



Natural drying performance of *Eucalyptus camaldulensis* timber in southeastern Turkey: Case study of Kahramanmaraş

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ESER BİLGİSİ / ARTICLE INFO

Araştırma Makalesi / Research Article

Geliş 18 Kasım 2025 / Received 18 November 2025

Düzeltilmelerin gelişi 18 Ocak 2026 / Received in revised form 18 January 2026

Kabul 19 Ocak 2026 / Accepted 19 January 2026

Yayınlanma 19 Nisan 2026 / Published online 19 April 2026

ABSTRACT: The drying process plays a crucial role in determining the quality and end-use performance of *Eucalyptus camaldulensis* timber, a species characterized by high initial moisture content and susceptibility to drying defects. This study investigates the effects of natural drying conditions on the quality of eucalyptus timber under the Mediterranean climate of Kahramanmaraş, Turkey. Timber specimens with thicknesses of 3 cm, 6 cm, and 12 cm were subjected to open-air and indoor drying over a one-year period. The results revealed that thinner timbers reached the target moisture content within 1.5–3.5 months, whereas thicker timbers continued to lose moisture throughout the drying cycle. Internal and heart cracking, as well as deformation behavior, were strongly influenced by timber thickness and drying environment. In addition, most specimens were classified as high quality according to EDG standards based on drying gradients, although achieving uniform quality was more challenging in thicker sections. Overall, the study demonstrates that natural drying is a cost-effective and environmentally sustainable method for timber processing, while emphasizing the need to carefully manage structural and climatic limitations. The findings offer valuable insights for optimizing industrial drying practices and improving the utilization of eucalyptus timber in similar environmental contexts.

Keywords: Eucalyptus timber, natural drying, timber quality, drying defects, Mediterranean climate

Kahramanmaraş iklim koşullarında *Eucalyptus camaldulensis* kerestesinin doğal kurutma davranışı

ÖZET: *Eucalyptus camaldulensis* kerestesinin yüksek başlangıç rutubeti ve kurutma kusurlarına yatkınlığı, kurutma sürecini ürün kalitesi ve nihai kullanım performansı açısından kritik hâle getirmektedir. Bu çalışma, Akdeniz iklim özelliklerine sahip Kahramanmaraş ilinde doğal kurutma koşullarının okaliptüs kerestesinin kurutma davranışı ve kalite parametreleri üzerindeki etkilerini incelemektedir. Kalınlıkları 3 cm, 6 cm ve 12 cm olan kereste örnekleri açık ve kapalı alanlarda bir yıl süreyle doğal olarak kurutulmuştur. Bulgular, ince ve orta kalınlıktaki kerestelerin hedef rutubet değerine yaklaşık 1,5–3,5 ay içerisinde ulaştığını, 12 cm kalınlığındaki örneklerde ise rutubet kaybının tüm kurutma süreci boyunca devam ettiğini göstermektedir. İç çatlaklar ve öz çatlaklarının oluşumu ile deformasyon davranışı, kereste kesit kalınlığı ve kurutma ortamına bağlı olarak belirgin farklılıklar göstermiştir. Ayrıca numunelerin büyük bir bölümü, kurutma gradyanlarına göre EDG standartları kapsamında yüksek kalite sınıfında yer almıştır. Bununla birlikte, kalın kesitlerde homojen kalite elde etmenin daha güç olduğu belirlenmiştir. Sonuçlar, doğal kurutmanın düşük maliyetli ve çevresel açıdan sürdürülebilir bir yöntem olduğunu ortaya koymakta; ancak kalın kesitlerde kurutma süresinin ve koşullarının dikkatle yönetilmesi gerektiğini vurgulamaktadır. Elde edilen bulgular, endüstriyel kurutma uygulamalarının optimize edilmesine ve benzer iklim bölgelerinde okaliptüs kerestesinin etkin kullanımına katkı sağlamaktadır.

Anahtar kelimeler: Okaliptüs kerestesi, doğal kurutma, kereste kalitesi, kurutma kusurları, akdeniz iklimi

INTRODUCTION

Drying is a critical stage in wood processing that shapes both end-product quality and economic performance, particularly for high moisture hardwoods such as *Eucalyptus* spp. Natural (air) drying is attractive due to its low energy requirement and modest capital cost, and under favorable climates it can achieve target moisture contents with a reduced environmental footprint (Travan et al., 2010; Bown & Lasserre, 2015; Resende et al., 2018). Yet, extended drying times and limited control over temperature, humidity, airflow increase risks of surface/internal checking, warping, and collapse; hence many operations pursue hybrid routes (air pre-drying + kiln finishing) to balance quality and cost (Dawson et al., 2020; Elustondo et al., 2023). Recent reviews likewise emphasize that kiln processes offer superior control at higher capital expenditure and operating expenditure (CAPEX/OPEX), whereas site-specific natural drying remains viable when climate and material management are optimized (Bown & Lasserre, 2015; Bond & Espinoza, 2016; Hermawan et al., 2024).

Within hardwoods, eucalyptus timbers are widely recognized as difficult to dry. Anatomical traits low permeability, pronounced tangential/radial shrinkage, and frequent tension-wood predispose lumber to cell collapse, internal checking, and dimensional instability (Yang et al., 2022; Zen et al., 2020; Kiliç Ak et al., 2021). A comprehensive review by Yang & Liu (2018) emphasized that collapse and internal cracking often restrict the use of eucalyptus for solid-wood applications and summarized various mitigation strategies, including optimized drying schedules, mechanical restraint, and post-drying reconditioning. Complementary studies have reported that the constant-rate drying period in eucalyptus is either absent or very short, indicating that diffusion-controlled drying dominates from early stages, which complicates

stress control and schedule design (Yang et al., 2022; Liu et al., 2023). Furthermore, the presence of interlocked grain and uneven vessel distribution results in heterogeneous moisture flow paths, intensifying moisture gradients between sapwood and heartwood zones (Redman et al., 2016; Zen et al., 2020; Yang et al., 2022). For these reasons, eucalyptus has consistently been regarded as one of the most challenging genera for both natural and kiln drying operations, particularly when thick sections are involved.

Accordingly, previous studies suggest that tailoring drying strategies to species and climatic conditions can improve outcomes for challenging timbers such as eucalyptus. Proper stacking, shading, and schedule adjustments by thickness are essential to moderate moisture gradients and minimize collapse formation under natural drying regimes (Yang & Liu, 2018; Liu et al., 2023).

Climatic context is pivotal for natural drying outcomes. Kahramanmaraş exhibits a hot-summer Mediterranean climate with hot, dry summers and relatively mild, wetter winters conditions that can accelerate summer moisture loss yet steepen moisture gradients and stress if airflow/shading are sub-optimal (Beck et al., 2018; Kiliç Ak et al., 2021). Characterizing thickness-dependent drying behavior and defect formation under open-air and indoor exposure in such climates is therefore essential. Recent region-specific research on *Eucalyptus camaldulensis* under Eastern Mediterranean (Kahramanmaraş) conditions compared outdoor and indoor natural drying environments and reported measurable property differences, supporting the need for exposure aware strategies (Kiliç Ak et al., 2021).

Beyond climate, board geometry and edge condition can modulate gradients and defect incidence (Yang et al., 2022; Elustondo et al., 2023; Fu et al., 2023). Drying gradient based quality assessments (e.g., EDG concepts) and moisture gradient monitoring are increasingly used to guide schedules and evaluate uniformity, aligning with industrial practice. Meanwhile, modelling work for eucalyptus (e.g., air-drying models for piled logs) provides decision support for time to target MC under given weather regimes useful for planning hybrid routes and yard logistics (Bown & Lasserre, 2015; Resende et al., 2018).

Despite the growing industrial interest in eucalyptus for structural and non-structural applications, systematic year-round field evidence under Kahramanmaraş conditions remains limited. Addressing this gap, the present study evaluates the natural drying behavior of *Eucalyptus camaldulensis* timber across thicknesses (3, 6, and 12 cm) and edge configurations (single vs double wane edges) under open-air and indoor setups over a full year. Specifically, we (i) characterize drying behavior and time-to-target moisture content by thickness and exposure, (ii) quantify defects as functions of board attributes and environment, and (iii) assess quality outcomes using drying-gradient criteria to determine the extent to which cost-efficient, sustainable natural drying can meet industrial requirements in Mediterranean climates comparable to Kahramanmaraş.

MATERIALS AND METHODS

Procurement and Preparation of Study Material

Nineteen *Eucalyptus camaldulensis* trees were procured in standing form from the Tarsus-Karabucak Forest Management Directorate, under the jurisdiction of the Mersin Regional

Forestry Directorate (southern Türkiye). The trees were felled in late spring (May) to minimize pre-harvest moisture loss and to ensure homogeneous initial conditions for subsequent drying experiments.

From the harvested trees, a total of 31 logs were obtained, each measuring 3.0 m in length with an average diameter of 39 cm. The logs were transported to the sawmill facility under careful handling conditions to prevent surface checking and to preserve their initial moisture content (Figure 1a-b).

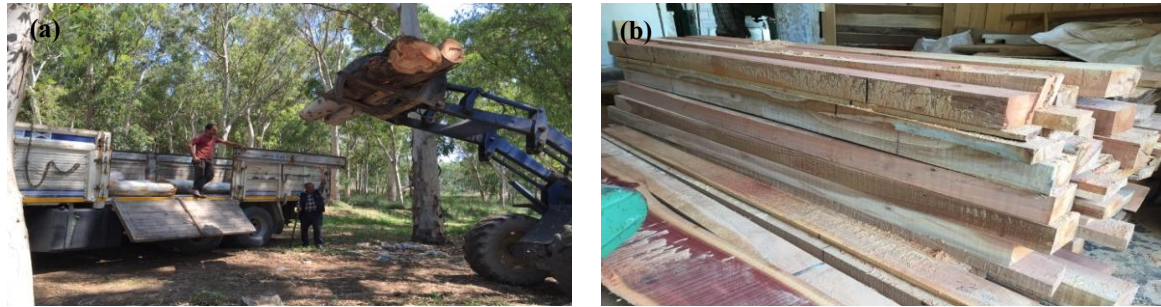


Figure 1. Field harvesting and transportation of *Eucalyptus camaldulensis* logs (a), and preparation of sawn timber specimens with different thicknesses (3, 6, and 12 cm) prior to drying experiments (b)

Subsequently, the logs were sawn into timber specimens of various thicknesses to assess the effects of cross-sectional size and edge configuration on drying performance. Specimens without wane were prepared at nominal thicknesses of 3 cm, 6 cm, and 12 cm, each 15 cm in width and 3 m in length. Additional specimens were sawn with single- and double-wane edges to simulate typical industrial cutting practices. All specimens were categorized and labeled immediately after sawing to preserve structural uniformity and prevent uncontrolled pre-drying moisture loss before the experiments began. The timber specimens consisted of naturally mixed heartwood and sapwood, reflecting typical industrial sawn timber characteristics, and no artificial separation between heartwood and sapwood was applied.

Description of the Experimental Site and Drying Conditions

The study was conducted in Kahramanmaraş, located in the Mediterranean region of Turkey, which offers favorable climatic conditions for natural timber drying. The drying experiments and all associated meteorological data correspond to the 2015 drying season, covering the period from June 2015 to May 2016. The area is characterized by hot, dry summers and mild, rainy winters, making it suitable for assessing open-air drying performance under variable environmental factors. The monthly average temperature ranges from approximately 5°C in winter to above 30°C in summer, while relative humidity varies between 30% and 70%. High solar radiation during the summer months enhances evaporation, and prevailing natural winds promote uniform moisture removal across timber surfaces.

To investigate the influence of drying environment, the timber specimens were exposed to two different conditions: open-air and semi-indoor. The open-air stacks were placed directly under ambient conditions in the Faculty of Forestry yard, fully subjected to local climate variations. In contrast, a comparable set of non-wane-edged timbers was stacked indoors, in a room within the same facility. The indoor space featured a concrete floor and continuously open doors and windows to maintain passive ventilation, ensuring steady air exchange without artificial

heating or dehumidification. These two configurations enabled a comparative evaluation of drying rates and quality parameters between fully outdoor and semi-controlled indoor environments.

Experimental Design

The timber stacks used in the drying experiments were arranged in a wooden slatted crate configuration, measuring approximately 100 cm in width and 140 cm in height. Wooden slats (stickers) were positioned between each timber layer to create uniform air gaps and to maintain the structural stability of the stacks during the drying process. This configuration ensured consistent airflow exposure across all timber surfaces and minimized the risk of warping or deformation during moisture reduction.

The stacks were designed according to the respective drying environments open-air and indoor and their construction details are described in the following subsections.

Preparation of Stack Slats and Supports

Wooden slats were placed between each timber layer to ensure uniform spacing and facilitate consistent airflow throughout the stacks. The dimensions of the slats were determined in proportion to the thickness of the timber, following common industrial practice (Kantay, 1993). In this study, slats were made of pine, with a uniform length of 100 cm and widths ranging from 25 to 30 mm. The slat spacing was kept constant at approximately 70 cm across all stack configurations to maintain regular air distribution.

Open-Air and Indoor Drying Stacks

Non-wane-edged timber specimens were stacked in the yard of the Faculty of Forestry at Kahramanmaraş Sutcu Imam University, in a partially shaded area that received direct sunlight until midday during summer and limited exposure during winter (Figure 2a-b). The stack was placed on 5×10 cm wooden supports above a concrete base, arranged in descending order of timber thickness from 12 cm at the bottom to 3 cm at the top to promote structural stability. Wooden weights were positioned on the upper layer to minimize distortion during drying.

Adjacent to this stack, a second pile consisting of single- and double-wane timbers was constructed and covered with a tarpaulin to provide protection against external climatic factors such as sunlight, rainfall, and snow.

A comparable non-wane-edged stack was also prepared indoors, in a well-ventilated room with continuously open windows and doors to allow passive airflow. Both setups were raised on 5×10 cm supports to prevent ground contact. For comparative analysis, single- and double-wane timbers were also placed on the upper layer of the indoor stack.



Figure 2. Covered open-air stack (a) and naturally ventilated indoor stack (b)

Determination of Timber Moisture Content

The moisture content of the timber specimens was monitored weekly using a Gann-Hydromette HT 65 electrical resistance moisture meter, suitable for timber thicknesses between 1 and 18 cm. Appropriate electrode nails were selected for each thickness, and the device parameters were adjusted for measurement mode, ambient temperature, and wood species group. According to the manufacturer's manual, the wood species group for *Eucalyptus camaldulensis* was set to "3" and ambient temperature data were obtained from the Kahramanmaraş Meteorological Service during each measurement session.

Moisture readings were taken approximately 50 cm from the timber ends, perpendicular to the grain direction on the cross-section. Due to the stacking configuration, measurements were performed on both cross-sectional and outer-facing surfaces, and the mean of three readings per specimen was used to represent the moisture content. This standardized protocol ensured accuracy, repeatability, and minimized deviation among samples.

Monitoring of Drying Environment

To accurately monitor the progress of natural drying, key environmental variables including air temperature, relative humidity, and wind speed were continuously tracked, as these parameters strongly influence the rate of moisture loss. For the open-air drying stacks, real-time data on these parameters were obtained from the Kahramanmaraş Meteorological Service, and weekly average precipitation levels were also recorded to evaluate their potential impact on drying performance.

In the indoor drying setup, air temperature and relative humidity were periodically measured using a Geratech DT-172 temperature and humidity data logger. The instrument recorded minimum and maximum values of temperature and relative humidity at 4-hour intervals, ensuring consistent and representative monitoring of the indoor drying environment.

Determination of Drying Quality

Timber samples were taken from the stacks and evaluated in accordance with the European Drying Group (EDG) Recommendation (1994). This standard, developed collaboratively by European timber trade professionals, wood industry researchers, and academic institutions, provides a systematic framework for assessing the quality of dried timber. It applies primarily to timber up to 80 mm in thickness, excluding larger-sized lumber.

In accordance with the EDG procedure, the final quality assessment of the stacks was based on four key criteria: moisture content, crack formation, collapse, and dimensional stability. Moisture content evaluation considered both the average moisture level and its distribution within and among samples. Crack formation was categorized into surface, internal, and end cracks, while collapse (cellular deformation) and dimensional changes were assessed visually and by measurement. Internal cracks were assessed by visual inspection on transverse sections taken at approximately 30 cm from the timber ends after drying, following the qualitative evaluation approach defined in the EDG recommendation. This approach ensured consistency and comparability with international standards.

In this context, the target final moisture content (MC_{targ}) for the present study was set at 12%. Accordingly, the allowable ranges defined by the EDG were 8.4-15.6% for the S class, 9.6-14.4% for the Q class, and 10.8-13.2% for the E class, corresponding to maximum permissible deviations of $\pm 4.8\%$, $\pm 3.6\%$, and $\pm 2.4\%$, respectively. These threshold values and classification rules were consistent with those previously applied to eucalyptus timber. In a previous conference paper presenting preliminary findings from the same experimental setup Kiliç Ak et al., (2017), *Eucalyptus camaldulensis* timbers were classified according to the EDG criteria, and both average and individual moisture content deviations were found to fall within the E-class limits (10.8-13.2% range and $\pm 2.4\%$ deviation). That study also evaluated collapse and surface checking severity, demonstrating that thinner sections (3-6 cm) generally exhibited low to moderate defect levels, whereas thicker timbers tended to show more severe collapse and cracking. These findings confirmed the applicability of the EDG framework for evaluating eucalyptus timber.

In the current study, the same EDG-based protocol was adopted to ensure methodological continuity and direct comparability with previously published data. Although the EDG recommendation is formally limited to timber up to 80 mm in thickness, the classification framework was applied to the 120 mm specimens as a comparative assessment tool rather than as an absolute compliance criterion. This approach enabled a consistent evaluation of drying behavior and defect development across different cross-sectional dimensions, thereby facilitating thickness-based comparisons under identical drying conditions. In addition to these assessments, the occurrence and characteristics of internal and heart cracks, as well as deformation patterns, were examined to provide a more comprehensive understanding of drying-induced defects in *Eucalyptus camaldulensis* timber.

Drying quality was primarily evaluated through visual inspection in accordance with EDG criteria, which are widely used in industrial practice. Although non-destructive techniques such as ultrasonic or acoustic methods could provide additional insights into internal defects, these methods were beyond the scope of the present field-based study.

RESULTS AND DISCUSSION

This section presents the results obtained from timber stacks exposed to open-air and indoor environments during a natural drying experiment conducted in the city center of Kahramanmaraş, which represents a typical Eastern Mediterranean microclimate. The results reflect the climatic conditions recorded during the 2015 drying season (June 2015-May 2016). Prior to sawing, the *Eucalyptus camaldulensis* logs exhibited an average initial moisture

content ranging from 85% to 90% on a wet basis. The natural drying process extended over an approximately one-year period, from June to May of the following year.

Environmental Conditions in the Open-Air Drying Stack

In open-air drying, temperature and relative humidity (RH) are among the most influential environmental factors that determine the rate of moisture loss in timber. To identify the most favorable period for drying, called the effective drying period, weekly average values of temperature and RH were analyzed throughout the study period (Figure 3).

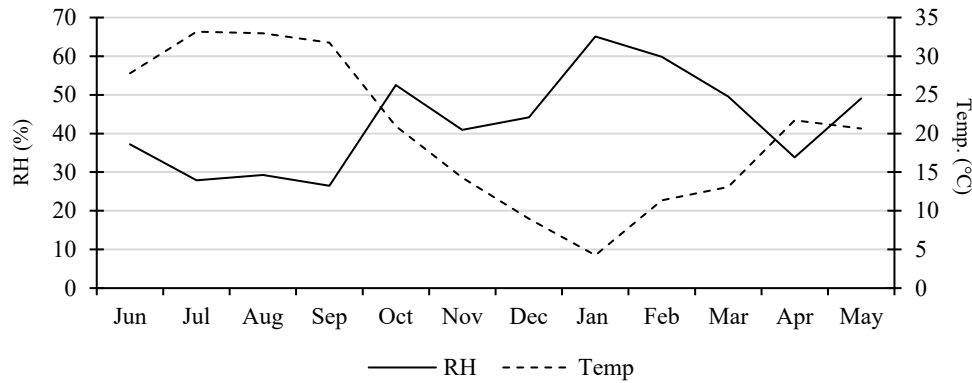


Figure 3. Monthly temperature and relative humidity during open-air drying

As shown in Figure 3, the summer months (June to early September) were characterized by high temperatures exceeding 30°C and low RH levels, which provided suitable conditions for faster evaporation. In contrast, during winter, lower temperatures combined with high humidity considerably reduced drying efficiency, particularly for thicker timber sections. Although the effective drying period ended in September, moisture content monitoring continued throughout the year to capture long-term seasonal variations.

Moisture Content Variation of Timber without Wane for Different Thicknesses (3,6,12 cm)

The moisture content variation of *Eucalyptus camaldulensis* timbers without wane and with different thicknesses (3, 6, and 12 cm) was evaluated during the effective drying period (June-September) based on weekly observations (Figure 4). Wind speed ranged between 0 and 5.4 km/h, and total precipitation remained below 0.4 mm, showing negligible influence on drying performance; therefore, these parameters were excluded from the graphical analysis.

The average temperature and relative humidity in June were 27.8°C and 37.2%, respectively. As temperatures increased in July, moisture content dropped further, reaching 10% by the third week. In the first week of August, the lowest value of 8.7% was recorded. From this point until the end of September, moisture levels remained stable, after which a slight increase was observed due to changing climatic conditions. Wind speeds and rainfall in this period were minimal and had negligible impact on drying.

At the beginning of drying, the 3 cm thick timbers had an average moisture content of 57%. A rapid decrease occurred during June, reaching 20.7% by month's end. This trend agrees with previous findings for eucalyptus timber under comparable summer conditions. As also reported in previous studies, eucalyptus timber with high initial moisture contents exhibits a rapid drying

phase above the fiber saturation point (FSP, ~30%), after which the drying rate slows markedly once the moisture content falls below FSP. Shorter samples (30–50 mm) tend to lose moisture more rapidly, with the drying rate above FSP being approximately three to three and a half times higher than below. Pronounced moisture gradients are observed in smaller specimens and at higher initial moisture levels, becoming more uniform as drying progresses (Yang et al., 2022; Liu et al., 2023).

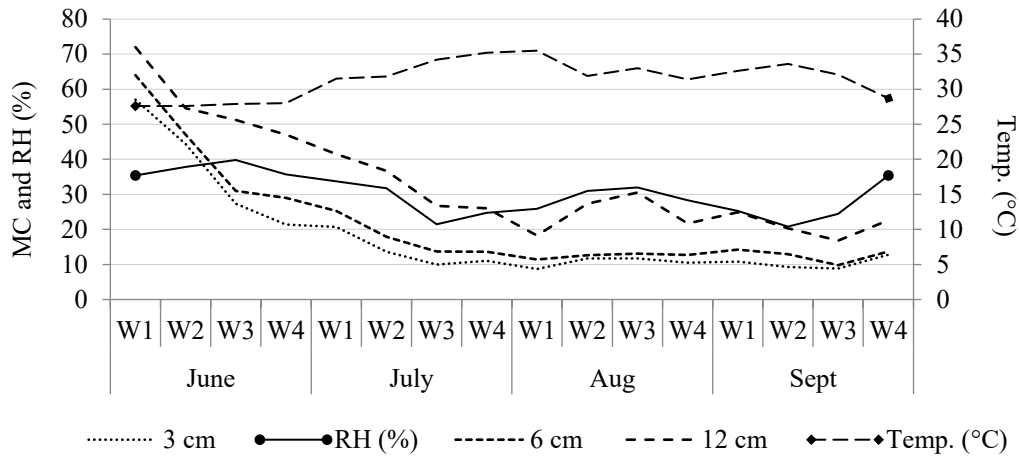


Figure 4. Weekly drying conditions and MC variation (3,6,12 cm timber)

For the 6 cm thick timber, initial moisture content was 64%. It declined gradually through June and July, reaching 25.3% and 13.6%, respectively. In the first week of August, it dropped to 11.4%, close to the target final moisture content (FMC). The minimum value of 9.8% was observed in the third week of September. Compared with findings in other regions such as Brazil and Poland (Eufrade-Junior et al., 2021; Jakubowski & Praczyk, 2022), the results of this study indicate that natural drying under Kahramanmaraş's summer conditions is relatively more effective.

In 12 cm-thick timber, the initial moisture content was 72%. By the end of June, it decreased to 41.5%, and reached 26% in July. The lowest value recorded was 18.3% in early August, followed by 16.8% in the third week of September. However, even by the end of the effective drying period, the target FMC was not reached, which can be attributed to the greater thickness and reduced drying rate of the timber.

These results indicate that under the climatic conditions of Kahramanmaraş, natural drying during summer months is sufficient to reach target moisture levels in thinner timbers (3, 6 cm), whereas thicker timbers (12 cm) require extended drying or supplementary techniques.

Moisture Content Variation in 6 cm Wane-Edged Timbers (Single and Double Edges)

In this section, the drying behavior of 6 cm-thick eucalyptus timbers with single-wane (SW) and double-wane (DW) edges was investigated throughout the effective drying period (June-September). The presence of wane edges can modify airflow exposure and surface area, thereby influencing moisture gradients and drying uniformity (Yang et al., 2022; Liu et al., 2023). Figure 5 illustrates the weekly changes in moisture content (MC) for both timber types, alongside ambient temperature and relative humidity (RH). Wind and precipitation data were excluded from the graph due to their negligible influence on drying.

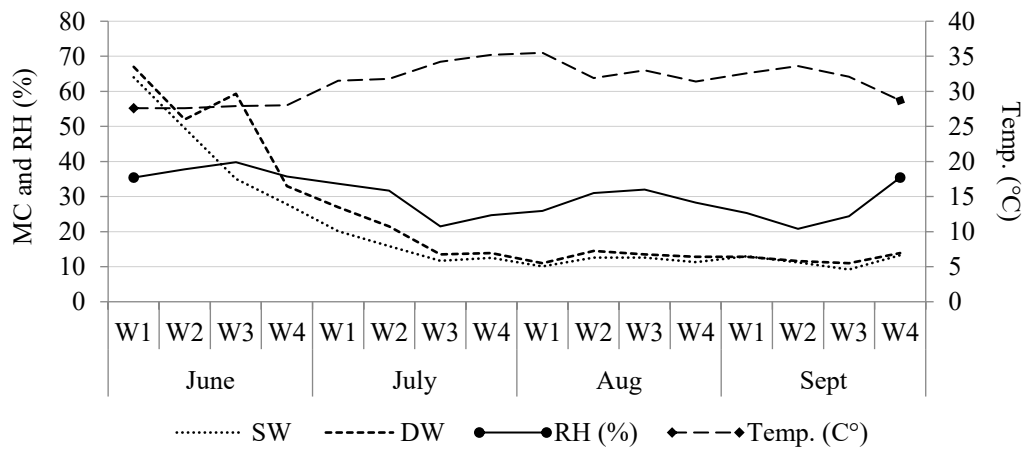


Figure 5. Weekly drying conditions and MC variation in 6 cm SW and DW timbers

The initial MC of SW timbers were measured at 64%. A notable reduction was observed during June, with MC dropping to 27.8% by the end of the month. The drying process continued steadily in July, and by the third week, the MC reached the target final moisture content (FMC) of 11.7%. The lowest value, 9.2%, was recorded in the third week of September, coinciding with the peak temperature (33.6°C) and minimum RH (20.8%) for the entire drying period. This reduction pattern indicates that elevated temperatures and lower relative humidity levels likely accelerated the drying process by increasing the vapor pressure deficit between wood and air, thereby enhancing the rate of moisture migration. Similar correlations between high temperature, low RH, and accelerated drying have been reported for eucalyptus and other hardwood species (Yang & Liu, 2021; Rozas et al., 2024).

DW timbers began with a slightly higher initial MC of 67%. While MC decreased to 52% after the first week, a temporary increase to 59.3% occurred in the third week of June, likely influenced by 1.3 mm of rainfall. This short-term rise is consistent with wood's hygroscopic nature, as rainfall and high humidity promote surface and near-surface moisture uptake. Due to sorption hysteresis, re-adsorbed moisture can exceed levels recorded during initial drying. Similar temporary increases in MC after rainfall have been reported in open-air drying studies (Dietsch et al., 2015; Žlahtič Zupanc et al., 2019). After this fluctuation, a rapid decline followed, with MC reaching 33% by the fourth week. During July, drying proceeded gradually, and by the final week, MC dropped to 13.9%. The minimum value of 11% was achieved in the first week of August, meeting the target FMC.

When the moisture profiles of SW and DW timbers are compared, SW samples consistently showed lower MC throughout the drying period. This difference is primarily due to the greater surface area and edge exposure in DW timbers, which increases their susceptibility to moisture reabsorption during humid conditions or rainfall (Bown & Lasserre, 2015; Resende et al., 2018). Additionally, DW timbers may have higher variability in drying due to asymmetrical surface exposure and airflow resistance (Collignan et al., 1993).

Overall, these results suggest that while both SW and DW timbers can reach the desired moisture levels under favorable climatic conditions, SW timbers exhibit more stable and efficient drying performance. This indicates that the number and orientation of wane edges

may influence the drying rate and moisture retention of eucalyptus timber, and should be considered when planning open-air seasoning strategies.

Environmental Conditions in the Indoor Drying Stack

Figure 6 illustrates the monthly average temperature and relative humidity recorded in the indoor environment where the timber was dried.

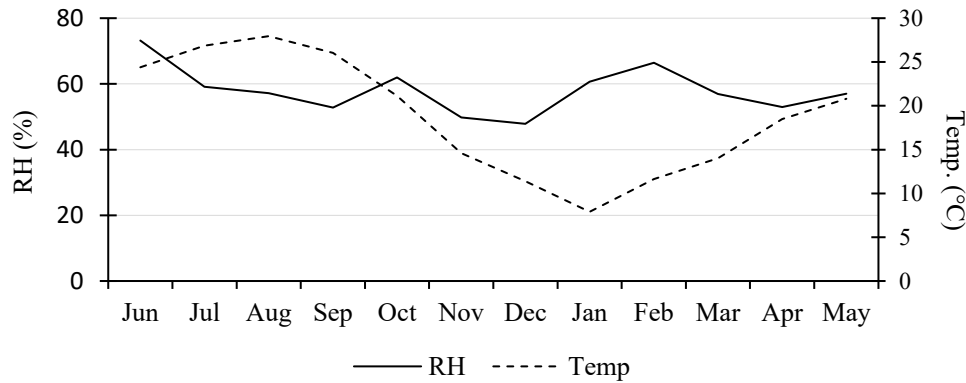


Figure 6. Monthly mean temperature and relative humidity in the indoor drying environment

The maximum temperature was observed in August (28.5°C), while the lowest was in January (7.9°C). Relative humidity peaked at 79.9% during initial stacking and dropped to a minimum of 41.8% in December. As in open-air drying, the most favorable period for drying in the indoor environment was identified as summer (June–September), when temperatures were high and humidity was low. Based on this, the upcoming moisture content graphs present weekly values for the effective drying period and monthly values for the remaining months.

Moisture Content Variation of Timber without Wane in Indoor Drying

Figure 7 presents the moisture content (MC) variations of 3, 6, and 12 cm thick eucalyptus timbers without wane stacked in an indoor environment during the effective drying period (June–September), alongside weekly average temperature and relative humidity (RH) values.

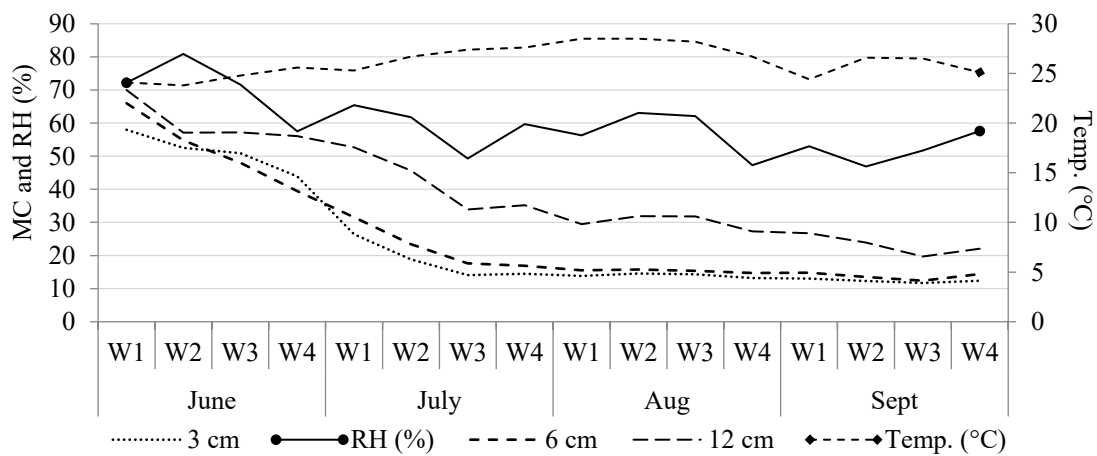


Figure 7. Weekly drying conditions and MC variation of 3, 6, and 12 cm eucalyptus timbers without wane under indoor conditions

At the beginning of drying, the initial MC values were measured as 58%, 66%, and 70% for the 3 cm, 6 cm, and 12 cm timbers, respectively. In 3 cm timber, a relatively slow moisture decrease was observed in June due to high RH. However, with rising temperatures and decreasing RH in July and August, MC declined rapidly, reaching the final moisture content (FMC) of 12.3% by the second week of September, and a minimum value of 11.7% in the third week.

For 6 cm timber, moisture content gradually decreased, reaching 17.6% by mid-July, and achieving the FMC of 12.4% in the third week of September. In contrast, the 12 cm-thick timber exhibited a slower drying rate, with MC decreasing to 35.2% by the end of July and fluctuating slightly in August due to increased RH. By the end of the drying period, the lowest value achieved was 19.7%, indicating that the FMC target was not reached. This behavior is consistent with previous reports showing that thicker and denser eucalyptus boards dry significantly slower and often fail to reach target MC thresholds under natural or indoor air-drying conditions (Phonetip et al., 2019; Yang et al., 2022).

Moisture Content Variation of Wane-Edged Timber in Indoor Drying (6 cm)

The drying behavior of single and double wane-edged eucalyptus timbers (6 cm thick) under indoor conditions during the effective drying period (June–September) is illustrated in Figure 8.

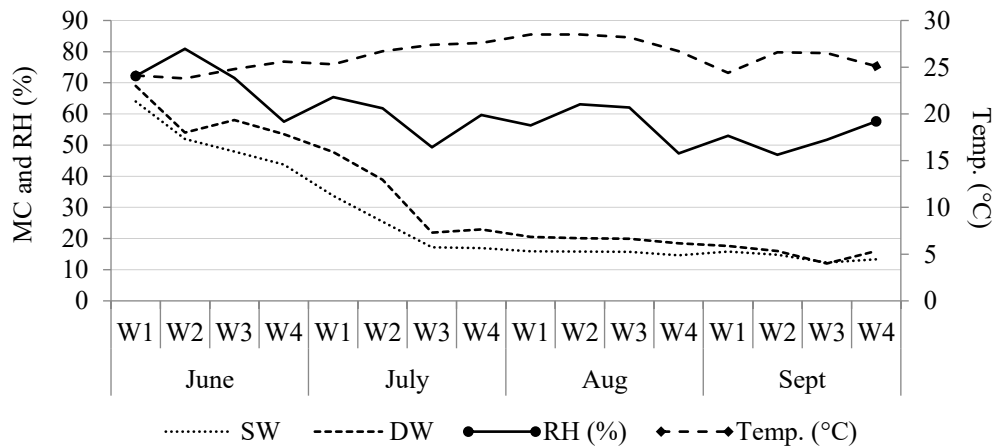


Figure 8. MC variation of 6 cm SW and DW timbers under indoor conditions

In the indoor drying environment, the initial moisture content (MC) of single wane (SW) timbers was measured at 64%. By the end of June, the MC decreased to 43.7%, followed by a steady decline throughout July, reaching 17.2% in the third week. As ambient relative humidity dropped particularly during the driest week (46.9%) drying accelerated, and the timber reached the final target MC of 12.3% by the third week of September.

For double wane (DW) timbers, the initial MC was slightly higher at 69%. With rising temperatures, the MC gradually decreased to 21.9% by the third week of July. During August, the values fluctuated between 20.5% and 18.5%. The final MC target (12%) was achieved in the third week of September, when the lowest MC was recorded.

Annual Moisture Content Variation in Timbers under Indoor and Open-Air Drying Conditions

The annual moisture content variations of timbers dried under open air (Figure 9) and indoor conditions are illustrated in Figure 10. Unlike the effective drying period, where rapid reductions were observed within the first three months, the yearly analysis highlights the long-term trends and seasonal fluctuations in moisture behavior. Detailed weekly moisture changes are presented for the effective drying period (June–September), while monthly measurements were used to evaluate long-term annual moisture behavior.

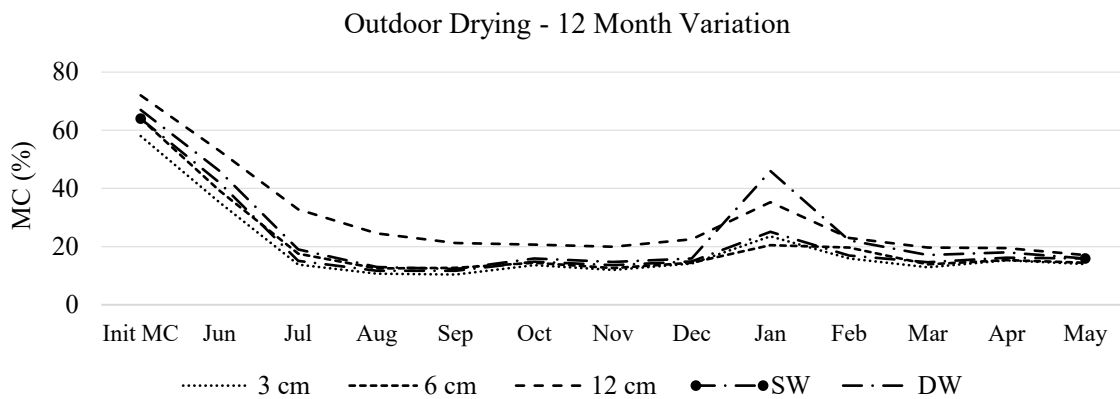


Figure 9. Year-round MC trends of eucalyptus timbers with different thicknesses and wane configurations under open-air drying

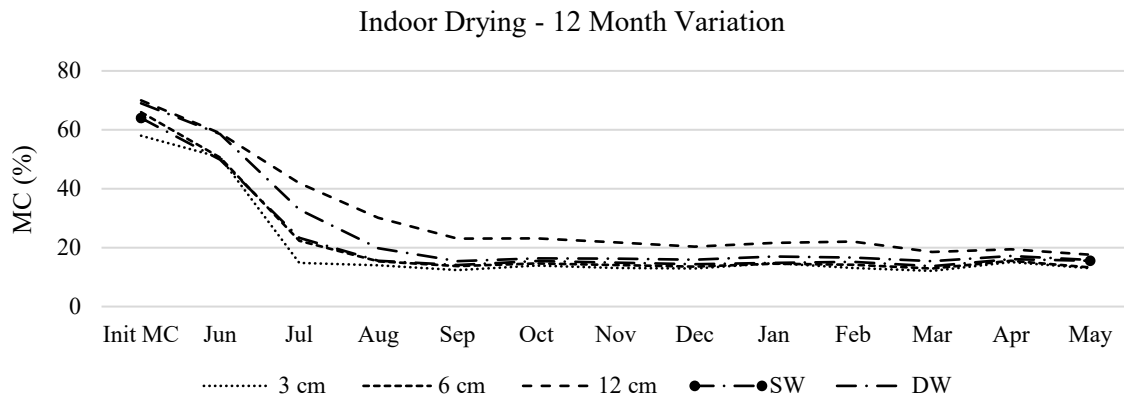


Figure 10. Twelve-month MC variation of SW and DW timbers under indoor drying

Thickness also played a critical role in long-term drying behavior. While 3 cm and 6 cm samples reached their equilibrium moisture content (EMC) earlier and maintained stable values throughout the year, 12 cm timbers showed continuous moisture reductions without stabilization even after 12 months. This indicates that thicker sections require substantially longer drying periods to achieve stable moisture conditions under natural drying, particularly in indoor environments (Plavčák et al., 2019).

When the effect of wane is considered, outdoor drying again demonstrated faster initial moisture reduction, whereas indoor drying required extended periods to reach similar values.

Despite this, indoor-stored timbers exhibited more uniform moisture profiles throughout the year.

Overall, the annual evaluation confirms that outdoor drying is more efficient in achieving EMC in shorter durations but is more susceptible to climatic variations, while indoor drying ensures a more controlled and steady process, albeit with slower kinetics (Simo-Tagne & Bennamoun, 2018). In conclusion, the annual results demonstrate that outdoor drying enables faster moisture reduction in the short term but is more vulnerable to abrupt environmental fluctuations, whereas indoor drying requires a longer period yet provides a more stable and uniform drying process.

Final Quality Control

The final quality control assessment, conducted in accordance with the EDG criteria, is presented in this section. A detailed explanation of the EDG framework, evaluation thresholds, and the methodological basis adopted in this study was provided earlier in Section 2.2.6, together with reference to the preliminary findings reported in our previous work Kiliç Ak et al., (2017), which demonstrated the applicability of the EDG system to *Eucalyptus camaldulensis*. In the present study, only the results obtained from the current drying experiments are summarized below.

Summary of Moisture Content Quality Results

EDG limits for the target value of 12%, whereas the 12 cm samples, particularly those dried indoors, fell outside the acceptable moisture ranges and remained partially or fully unclassified. Among the 3 cm timbers, indoor drying produced the highest level of conformity, while outdoor drying yielded better performance for the 6 cm group. This thickness-dependent behavior aligns with previous findings reporting that increased cross-sectional dimensions reduce moisture uniformity and prolong the time required to reach equilibrium (Albrektas & Ukvalbergienė, 2015; Yang et al., 2022; Batjargal et al., 2025)

Wane edged samples (SW and DW) also exhibited high compliance with the EDG requirements, consistent with the expectation that exposed wane surfaces enhance evaporation uniformity. Similar trends were reported in our previous study, where thinner sections showed a higher proportion of E-class classifications under the EDG framework (Kiliç Ak et al., 2017). Overall, these results demonstrate that drying environment, thickness, and wane configuration strongly influence final moisture quality. Indoor drying provided more uniform moisture distribution for thin timbers, whereas increasing thickness shifted the advantage toward outdoor drying. This finding is in agreement with earlier studies highlighting the greater stability of indoor drying but also its slower kinetics (Baranski, 2018; Amoo-Onidundu et al., 2023)

Crack Formation and Deformation Behavior

Internal cracks: Internal cracks observed on transverse sections taken 30 cm from both ends of each timber are summarized in Table 1.

Table 1. Distribution of Internal Crack Severity in Outdoor and Indoor-Dried Timbers

Drying Environment	Thickness (cm)	Number of Samples	Timbers with Internal Cracks (n)	Severe (%)
Outdoor	3	15	2	13
	6	20	6	30
	12	20	9	45
Indoor	3	15	-	0
	6	20	5	25
	12	20	17	85

According to EDG tolerances which classify internal cracking as severe when more than 10% of the batch is affected all groups except the 3 cm indoor samples fell into the severe category. The complete absence of internal cracking in the 3 cm indoor timbers indicates that thin sections dried under controlled indoor conditions experienced lower stress gradients and exhibited more stable drying behavior. In contrast, the 12 cm indoor group showed the highest severity (85%), consistent with the greater moisture gradients and internal stress accumulation typically observed in thicker hardwood sections (Phonetip et al., 2019; Elustondo et al., 2023).

Heart cracks: Heart cracks were observed almost exclusively in the 12 cm timbers, occurring in approximately 50% of outdoor dried samples and 45% of indoor dried samples. This concentration of heart checks in the thickest timbers highlights the influence of steep radial moisture gradients and the inherent anatomical susceptibility of eucalyptus to pith-centered stress accumulation. Similar observations have been documented for thick eucalyptus boards, which exhibit pronounced differential shrinkage (Muthike et al., 2022).

Deformations: Deformation was rare across all timber groups. Only one 3 cm indoor timber exhibited slight bowing, and one 3 cm outdoor sample showed minor cupping. The generally low deformation levels suggest effective stacking, uniform air circulation, and limited stress asymmetry during drying. Outdoor-dried timbers exhibited a darker surface color compared to indoor-dried samples, likely due to prolonged ultraviolet exposure and lignin photodegradation (Timar et al., 2016).

Representative examples of collapse, internal and heart cracks observed during the drying process are presented in Figure 11.

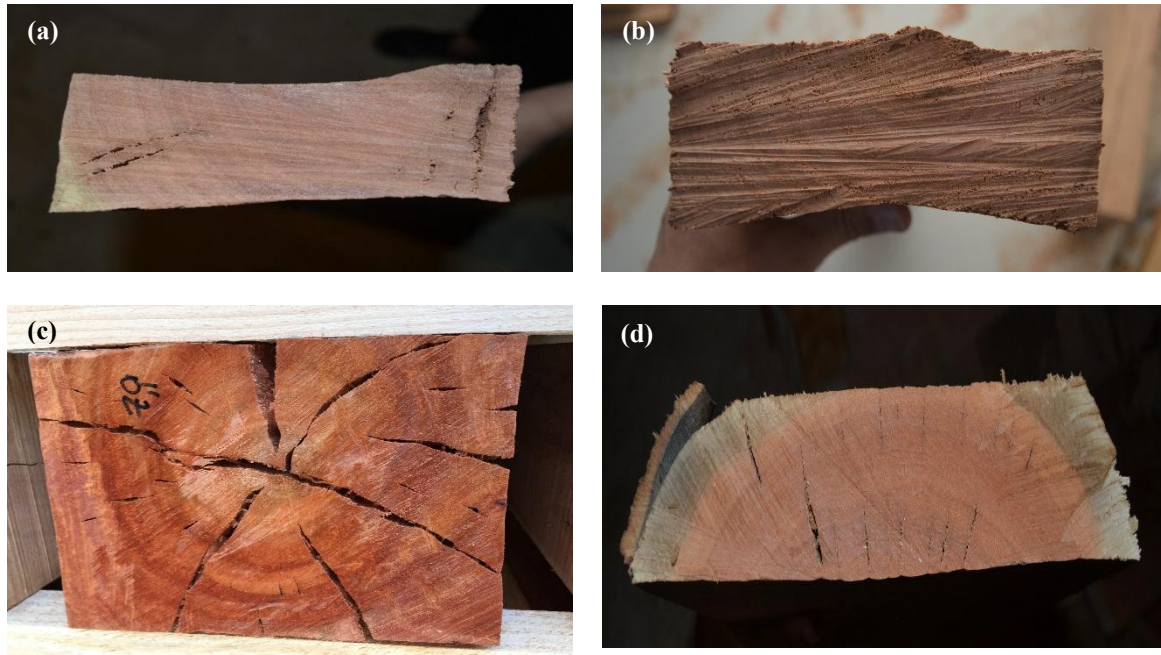


Figure 11. Representative photographs of defects in dried eucalyptus timbers: (a) severe collapse in a 6 cm outdoor sample; (b) severe collapse in a 6 cm indoor sample; (c) heart cracks and surface checks in 12 cm outdoor timbers; and (d) internal cracks in a 6 cm outdoor timber

CONCLUSIONS

This study investigated the natural drying performance of *Eucalyptus camaldulensis* timbers with three thicknesses (3, 6, and 12 cm) under outdoor and indoor conditions for one year in the climatic environment of Kahramanmaraş, Turkey. The findings demonstrated that both timber thickness and drying environment exert a strong influence on drying rate, moisture uniformity, and final quality. Thin and medium-sized timbers (3 and 6 cm) reached the target final moisture content (~12%) within approximately 3.5 months in both environments, whereas 12 cm timbers failed to achieve the target even after one year, despite a continued gradual decrease in moisture content.

Outdoor drying enabled faster moisture reduction during summer due to elevated temperatures and lower relative humidity, but was more vulnerable to rehumidification during winter months. Indoor drying, by contrast, provided a slower yet more stable process, reducing fluctuations and preventing seasonal rewetting. According to EDG (1994) classification, 3 cm indoor dried timbers exhibited the highest proportion of E-class conformity (93%), while a large share of 6 cm outdoor dried timbers also met the same quality class.

Defect evaluations revealed a clear thickness-dependent behavior in naturally dried *Eucalyptus camaldulensis* timbers. Internal cracking increased with timber thickness and was mainly observed in 12 cm specimens under both drying conditions, while 3 cm indoor-dried timbers showed no internal cracking, indicating more uniform moisture redistribution. Heart cracks were almost exclusively detected in the thickest timbers, reflecting pith-centered stress accumulation. Deformation defects were generally limited across all groups. Overall, natural drying can yield acceptable quality for thin and medium-thickness eucalyptus timbers under

moderate climatic conditions; however, thick sections require extended drying periods or additional conditioning measures to reduce crack formation.

The outcomes of this study enhance the understanding of natural drying behavior in *Eucalyptus camaldulensis* and provide practical guidance for industrial applications. For improved drying performance, natural drying is recommended to begin in spring or early summer, when moderate ambient conditions favor gradual moisture loss. For thicker timbers (>6 cm), extended natural drying durations or hybrid approaches combining natural pre-drying with controlled kiln drying are advisable to improve moisture uniformity and reduce internal cracking. Future research should focus on optimizing regional drying schedules, evaluating different eucalyptus species under varying climatic conditions, and developing energy efficient drying strategies to enhance the sustainability of timber processing.

AUTHOR CONTRIBUTIONS

Ayşenur Kılıç Ak: Conceptualization, methodology, investigation, data curation, formal analysis, writing-original draft, review & editing, visualization. **İbrahim Bektaş:** Conceptualization, methodology, validation, resources, supervision, writing- review & editing.

FUNDING STATEMENT

The study received no financial support.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS COMMITTEE APPROVAL

This study does not require an ethics committee approval

ACKNOWLEDGEMENTS

This study was supported by the Scientific Research Projects Coordination Unit of Kahramanmaraş Sütçü İmam University (Project No: 2015/1-86YLS). The authors gratefully acknowledge Prof. Öner Ünsal for his valuable scientific contributions and constructive suggestions.

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