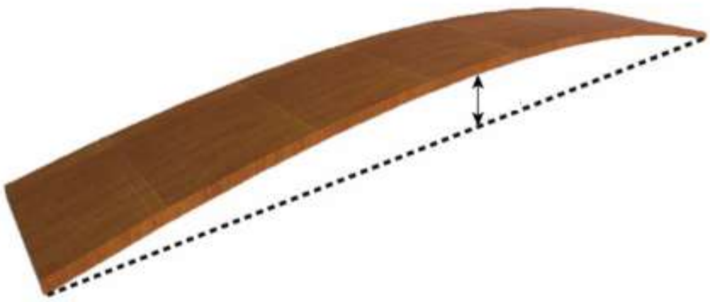
Crook was measured as shown in Figure 7 and using Equation 3.

$$\text{Crook} = \frac{\text{CB}}{l} \qquad (3)$$

Note:

CR = crook (mm/m);
f = crook bow (mm);
c = length of the piece (m).

Figure 7 - Demonstration of crook measurement



Source: The authors (2024)

Warping was measured as shown in Figure 8, and its values were presented as its maximum bow in millimeters. For bow and crook, boards with values above five mm/m were classified as defective, and for warping, values above four mm were considered defective.

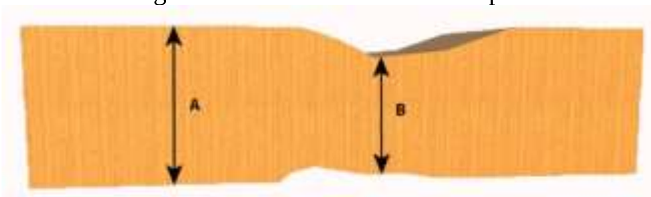
Figure 8 - Demonstration of warping measurement

Source: The authors (2024)

Collapse (Figure 9) was evaluated for presence and absence, and if present, quantified by the difference between thicknesses A and B (Equation 4).

$$\text{Collapse} = \text{A} - \text{B} \qquad (4)$$

Figure 9 - Demonstration of collapse



Source: The authors (2024)

In evaluating the defects, cracks were not considered because they were removed when preparing the boards for drying, making this analysis biased.

Analysis and Evaluation of Results

For the statistical analysis and evaluation of the results, an analysis of variance (ANOVA) was performed to compare the results of solar drying and conventional drying. In situations where the null hypothesis (H0) was rejected, the results were considered statistically different. When necessary, the Tukey test was applied for differentiation of the means.

RESULT AND DISCUSSION

Drying Rate

Drying rates are presented in Table 3 in both %/h and %/day for better comparison. It is observed that conventional drying is twice as fast above the fiber saturation point (FSP) and approximately four times as fast below the FSP compared to solar drying, demonstrating the higher drying speed in the more automated method.

Table 3 – Drying rate

Method	DR (%/h)			DR (%/day)		
	IMC-32%	IMC-10%	32%-10%	IMC-32%	IMC-10%	32%-10%
Solar drying	0,17	0,08	0,04	4,16	2,01	0,98
Conventional drying	0,34	0,29	0,25	8,02	7,15	6,11

Source: The authors (2024)
Note: DR = drying rate; IMC = initial moisture contente.

The difference in the removal of capillary and hygroscopic water is notable, being approximately four times greater in the conventional method and 30% higher in the solar drying method. This occurs because, at the beginning of both methods, the demanded temperature is similar (40ºC), but as the moisture content of the wood decreases, temperatures in conventional drying increase according to the drying schedule, a variable that solar drying cannot achieve and is not controllable. Thus, conventional drying has a greater compensation for the drying rate in the removal of hygroscopic water. Another factor that can be noted is the decrease in temperature and increase in relative humidity that occurs during the night inside the solar kiln, reducing the drying potential.

For solar drying, Souza (2015) achieved an average drying rate of 2.33%/day or 0.10%/hour for the species *Eucalyptus* dunnii, slightly higher values than those found in this research. Stangerlin (2009) obtained 3.39%/day above the FSP, 1.69%/day below the FSP, and an average of 2.7%/day for *Eucalyptus* saligna using the same drying method, values considered high for solar drying, as in this study.

Santini (1981) achieved a drying rate of 4%/day on average, a value that corroborates with this research. On the other hand, Ono and Ventorino (2006) and Ono (2006) used *Eucalyptus* camaldulensis with 4 cm thick boards, achieving 0.63%/day and 0.53%/day in summer and winter respectively, which is significantly lower than the values found in this study. Table 4 presents some studies with hardwoods worldwide for comparative purposes.

Wood Shrinkage

The volumetric shrinkage of the boards in solar drying and conventional drying is shown in Table 4.

Table 4 – Wood shrinkage

Solar drying			
	SW (%)	ST (%)	VS (%)
Average	6,66 A	4,62 B	11,35 C
SD	1,84	2,02	1,93
Conventional drying			
	SW (%)	ST (%)	VS (%)
Average	6,95 A	4,86 B	11,88 C
SD	2,24	2,03	2,13

Source: The authors (2024)

Note: SW: contraction in width; SE: contraction in thickness; SD: standard deviation; VS= volumetric shrinkage. Different capital letters in the same line indicate statistical differences between the means.

Rocha (2000) found an average contraction of 3.25% in width and 4.17% in thickness for *Eucalyptus grandis*, which are lower than the results of this study; however, the author's final moisture content was 15%, 5% higher than in this study, leading to less shrinkage. Stangerlin (2009) observed a contraction of 3.64% in width and 4.5% in thickness for *Eucalyptus* saligna, with the width showing a value significantly lower than in this study. Ono and Ventorino (2006) found a contraction of 7.2% in width and 8.3% in thickness for a thicker 4 cm *Eucalyptus* camaldulensis wood, which are higher than those found in this research, possibly due to a greater amount of woody material. Susin (2012) observed tangential contraction values of 12.83% and 9.65% for *Eucalyptus* robusta and *Eucalyptus grandis*, respectively, and thickness contractions of 7.92% and 5.54%, with anisotropy factors of 1.6 and 1.6, respectively. Coefficients of anisotropy similar to those achieved in this study.

According to Nock, Richter, and Burger (1975), anisotropy values below 1.5 are excellent for wood quality. Contraction occurs due to the removal of water from the wood cell wall; differences in anisotropic behavior can lead to defects, which are accompanied by moisture gradients and drying stresses (SANTINI, 1992). Contraction also predicts the final volume of dry wood, which is important in the logistics and industrialization of the material.

Moisture Gradient and Drying Stresses

The average values of moisture gradient and drying stresses are shown in Table 5. There is no statistical difference in moisture gradient between the drying methods studied, with the values considered low.

Table 5 – Moisture gradient and drying stresses

Method	Gradient (%)	Tensions (%)		
		Absent	Mild	Severe
Solar drying	0.58 A (0.41)	20	67	13
Conventional drying	0.67 A (0.35)	0	53	47

Source: The authors (2024)

Note: In parentheses are the values for standard deviation; Different capital letters represent statistical differences (Tukey, $p \leq 0.05$).

For moisture gradient, Batista (2009) reported values of 0.50 to 0.62 for *Eucalyptus* saligna and 0.49 to 0.58 for *Eucalyptus grandis*, while Mellado (1993) found a value of 0.6. Both authors obtained results similar to those in this study; however, Susin (2012), working with *Eucalyptus* saligna and *Eucalyptus* robusta wood, reported higher moisture gradients of 1.26 and 4.16, likely due to the fact that they had a higher specific gravity. Moisture gradient is of fundamental importance for the removal of water from wood, however, finishing stages such as equalization and conditioning can minimize this effect. Despite the lack of statistical difference between the gradients of the solar and conventional kiln, the former shows 13% less moisture difference at the ends.

This can be explained by the nighttime periods of solar drying, during which there is a drop in temperature and an increase in relative humidity, causing uniform moisture distribution in the load. Drying stresses were more prevalent in conventional drying, where 100% of the pieces were under stress.

However, Santos (2002) reported slightly lower values for conventional drying, with 85% of the pieces under stress. Batista (2009) found that *Eucalyptus* saligna had 88.89% mild stress and 3.70% severe stress, while *Eucalyptus* robusta had 81.46% mild stress and 0% severe stress. The fact that conventional drying showed all the pieces under stress in this study may be related to the short drying time the wood was subjected to.

Drying Defects

The values for bowing in the drying methods used are presented in Table 6. It is observed that there was an increase in all cases in the percentage of this defect, with the difference between solar drying and conventional drying being 6 percentage points. It is worth noting that pieces considered defective have a bowing index and deflection greater than 5 mm/m.

Table 6 – Bowing of wood in solar drying and conventional drying of *Eucalyptus* spp. Wood.

Method	Before		After		Difference
	BI (mm/m)	(%)	BI (mm/m)	(%)	BI (mm/m)
Solar drying	2,32	0	3,01	9	0,69 A
Conventional drying	0,60	0	1,75	15	1,15 A

Source: The authors (2024)

Note – BI: Bowing index; Different capital letters represent statistical difference (Tukey, $p \leq 0.05$).

Conventional drying resulted in a higher percentage of pieces considered defective and greater differences in the bowing index. However, there was no statistical difference between the methods. This defect is caused by the difference in longitudinal shrinkage between the sides of the boards, which may be due to the variation in wood types (juvenile and mature) within the same piece, as they exhibit different behaviors regarding shrinkage during drying (SUSIN, 2012). Growth stresses in the pieces can also be a primary cause of bowing (MATOS *et al.*, 2003).

The results for the difference between the indices are greater than those obtained by Stangerlin (2009) and Susin (2012). On the other hand, Rocha and Tomaselli (2002), Rocha and Trugilho (2006), and Souza *et al.* (2015) found no differences in bowing after drying. Considering that the indices after drying are higher than those before drying, it can be said that the water removal process had a greater influence than the cutting.

The values for crook in the drying methods used are shown in Table 7. It is noted that the percentage of defective pieces increased significantly after drying, but the methods did not show statistically significant differences for this defect.

Table 7 – Crook in wood during solar and conventional drying of *Eucalyptus* spp.

Method	Before		After		Difference
	BI (mm/m)	(%)	BI (mm/m)	(%)	BI (mm/m)
Solar drying	4,91	15	5,3	54	0,39 A
Conventional drying	3,45	12	4,38	27	0,93 A

Source: The authors (2024).
Note: IEc: Crook index; different capital letters represent statistical difference (Tukey, $p \leq 0.05$).

Solar drying had the highest percentage of pieces considered defective, with an increase of 39 percentage points after drying; however, this can be explained by the high crook index presented even before drying, so the absolute difference before and after drying is not different from those obtained in other methods. In conventional and solar drying, the boards already exhibited a high crook index, compromising the final quality of the pieces. But the differences between the indices after drying were not elevated, as in the results found by Rosso (2006), Stangerlin (2009), and Susin (2012). Even though there was no statistical difference, the total difference in the crook index in conventional drying was higher due to a greater speed of drying.

Santos (2002) observed an increase of approximately 34 percentage points in crook during conventional drying, which is much higher than that found in this study, while before a pre-drying to conventional drying had an increase of 5.8 percentage points. Rocha (2000), unlike this research, observed a reduction in crook after drying.

Crook occurs due to shrinkage in the wood as a result of faster drying on one face compared to the other, making the anisotropic wood more prone to crook (BRANDÃO, 1989). This defect is not one of the most severe in drying as it can be minimized during stacking (SIMPSON, 1991; DENIG *et al.*, 2000). Growth tensions also cause warping (MATOS *et al.*, 2003).

The values for Warping obtained during drying are presented in Table 8. It is notable that only in conventional drying were there pieces considered defective after drying. Values above 4 mm/m were classified as defective.

Table 8 – Warping in solar and convetional drying of *Eucalyptus* spp. Wood.

Method	Before		After		Difference
	BI (mm/m)	(%)	BI (mm/m)	(%)	BI (mm/m)
Solar drying	0	0	1,15	0	1,15 A
Conventional drying	0	0	1,14	3	1,14 A

Source: The authors (2024).
Note: IEn: Warping index. Different capital letters represent statistical difference (Tukey, $p \leq 0.05$).

This result can be explained by the relatively low width of the boards (10 cm) and the relatively low coefficient of anisotropy. Galvão and Jankowsky (1985) and Simpson (1991) assert that cup may result from the difference between transverse shrinkages of the wood, as well as from exposing only one face of the board to drying.

The percentage of pieces considered defective is much lower than that reported by several authors: Mellado (1993), Severo (2000), Batista (2009), and Batista *et al.* (2012). The difference aligns with Susin (2012).

Regarding collapse, there was only one piece that exhibited this defect, and it was after conventional drying, demonstrating successful recovery from collapse, consistent with Mellado (1993), Severo (2000), and Stangerlin (2009). Ponce (1995) states that medium-density *Eucalyptus*es are more prone to collapse, suggesting that the results of this study are satisfactory. Other authors who did not use vapor recovery, such as Santos (2002), Batista (2009), Batista *et al.* (2012), and Susin (2012), experienced incidences of this defect.

Collapse is a form of abnormal and irregular shrinkage that occurs during capillary water removal, causing internal deformation of the cells (KOLLMANN and CÔTÈ, 1968; SANTINI, 1992). According to Jankowsky (1995), the main cause of collapse is capillary tension, which occurs in the initial stages of drying, thus demonstrating that the program used in this study was effective. This defect is one of the most severe and complicates wood use, rendering it unusable for many purposes.

CONCLUSION

The results showed that there was no significant difference in the final quality of the wood between the methods, but conventional drying presented a higher incidence of stresses and warping in the wood. The drying rate in the solar kiln was half that of conventional drying above 32% wood moisture content and five times lower below 32%. The higher incidence of defects and stresses in conventional drying can hinder the mechanical processing of the wood. Despite the slower drying rate, solar drying proved to be an efficient and viable alternative, offering benefits such as lower costs and environmental sustainability. Thus, it can be an interesting option for smaller companies and rural areas.

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