

Drying *Ochroma pyramidale* from Costa Rican plantations using kiln, solar and air drying: time, moisture content, color and drying defects

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Abstract. Balsa (*Ochroma pyramidale*) holds significant market importance due to its rapid growth and the low density ($<0.2 \text{ g/cm}^3$) of its wood. Extensive areas of balsa have been established in many tropical regions; however, knowledge about drying wood from this species remains limited. This study evaluated kiln drying (KD), solar drying (SD), and air drying (AD)—in terms of drying time, wood color, and the presence of defects such as warp, splits, and cracks—of 6-cm-thick lumber from 1.7- and 4.5-year-old balsa plantations in Costa Rica. Drying time was shortest for KD, while SD required an intermediate duration between KD and AD. Balsa wood dried using KD exhibited statistically significant differences in all three color parameters, with the highest overall color change. Conversely, wood dried using SD and AD displayed similar values for the three color parameters, with minimal color change. Boards exhibited varying levels of warping (crook, bow, cup, and twist), splits, and checking before drying. SD resulted in similar defect levels (incidence, magnitude, and quality index) to AD. However, KD caused the greatest changes in wood quality and the highest defect incidence. While KD allowed for drying balsa wood with fewer defects in the shortest time, the highest wood quality was achieved with SD and AD, albeit requiring longer drying durations.

Keywords: Balsa wood, *Ochroma pyramidale*, Drying process, Drying defects, Tropical wood, Low density, Quality

Introduction

Ochroma pyramidale (balsa) is a tropical species that grows naturally from southern Mexico to Bolivia, covering latitudes from 22° N to 15° S (Francis 2000). This species is wide-

spread across tropical regions of the Americas, and is particularly abundant in Ecuador, where it is highly commercialized (Condoy et al. 2023). Following the Second World War, *O. pyramidale* was cultivated in commercial plantations across various countries in Asia and Oceania (Francis 2000). More recently, it has been established as a fast-growing plantation species in tropical America and other tropical regions worldwide (Business Research Insights 2024), with the primary

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objective of producing sawlogs in the shortest time possible, while maintaining the appropriate density (Francis 2000).

Balsa wood is characterized by its low density, ranging from 50 to 350 kg/m³ (Borrega et al. 2015). Balsa wood has diverse applications in engineering products for civil infrastructure (e.g., wind turbines and bridges), transportation (e.g., cars, trucks, caravans, trains, aircraft, and boats), industrial uses (e.g., packaging and storage), and leisure (e.g., sports equipment and musical instruments) (Galos et al. 2022). The wood must achieve a moisture content (MC) of 10%–12% for these applications, which can be attained using various drying processes (Thybring et al. 2022).

The purpose of drying is to reduce the moisture content to an optimal level, enabling maximum performance during the final use of the wood (Elustondo et al. 2023). Different drying methods are available, and various classifications exist. Teischinger et al. (2023) provided a classification based on heat and energy transfer mechanisms, which included convection, conduction, and radiation/electric field drying. The most common convection-based methods are air drying (AD), solar drying (SD), and conventional kiln drying (KD).

These drying methods are widely used in tropical regions and for plantation-grown wood in Costa Rica (Salas and Moya 2014; Tenorio et al. 2016; Moya et al. 2013; Moya and Tenorio 2022). However, most studies have focused on KD, with limited research examining the behavior of wood in other drying methods (Salas and Moya 2014). An exception was research on *Gmelina arborea* and *Tectona grandis*, where the performance under KD, SD, and AD conditions was studied across varying periods and climatic conditions in Costa Rica (Salas and Moya 2014).

Research on drying balsa remains limited, particularly for plantation-grown wood, as most studies have focused on trees from natural forests. For instance, the USDA Forest Products Laboratory (Boone et al. 1988) recommended kiln drying schedules T10-D4S for lumber up to 2.5 cm thick and T8-D3S for thicker lumber. Similarly, the French Agricultural Research Centre for International Development (CIRAD 2024) proposed drying schedules where balsa wood could achieve a moisture content of 10%–14% within 2–3 days, although the thickness of the wood was not specified (Midgley et al. 2010). Eddowes (Eddowes 2005) highlighted the need to evaluate the applicability and profitability of solar drying systems to achieve high-quality drying outcomes and cost efficiency. Additionally, Jenkin et al. (2019) emphasized that logs must be processed and kiln-dried within 48 hours of harvesting to minimize drying defects and improve wood quality.

Although some studies have explored balsa wood drying methods in Ecuador and Peru, they often lack methodological details about the behavior of wood under KD, SD, and AD conditions. For example, Guevara (1996) used AD to dry lumber (15 cm wide, 20 mm thick, and 1.2 m long) from secondary forest trees in Peru and reported an initial MC of 286%. However, drying times varied widely, ranging from 30 to 45 days, and the wood was classified as fast-drying with type A warping defects. Meanwhile, Utia (2012) studied AD using triangle crib piling and inverted “V” end-racking methods for wood (2.5 cm thick, 10 cm wide, and 1.3 m long) from natural forests. While drying defects were assessed at different tree heights, additional drying data were limited.

The objective of this study was to compare KD, SD, and AD—in terms of drying time, wood color, and the presence of defects such as warping, splitting, and cracking in 6 cm thick lumber from 1.7- and 4.5-year-old plantations in Costa Rica. The findings of this study will provide valuable insights into producing balsa wood for use in wind turbine blades, where international markets demand wood with a thickness of 5 cm.

Methodology

Tree sampling

Two different provenances were sampled: one plantation located near the Pacific Coast and the other near the Caribbean Coast (Figure 1a). The tree characteristics for each site are presented in Table 1. The Pacific plantation consisted of naturally regenerated balsa, covering approximately 0.25 ha in Parrita (10° 52' 41" N, 84° 21' 88" W). This site contained 25 naturally regenerated trees, of which 10 were sampled. Stand density at sampling time was approximately 600 six-year-old trees/ha. The Caribbean plantation, was a 4.5-year-old managed stand located in Guácimo (10° 52' 41" N, 84° 21' 88" W), established with a 2 × 2 m spacing (initial stand density of 2,500 trees/ha). At the time of sampling, the stand density had decreased to 2,080 trees/ha. No thinning was applied to either plantation, and weed control was conducted manually. Fertilization was carried out at the time of establishment and subsequently at the beginning of each rainy season in May. Six to eight 1.25 m-long sawlogs were extracted from each sampled tree. Sawlog diameter ranged from 18 cm to 25 cm for trees from the natural regeneration area and 14 cm to 18 cm for those from the managed plantation.

Sawing pattern

The logs were through-sawn into 60-mm-thick planks using a pattern commonly employed by the Costa Rican furniture

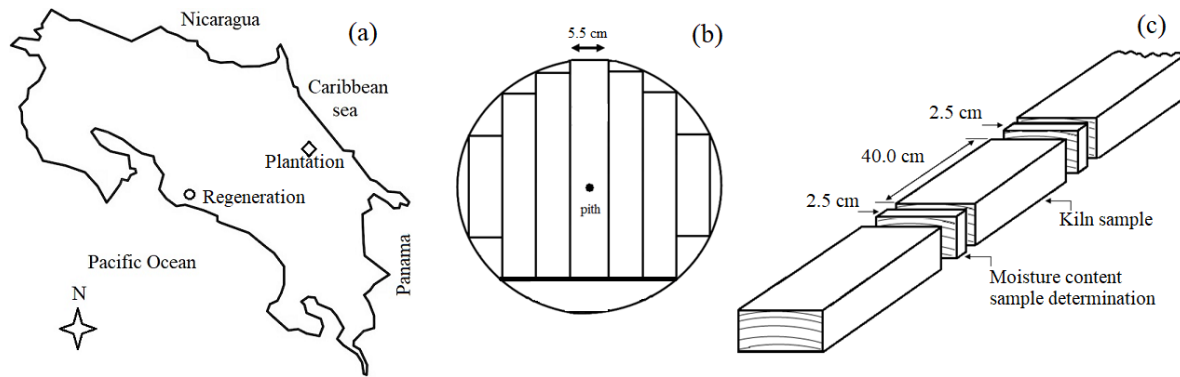


Figure 1. Geographic location (a), sawing pattern (b) and sample extracted for moisture content determination (c) used for *Ochroma pyramidale* lumber.

Table 1. Characteristics of *Ochroma pyramidale* trees used to produce lumber used in different methods of drying.

Precedence	Age (months)	Diameter at breast height (cm)	Commercial height (m)	Total height (m)	Type of drying		
					Kiln	Solar	Air
Regeneration	4.5	20.26	6.64	16.52	x		
Plantation	1.7	15.66	6.50	14.13		x	x

industry; however, the initial cut was varied. This initial cut was made to relieve growth stresses, and then the log was rotated to rest on the straight face (Figure 1b). The thickness was selected because the international market requires dried lumber with a final thickness of 50 mm and this allowed for shrinkage and planing (Condoy et al. 2023; Moya and Muñoz 2008). The boards included flat sawn, quarter sawn, rift sawn, and double rift sawn material. All boards were edged, ensuring that each had four finished edges.

Drying processes

The balsa wood drying was evaluated using three different drying schedules:

- AD—dried by stacking outdoors on stickers and protecting from sun and rain
- SD—dried using a solar dryer based on the design of Salas and Moya (2014)
- KD—dried in a Nardi chamber (San Bonifacio, Italy) following T10-D4S program (Table 2) proposed by Boone et al. (1988) with a target MC of 10%.

Air and solar drying were carried out in Cartago, Costa Rica (09° 50' 56" N, 83° 54' 38" W). The three drying methods were evaluated between December 2024 and January 2025. Cartago had an average temperature of 18.16°C, daily precipitation of 0.91 mm, and an average solar radiation of 19.12 MJ/m²/day (Figure 2a).

Stacking

Green lumber was stacked in packages measuring 1.0 m wide, 1.3 m high, and 1.2 m long. Each of the 12 layers was 5 to 10 boards wide, depending on the drying method. Stickers (2.5 cm × 2.5 cm in cross-section) were placed between the layers.

Table 2. Kiln schedules used for the conventional drying of *Ochroma pyramidale* wood.

Step	Chamber condition				
	TBS °C	TBH	EMC %	MC %	HR
Heating	60	-	-	-	-
	60	-	16.0	-	-
Drying	60	56	14.2	Above 50	82
	60	54.5	12.0	50-40	75
	60	51.5	9.6	40-35	64
	60	49.0	8.0	35-30	55
	65.5	51.5	6.8	30-25	49
	71.0	54.5	5.8	25-20	43
	76.5	57.0	5.1	20-15	39
82.0	54.5	3.5	15-12	26	
Equalization	82	-	10	10	-
Conditioning	82	-	10	-	-
Cooling	40	-	-	-	-

Legend: TBS = Dry-bulb temperature; TBH = Wet-bulb temperature; EMC = equilibrium moisture content; MC = lumber moisture content, HR = Relative humidity. Source: Boone et al. (1988)

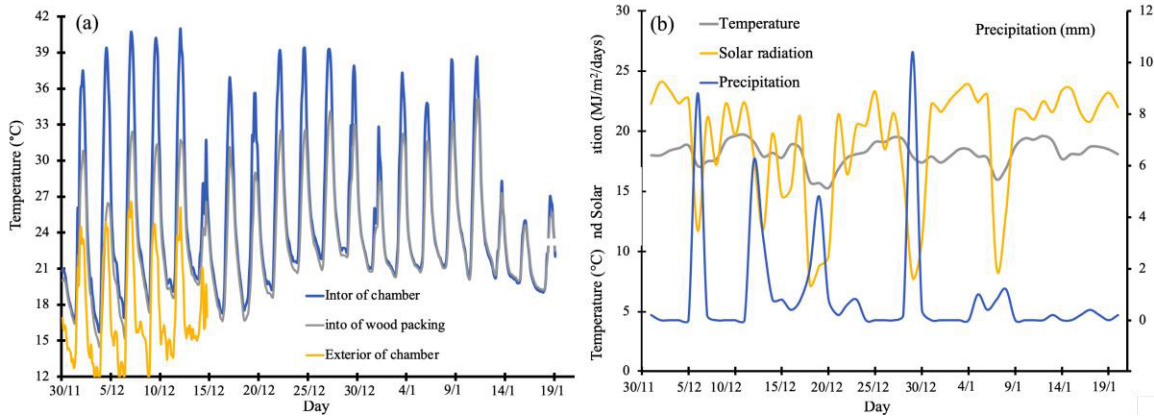


Figure 2. Temperature, solar radiation, and precipitation in Cartago during air drying and (a) and temperature variations in the solar chamber during solar drying of balsa wood(b).

Single stacks were prepared for AD and KD, while two stacks were used for SD to maximize the chamber capacity.

Moisture control

Moisture content during the drying process was monitored using six samples from six representative boards in each drying batch placed at different heights on each side of the pile. Kiln samples (400 mm long) were obtained from the middle of six representative boards in each lumber stack (Simpson 1991). A 2.5-cm-thick cross-section was removed from each end of kiln samples for MC determination, “Initial Moisture Content” (Figure 1c). The end cross-sections of each kiln sample were sealed with silicon paint to retard longitudinal drying. Two samples were placed 20 cm from the ground, two were placed 15 cm from the top, and the remaining two were positioned 25 cm away from the other samples. The target MC was set to 10% for KD, and the drying was considered complete when the MC reached 12% for AD and SD samples. The SD and AD samples were weighed once a day until the control sample reached constant MC. The KD samples were weighed twice a day.

The MC before drying, referred to as “initial moisture content” (Initial-MC), was measured in two 2.5-cm-thick cross-section extracted from each end (Figure 1c). The Initial-MC was determined by weighing, oven drying at 103°C, and weighing according to ASTM D4442-20 (ASTM 2020). The final moisture content (Final-MC) was determined by removing a 6.0-cm-thick cross-section from each board after drying and following the same procedure (ASTM 2020).

Color evaluation

Wood color was determined on a marked area before drying using 30 pieces randomly selected for each drying method. A MiniScan XE Plus spectrophotometer (Hunter Lab Corporate

Headquarters, VI, USA) was used to obtain color parameters in the CIE $L^* a^* b^*$ color space. The measurement range of the device was from 400 to 700 nm, with a measurement aperture of 11 mm. For the reflection observation, the specular component (SCI mode) was included at a 10° angle, which is normal to the specimen surface (D65/10), with a field of vision of 2° (Standard observer, CIE 1931) and D65 illumination standard (corresponding to daylight at 6500 K). Color was remeasured on the same locations after drying.

The MiniScan XE Plus generated three parameters for each measurement: L^* (luminosity), a^* (color tendency from red to green), and b^* (color tendency from yellow to blue). ΔE^* was calculated from the values of the L^* , a^* , and b^* parameters before and after drying, following the formula outlined in ASTM D2244-23 (ASTM 2023).

Drying defects

Warp (twisting, curvature, bowing, and cupping), cracks, and splits were measured before and after drying following procedures detailed by Moya and Tenorio (2022). All defects were measured using rulers with an accuracy of ± 0.05 mm.

The severity of warping and other drying defects was quantified using Chilean standard NCh993EO72 as described by Pérez et al. (2007), which establishes quality limit values for different parameters. A quality index (QI) was established for each parameter as outlined in equation (1):

$$QI = \frac{(Na * 0) + (Nb * 0,5) + (Nc * 2) + (Nd * 2,5)}{M} \quad (1)$$

Where: QI is the quality index, which can be QI_{Crook} , QI_{Bow} , QI_{Cup} , or QI_{Twist} ; Na is the number of pieces without warp or other defects; Nb is the number of pieces with slight warp or

other defects; Nc is the number of pieces with moderate warp or other defects; Nd is the number of pieces with severe warp or other defects; and M is the total number of pieces.

It is important to note that the magnitude of splits and checks was not measured if the length was shorter than 1 cm. An increase in the QI index indicated a higher severity of drying defects, while a decrease in the QI indicated a reduction in the defects.

Statistical analysis

The average values of Initial-MC, Final-MC, air dry density, color parameters, ΔE^* , and drying defects (warp, split, and crack) were determined for each drying method. The variation of the two MC parameters over time was graphed for each drying method. A one-way ANOVA was applied to the different parameters (Initial-MC, Final-MC, air density, color parameters, ΔE^* , and drying defects of warp, split, and crack) to determine statistical differences between the drying methods. A Tukey modified least significant difference test was used to identify statistical differences at $p < 0.01$ between the averages of each drying method. The statistical software SAS 8.1 for Windows (SAS Institute Inc., Cary, NC, USA) was used for analysis. Each quality index (QI) parameter was analyzed based on the percentage of incidence and the magnitude of severity before and after drying.

Results and discussion

Moisture content and dried density of wood utilized

The Initial-MC of KD balsa wood was lower than that of SD or AD wood. The KD wood also reflected the provenance of the trees (Table 3). The wood used for kiln drying came from a natural regeneration plot, whereas the wood for solar drying and air drying came from fast-growth plantation trees (Table 1).

The differences in wood density and Initial-MC between wood from natural regeneration and fast-growth plantations can be attributed to two main factors. Tree age plays a significant role, with trees from naturally regenerated stands tending to be older (4.5 years old) and containing denser wood than those from fast-growth plantations (Table 1). As trees age, in addition to an increase in diameter, there is variation in the anatomical features across the diameter (Zobel and Van Buitenen 1989). Generally, the diameter of vessels decreases with age, but their frequency increases. Fibers, which are the anatomical tissue with the highest variation, experience an increase in cell wall thickness as the tree ages (Bucur 2016). This results in an increase in specific gravity (SG) or wood density, and a decrease in Initial-MC (Zobel and Van Buitenen 1989).

Table 3. Initial and final moisture content (MC), density at 12% MC and time to the final MC of *Ochroma pyramidale* wood dried using three different methods.

Type of drying	Initial MC (%)	Final MC (%)	Dried density 12 % (g/cm ³)	Time (hours)
Kiln	104.34	10.16	0.23	136.5
Solar	134.64	12.17	0.11	480
Air	134.64	15.11	0.11	1081

The second factor is the growing conditions, which vary between natural forests and fast-growth plantations. Compared to natural forests, conditions in plantation forests are generally more favorable for tree growth, which leads to faster growth and lower density. These trees produce a higher percentage of juvenile wood, which has thinner cell walls, compared to natural forest wood. Decreased wood density, and an increase in voids are also likely to result in a higher Initial-MC (Moya et al. 2025).

Thus, older trees from natural regeneration exhibit higher density due to their greater age. Numerous studies on balsa wood (Moya et al. 2025; Williamson and Wiemann 2010; Wiemann and Williamson 1988; Whitmore 1973; Rueda and Williamson 1992; Baker 2000; Pertiwi et al. 2017, 2022; Listyanto et al. 2021) confirm that density increases with tree age. Baker (2000) concurred that wood from balsa plantations tended to have lower density than that from natural forest trees.

Moisture content variation and time of drying

As expected, the drying time to reach the target final moisture content was shortest with KD (Table 2, Figure 3). The drying time for SD was intermediate between KD and AD, with AD requiring the longest drying time. The highest Final-MC was observed in AD, while SD resulted in an intermediate value for Final-MC (Table 3).

The decreasing of MC with drying time across the three drying methods (Figure 3) are attributed to the degree of control over temperature, relative humidity, and wind speed conditions (Yin and Liu 2021). For KD, drying conditions can be regulated within the chamber and are not dependent on external environmental factors (Elustondo et al. 2023). In contrast, AD is slower due to the effects of environmental conditions, such as temperature, rain events, and relative humidity where the green lumber is stacked (Lingayat et al. 2021). Solar drying exhibited shorter drying times than AD (Figure 3), likely because SD benefits from better control of temperature and relative humidity (Figure 2b). These conditions in SD were driven by solar radiation hitting the collector, which increased

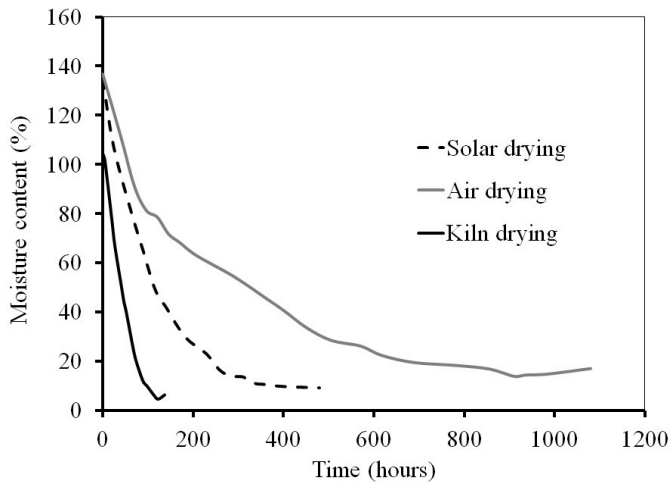


Figure 3. Moisture content variation in *Ochroma pyramidale* lumber during air, solar and kiln drying.

the internal temperature within the chamber (Lamrani et al. 2023; Kamarulzaman et al. 2021).

A key advantage of AD is that the Final-MC tends to be higher than that seen in Costa Rica for other drying methods, such as KD and SD. Air drying can result in EMC values ranging from 13% to 14% (Salas and Moya 2014), which are higher than those for KD and SD. This higher Final-MC likely reflects the low temperatures (below 20°C), rain events and elevated humidity during the drying process (Figure 2b). However, the Final-MC condition in AD may vary depending on the season. In the same region where balsa wood for this study was dried, Salas and Moya (2014) found that balsa wood could be dried to a Final-MC of less than 15% during the dry season, although Final-MC may exceed 16% at other times of the year.

Wood color variation

The color of KD balsa wood differed significantly from that of the AD and SD materials in all three color parameters, with lower values in L^* and b^* , but a higher value in the a^* parameter. In contrast, the SD and AD wood presented similar values for all three parameters (Table 4). The differences between KD and SD or AD can be attributed to the origin of the material and tree age (Table 1).

Wood color variation can be influenced by several factors, including the presence of sapwood and heartwood, tree age, wood origin, growth conditions (natural forest or plantation forest), soil type, and grain pattern (Hu et al. 2020). Thus, the differences in color parameters between KD and AD or SD materials may reflect tree age and wood origin (Table 1). Wood used for KD came from older trees than the wood used for SD and AD and was sourced from naturally regenerated

Table 4. Color variation of *Ochroma pyramidale* lumber before and after air drying, kiln drying, and solar drying.

Drying type	Color parameter before			Color parameter after			ΔE^*
	L^*	a^*	b^*	L^*	a^*	b^*	
Kiln	68.4 ^A	12.8 ^A	28.8 ^A	64.8 ^A	11.4 ^A	26.1 ^A	5.7 ^A
Solar	80.2 ^B	7.1 ^B	26.0 ^B	73.2 ^B	8.1 ^B	24.4 ^A	8.3 ^B
Air	82.6 ^B	5.9 ^B	25.5 ^B	73.8 ^B	6.9 ^B	23.5 ^A	10.2 ^B

Legend: Different letters for each parameter color mean statistical difference at 99% level of confidence.

trees, (Table 1). The aging process of trees tends to reduce the L^* and b^* parameters, while the a^* parameter increases (Bessa et al. 2023), which is consistent with the results observed in this study (Table 4).

Well-managed forest plantations typically offer more favorable growth conditions compared to natural forests (Eddowes 2005; Bredemeir et al. 2015). Higher growth rates generally result in a greater proportion of sapwood, which tends to have a lighter color (Quiñonez-Piñón and Valeo 2018). Additionally, the production of extractives increases with tree age, contributing to a reddish color in the wood (Yang et al. 2024). Therefore, wood from natural forests is generally darker than wood from plantations.

During drying, the wood undergoes color changes, showing decreases in the L^* and b^* parameters, and an increase in the a^* parameter (Keey 2005). This behavior was observed in balsa wood across all three drying methods (Table 4). The variations in color parameters have been attributed to loss of the C=O group, which is linked to the aromatic skeleton of lignin. The C=O group is associated with the L^* and b^* parameters, causing these values to change, while lignin, which is more associated with the a^* parameter, remains in the wood (Zelinka et al. 2022). Consequently, the a^* parameter is relatively consistent across the different drying methods (Table 4).

Color parameters and color change (ΔE^*) after drying followed a similar trend to those before drying. Kiln-dried wood exhibited color parameters that were different from those of wood dried in SD and AD (Table 4). This result supports the premise that dried lumber will experience a color change regardless of the drying method used, and that this change is related to the origin of the wood and tree age (Hu et al. 2020). However, the greatest color change (ΔE^*) was observed in wood dried using KD or sourced from natural regeneration, which likely indicates that older wood and KD wood was more affected by the drying process compared to wood from fast-growing plantations, which maintained a lighter color.

The change in wood from older trees or through KD leads to a lower loss of the C=O group, which was associated with the L* and b* parameters (Zelinka et al. 2022). In contrast, wood from younger trees tends to have a lighter color, and the C=O group is lost during drying, resulting in an increase in lignin. As a result, the L* and b* parameters decrease, but the a* parameter increases, leading to a greater change in color (ΔE^*) (Table 4).

Drying defects

The wet (green) boards had warping (crook, bow, cup, and twist), splitting, or checking before drying. Among the warping defects, cup and twist had the lowest incidence, and, in fact, these defects were absent in both SD and AD materials (Table 5). However, crook and bow, as well as splitting and checking, showed a high incidence, with crook reaching 100% in SD, for example. After drying, an increased warping was observed across all three drying methods (Table 5). Incidence of crook and bow was lower than that of cup and twist, increased with drying.

The effect of drying method on defects was not prominent; the increases in crook and bow were similar across methods. However, cup and twist defects increased more in SD and AD

compared to KD (Table 5). Incidence of splits and checks was lower than that of warping defects, and in fact, the incidence of the splits either remained the same or decreased in AD (Table 5).

Cupping and twisting were present at low levels before drying (Table 5). Warping was present after drying, with the greatest change in the magnitude of the four drying defects occurring with KD. Crook, bow, and cup defects had the smallest increases in magnitude in SD and AD, but twisting saw the greatest increase in magnitude in comparison to KD (Table 5). As noted, the magnitude of split and check defects was not measured.

Warping defects (crook, bow, cup, and twist) before drying, assessed with the Quality Indices (QI), varied across the different drying methods. The QI for crook (QI_{Crook}), QI for bow (QI_{Bow}), and cup (QI_{Cup}) were lowest in KD compared to AD or SD (Figure 4a-c). QI_{Crook} and QI_{Twist} both increased across all three drying methods tested (Figure 4a,d), indicating a decrease in wood quality. In contrast, the QI_{Bow} and QI_{Cup} decreased in KD, suggesting a slight improvement in wood quality, while they increased in SD and AD wood, reflecting a decrease in quality (Figure 4b-c).

Table 5. Incidence and magnitude for different defects before and after kiln, solar, and air drying of *Ochroma pyramidale* lumber.

Type	Parameter	Time	Drying defect					
			Crook	Bow	Cup	Twist	Split	Check
Kiln	Incidence (%)	Before	41.7	86.1	19.4	38.9	33.4	38.9
		After	91.7	91.7	27.22	100	16.7	41.7
		Change	↑ 50.0	↑ 5.6	↑ 7.82	↑ 61.1	↓ 16.7	↑ 2.8
	Magnitude (mm)	Before	2.4	3.4	1.7	2.8	*	*
		After	4.0	2.7	14.5	14.0	*	*
		Change	↑ 50	↑ 5.6	↑ 12.8	↑ 11.2		
Solar	Incidence (%)	Before	100	36.7	0.0	0.0	40.0	36.7
		After	100	43.4	53.4	90.0	43.4	43.4
		Change	↑ 50	↑ 5.6	↑ 53.4	↑ 90	↑ 3.4	↑ 6.7
	Magnitude (mm)	Before	4.4	1.9	0.0	0.0	*	*
		After	4.5	1.9	1.7	21.7	*	*
		Change	↑ 50	↑ 5.6	= 1.7	= 21.7		
Air	Incidence (%)	Before	83.3	26.7	0.0	0.0	36.7	33.4
		After	96.7	56.7	36.7	93.4	36.7	30
		Change	↑ 50	↑ 30.0	↑ 36.7	↑ 93.4	= 0	↓ 3.4
	Magnitude (mm)	Before	4.6	2.6	0.0	0.0	*	*
		After	4.8	2.9	1.6	22.4	*	*
		Change	↑ 0.2	↑ 0.3	↑ 1.6	↑ 22.4		

Legend: * split and check magnitudes were not measured. ↑ : drying defects increased after drying; ↓ drying defects decreased after drying; and = drying defects was similar before and after drying.

The increases in incidence, magnitude, or QI of defects after drying (Figure 4, Table 5) can be attributed to shrinkage within the boards due to the presence of juvenile wood (Elustondo et al. 2023; Tomad et al. 2023), growth stresses (Moya et al. 2025), and internal stresses produced during the drying process (Elustondo et al. 2023; Tomad et al. 2023; Srisuchart et al. 2023). These three factors are likely the main causes of warping in wood after drying. Juvenile wood in the balsa trees sampled in this study (Table 1), is characterized by a higher microfibril angle in the S2 wall. This type of wood is more prone to warping and splitting, both during sawing and drying processes (Elustondo et al. 2023; Tomad et al. 2023). As trees age, the microfibril angle of newly formed wood on the exterior decreases, but the core wood remains more prone to different shrinkage rates, resulting in warping, splitting, or checking in dried lumber (Tenorio et al. 2012; Moya et al. 2025).

Growth stresses in balsa wood, as in other fast-growing species, are caused by mechanical stress in the xylem tissue during growth, and these stresses tend to be more intense in young trees (Kojima et al. 2009; Gril et al. 2017). These stresses result

from the maturation of the cell wall and the increase in canopy load on the stem (Jarvis 2024). The deformation of fibers in axial and transversal directions during the maturation process leads to mechanical stress at the outermost surface of the secondary xylem, just beneath the layer of differentiating xylem (Gril et al. 2017; Thibaut and Gril 2021). Growth stresses in balsa logs are released when the trunk is sawn and manifest in the lumber through warping (crook, bow, and twist), split, and check (Entwistle et al. 2012), as observed in the lumber (Figure 4). Residual growth stresses are further released during drying, causing an increase in distortions such as warping, splitting, and cracking in the lumber (Elustondo et al. 2023; Tomad et al. 2023).

Another cause of distortion in balsa lumber can be attributed to stress tensions during drying. Lumber does not dry uniformly throughout its thickness, as the outer layers dry faster than the inner layers. This discrepancy causes internal stress tensions that can lead to warping, splitting, or cracking, and particularly cup defects (Moya et al. 2017; Tomad et al. 2023; Srisuchart et al. 2023).

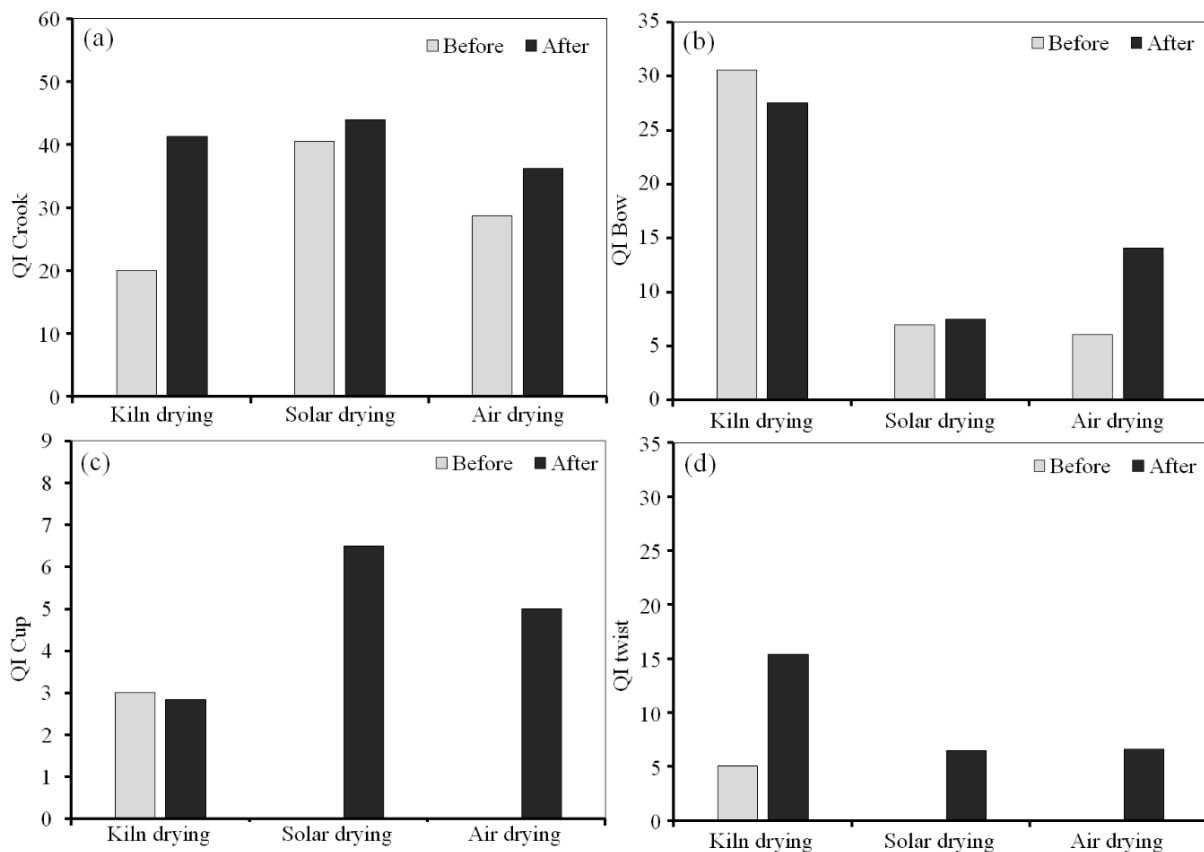


Figure 4. Quality indices of *Ochroma pyramidale* lumber before and after kiln drying.

Cupping was absent, and twist had low incidence prior to drying (Table 5). These defects are linked to the dimensions of the boards (Bond and Espinoza 2016). In the case of cup, narrower boards, like those in this study (less than 10 cm), do not show cupping before drying. However, cupping becomes more pronounced after drying. These results align with findings in other tropical woods from fast-growing forest plantations in Costa Rica (Boone et al. 1988; Tenorio et al. 2012; Salas and Moya 2014; Moya et al. 2017; Moya and Tenorio 2022). Cupping increases after drying due to differences in shrinkage between the two faces of the boards (Bond and Espinoza 2016), which are not present in the green condition. Twist results from longitudinal shrinkage of the board (Bond and Espinoza 2016), and the curvature of the growth ring greatly impacts this defect after drying (Straze et al. 2011). However, the boards used in this study were less than 1.3 m in length and had few growth rings (1-2 per thickness), resulting in less twist. In contrast, twist defects would be more pronounced in longer boards (Bond and Espinoza 2016; Straze et al. 2011). The greatest increase in cup and twist defects in balsa wood (Table 5, Figure 4) was likely due to the influence of juvenile wood, growth stresses in young trees, and internal stress tensions during drying—factors that strongly contribute to the development of drying defects (Tomad et al. 2023; Srisuchart et al. 2023).

Splitting and cracking are also caused by growth stresses in standing trees (Gril et al. 2017), and these stresses are more prominent in wood from fast-growing plantations (Kojima et al. 2009). The high incidence of growth stresses before drying (Table 5) clearly indicated that the balsa trees had a significant amount of internal stress. Splitting and cracking increased after drying, although the levels were lower than those of other defects in dried lumber. This slight increase can be explained by the relatively low variation in temperature observed across different drying methods. These defects tend to develop when there is significant variation in the surface temperature of the boards (Bond and Espinoza 2016). Kiln-dried wood exhibited the greatest temperature fluctuations, whereas SD and AD wood showed more consistent temperatures (Figure 2b), which minimized the development of splitting and cracking (Table 2).

Different drying methods produced distinct effects on the presence of warping, splitting, and checking in balsa wood (Table 5, Figure 3). Kiln-dried wood exhibited the highest incidence and magnitude of defects. Air-dried wood, on the other hand, had the least defects, and SD wood exhibited intermediate values between that of KD and AD. According to Youngs (Youngs 1997), tensions generated during drying are more pronounced

in KD because it is a short-term method with drastic changes in temperature and relative humidity inside the chamber. This behavior has also been observed in other tropical woods from natural forests (De Souza-Mendes et al. 1995) or fast-growing plantations, where twisting, cupping, and splitting were the drying defects most easily induced by KD (Moya et al. 2013).

An important distinction was that KD lumber showed different values for crook and bow compared to SD and AD, but these differences may also reflect either tree age or the different growing site (Table 1). This resulted in differences in QI values, incidence percentages, and the magnitude of drying defects.

Meanwhile, SD presented intermediate values for incidence, magnitude, and QI (Table 5, Figure 4). Intermediate temperatures and relative humidities in the solar chamber were maintained, with cyclic variations throughout the day (Figure 2b), as well as a constant air speed, which could have contributed to defect formation (Lamrani et al. 2023). However, the severity of defects in SD was lower than that in KD (Lamrani et al. 2023; Kumar et al. 2023). SD reached higher temperatures and wind speeds than AD, leading to more defects that were more severe (Elustondo et al. 2023). The slower drying process in AD allowed for the gradual release of wood stresses (Yin and Liu 2021).

Conclusion

As expected, KD had the shortest drying time, followed by SD and finally AD. The evaluation of the color and drying defects of balsa wood revealed that KD resulted in the greatest color changes and produced the highest incidence percentages, magnitude values, and changes in QI for various drying defects. Warping defects (crook, bow, cup, and twist), as well as splitting and cracking, were present after the sawing process and became more pronounced after drying. Crook and bow showed the greatest increase in intensity after drying, regardless of the drying method, followed by twisting, while the cupping, splitting, and cracking exhibited the least intensity increase.

Air drying presented the best drying quality, with the fewer defects, but it had the disadvantage of the longest drying time. Solar drying produced similar values for defects (incidence, magnitude, and QI) to AD, but with shorter drying times. Kiln-drying, on the other hand, resulted in the greatest changes in wood quality and a higher incidence of defects. Kiln-drying can be used to dry lumber in the shortest possible time, but this comes with higher costs and a greater number of defects. For the best wood quality, AD and SD are more favorable, offering superior results, albeit with longer drying times.

References

- ASTM-American Society for Testing and Materials (2020) Standard test methods for direct moisture content measurement of wood and wood-base materials. ASTM D4442-20. ASTM: West Conshohocken, PA, USA. <https://doi.org/10.1520/D4442-20>
- ASTM-American Society for Testing and Materials (2023) Standard practice for calculation of color tolerances and color differences from instrumentally measured color coordinates; ASTM D2244-23. ASTM: West Conshohocken, PA, USA. <https://doi.org/10.1520/D4442-20>
- Baker DC (2000) Wood density patterns of young Costa Rican trees in planted and natural forests. Thesis of Master and Science. Oregon State University. Oregon, USA. 161 p.
- Bessa F, Sousa V, Quilhó T, Pereira H (2023) Diversity of wood colour in tropical timber species and its relationship with wood density and anatomical features. *IAWA J* 45(3):335–357. doi: 10.1163/22941932-bja10148
- Bredemeier M, Busch G, Hartmann L, Jansen M, Richter F, Lamersdorf NP (2015) Fast growing plantations for wood production—integration of ecological effects and economic perspectives. *Front Bioeng Biotechnol* 3:72. doi: 10.3389/fbioe.2015.00072
- Bond BH, Espinoza O (2016) A Decade of improved lumber drying technology. *Curr Forestry Rep* 2:106–118. doi: 10.1007/s40725-016-0034-z
- Boone RS, Kozlik CJ, Bois PJ, Wengert EM (1988) Dry kiln schedules for commercial woods: temperate and tropical. FPL–GTR–57. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 158 p.
- Borrega M, Ahvenainen P, Serimaa R, Gibson L (2015) Composition and structure of balsa (*Ochroma pyramidale*) wood. *Wood Sci Technol* 49:403–420. doi: 10.1007/s00226-015-0700-5
- Bucur V (2016) Ageing of Wood. In: Bucur V (eds) *Handbook of Materials for String Musical Instruments*. Springer, Cham, Springer International Publishing Switzerland. doi: 10.1007/978-3-319-32080-9_7
- Business Research Insights (2024) Balsa wood market size, share, growth, and industry analysis by type (grain A, grain B, and grain C) By Application (Aerospace & defense, marine, road & rail, and industrial construction), Regional Forecast To 2031. Accessed 28 May 2024. <https://www.businessresearchinsights.com/market-reports/balsa-wood-market-100512>
- Condoy VGS, Chuchuca IPB, Romero KHP (2023) Análisis de las exportaciones de madera de balsas y su influencia en ámbitos económico-ambiental. *Polo del Conocimiento: Rev Cient-Prof* 8(11):1275–1302.
- CIRAD (2024) Balsa. In: Tropix 5.0. CIRAD: Paris. Accessed 15 January 2025. <http://www.cirad.fr/en/index.php>
- De Souza-Mendes A, Simpson WT, Verrill SP (1995) Laboratory test for grouping tropical species for kiln drying. *Wood Sci Technol* 29:353–362. doi: 10.1007/BF00202583
- Elustondo D, Matan N, Langrish T, Pang S (2023) Advances in wood drying research and development. *Drying Tech* 41(6):890–914. doi: 10.1080/07373937.2023.2205530
- Eddowes PJ (2005) Balsawood. In: Solomon Islands Timber. Solomon Islands Forestry Management Project: Honiara, Solomon Islands. Accessed 2 January 2025. <http://www.solomon-timbers.com.sb/altHome/brochures/Balsawood.pdf>
- Entwistle K, Chauhan S, Sharma M, Walker J (2012) The effect of saw kerf width on the value of the axial growth stress measured by slitting a log along its axis. *Wood Mater Sci Eng* 11:1–12. doi: 10.1080/17480272.2014.929176
- Francis JK (2000) *Ochroma pyramidale* Cav. balsa. In: Francis JK, Lowe CA (eds) *Silvics of Native and Exotic Trees of Puerto Rico and the Caribbean Islands*. General Technical Report IITF-GTR-15 U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry, Río Piedras, pp 371–376. <https://www.fs.usda.gov/research/treesearch/2862#>
- Galos J, Das R, Sutcliae MP, Mouritz AP (2022) Review of balsa core sandwich composite structures. *Mater Des* 221:111013. doi: 10.1016/j.matdes.2022.111013
- Guevara L (1996) Comportamiento al secado natural de cuatro especies maderables de bosques secundarios. *Folia Amazónica* 8(1):79–90
- Gril J, Jullien D, Bardet S, Yamamoto H (2017) Tree growth stress and related problems. *J Wood Sci* 63:411–432. doi: 10.1007/s10086-017-1639-y
- Hu J, Liu Y, Wu Z (2020) Structural color for wood coloring: A Review. *BioRes* 15(4):9917. doi: 10.15376/biores.15.4
- Jarvis MC (2024) Forces on and in the cell walls of living plants. *Plant Physiol* 194(1):8–14. doi: 10.1093/plphys/kiad387
- Jenkin B, Minimulu J, Kanowski P (2019) Improving the smallholder balsa value chain in East New Britain Province, Papua New Guinea. *Aust For* 82(sup1):23–31. doi: 10.1080/00049158.2018.1537541
- Kamarulzaman A, Hasanuzzaman M, Rahim NA (2021) Global advancement of solar drying technologies and its future prospects: A review. *Sol Energy* 221:559–582. doi: 10.1016/j.solener.2021.04.056
- Key RB (2005) Colour development on drying. *Maderas Cienc Tecnol* 7(1):03–16. doi: 10.4067/S0718-221X2005000100001
- Kojima M, Yamamoto H, Okumura K, et al (2009) Effect of the lateral growth rate on wood properties in fast-growing hardwood species. *J Wood Sci* 55:417–424. doi: 10.1007/s10086-009-1057-x
- Kumar B, Raj AK, Szepesi G, Szamosi Z (2023) A conspectus review on solar drying of wood: regional and technical contrivances. *J Therm Anal Calorim* 148(17):9237–9261. doi: 10.1007/s10973-023-12093-5
- Lamrani B, Bekkioui N, Simo-Tagne M, Ndukwu MC (2023) Recent progress in solar wood drying: An updated review. *Drying Technol* 41(5):605–627. doi: 10.1080/07373937.2022.2112048
- Lingayat A, Balijepalli R, Chandramohan VP (2021) Applications of solar energy based drying technologies in various industries—A review. *Sol Energy* 229:52–68. doi: 10.1016/j.solener.2021.05.058
- Listyanto T, Poedyastanto EPF, Abqoriah SM, Lukmandaru G (2021) Specific gravity, extractive content, and natural durability of balsa (*Ochroma pyramidale*) wood at 3 and 4 years old. *IOP Conf Ser: Earth Environ Sci* 891:012013. doi: 10.1088/1755-1315/891/1/012013
- Midgley S, Blyth M, Howcroft N, Midgley D, Brown A (2010) Balsa: biology, production and economics in Papua New Guinea. *ACIAR Technical Reports No. 73*. Australian Centre for International Agricultural Research, Canberra, 98 pp. https://www.aciar.gov.au/sites/default/files/legacy/node/12685/balsa_biology_production_and_economics_in_papua_40057.pdf
- Moya R, Muñoz F (2008) Wet pockets in kiln-dried *Gmelina arborea* lumber. *J Trop For Sci* 22(3):317–328
- Moya R, Ureña E, Salas C, Muñoz F, Espinosa O (2013) Kiln drying behavior of lumber from ten fast-growth plantation species in Costa Rica. *Wood Mater Sci Eng* 8:37–45. doi: 10.1080/17480272.2012.707686
- Moya R, Berrocal A, Rodríguez-Solis M, Muñoz F (2017) Effect of steam-drying treatment on moisture content, drying rate, color, and drying defects in juvenile wood of *Tectona grandis* from fast-growth plantations. *Drying Technol* 35(15):1832–1842. doi: 10.1080/07373937.2017.1280503
- Moya R, Tenorio C (2022) Application of the steaming step during kiln drying of lumber of two tropical species with high growth stress presence. *Drying Technol* 40(15):3231–3240. doi: 10.1080/07373937.2021.2017299
- Moya R, Tenorio C, Villalobos-Barquero V, Meza-Montoya (2025) Variation of physical wood properties and effect of dasometric variables in *Ochroma pyramidale* trees growing in plantation. *Heliyon* 11(1):e41210. doi: 10.1016/j.heliyon.2024.e41210
- Pérez P, Ananías RA, Hernández G (2007) Estudio experimental del secado de renovales de canelo *Drimys winteri*. *Maderas Cienc Tecnol* 9:59–70.
- Pertiwi YAB, Ishiguri F, Nezu I, Aiso H, Hiraoka Y, Marsoem SN, Ohshima J (2022) Evaluation of xylem maturation process and effects of radial growth rate on cell morphologies in wood of balsa (*Ochroma pyramidale*) trees. *Wood Fiber Sci* 54(2):149–159. doi: 10.22382/wfs-2022-15
- Pertiwi YAB, Ishiguri F, Aiso H, Ohshima J, Yokota S (2017) Wood properties of 7-year-old balsa (*Ochroma pyramidale*) planted in East Java. *Inter Wood Prod J* 8(4):227–232. doi: 10.1080/20426445.2017.1394560

- Quiñonez-Piñón MR, Valeo C (2018) Assessing the translucence and color-change methods for estimating sapwood depth in three boreal species. *Forests* 9(11):686. doi: 10.3390/f9110686
- Rueda R, Williamson GB (1992) Radial and vertical wood specific gravity in *Ochroma pyramidale* (Cav. ex Lam.) Urb. (Bombacaceae). *Biotropica* 24(2):512–518. doi: 10.2307/2389013
- Salas C, Moya R (2014) Kiln-, solar-, and air-drying behavior of lumber of *Tectona grandis* and *Gmelina arborea* from fast-grown plantations: Moisture content, wood color, and drying defects. *Drying Technol* 32(3):301–310. doi: 10.1080/07373937.2013.829087
- Simpson, W (1991) Properties of wood related to drying. In *Dry Kiln Operator's Manual Handbook AH-188*, Simpson, WT, ed.; USDA Forest Service, Forest Products Laboratory: Madison, WI: 1–42.
- Srisuchart K, Tomad J, Leelatanon S, Jantawee S, Matan N (2023) Internal stress development within wood during drying: A master curve concept and its application on drying stress evaluation. *Drying Technol* 41(15):2516–2532. doi: 10.1080/07373937.2023.2259467
- Straze A, Kliger R, Johansson M, Goriek Z (2011) The influence of material properties on the amount of twist of spruce wood during kiln drying. *Eur J Wood Wood Prod* 69:239–246. doi: 10.1007/s00107-010-0422-1
- Teischinger A, Avramidis S, Hansmann C, Mayrhofer A (2023) Sawn Timber Steaming and Drying. In: Niemz P, Teischinger A, Sandberg D (eds) *Springer Handbook of Wood Science and Technology*. Springer Handbooks, Springer, Cham. doi: 10.1007/978-3-030-81315-4_23
- Tenorio C, Moya R, Salas C (2016) Kiln drying behavior utilizing drying rate of lumber from six fast-growth plantation species in Costa Rica. *Drying Technol* 34(4):443–453. doi: 10.1080/07373937.2015.1060493
- Tenorio C, Moya R, Quesada-Pineda H (2012) Kiln drying of *Acacia mangium* wood: colour, shrinkage, warp, split and check in lumber before and after drying. *J Trop For Sci* 24:125–139.
- Thibaut B, Gril J (2021) Tree growth forces and wood properties. *Peer Community J* 1:e446. doi: 10.24072/pcjournal.48
- Thybring EE, Fredriksson M, Zelinka SL, Glass SV (2022) Water in wood: A review of current understanding and knowledge gaps. *Forests* 13(12):2051. doi: 10.3390/f13122051
- Tomad J, Leelatanon S, Jantawee S, Srisuchart K, Matan N (2023) Internal stress development within wood during drying: regime and kinetics. *Drying Technol* 41(1):77–88. doi: 10.1080/07373937.2022.2084750
- Utia KY (2012) Secado al natural en métodos de apilado en triangulo y caballete de la especie forestal Topa (*Ochroma pyramidale* (Cav. Ex Lam) Urban). Tesis Ing en Recursos Naturales Renovables Mención: Forestales, Universidad Nacional Agraria de la Selva, Tingo María, Perú.
- Wiemann MC, Williamson GB (1988) Extreme radial changes in wood specific gravity in some tropical pioneers. *Wood Fiber Sci* 20(3):344–349.
- Williamson GB, Wiemann MC (2010) Age-Dependent Radial Increases in Wood Specific Gravity of Tropical Pioneers in Costa Rica. *Biotropica* 42(5):590–597. doi: 10.1111/j.1744-7429.2009.00618.x
- Whitmore JL (1973) Wood density variation in Costa Rican Balsa. *Wood Sci* 5:223–229.
- Yang H, Huang X, Gu Y, et al (2024) Influence of tree age on the wood color and compounds involved in the “golden-thread” wood color formation in *Phoebe zhenan*. *Ind Crops Prod* 221:119406. doi: 10.1016/j.indcrop.2024.119406
- Yin Q, Liu HH (2021) Drying stress and strain of wood: A Review. *Appl Sci* 11(11):5023. doi: 10.3390/app11115023
- Youngs RL (1997) Present methods of drying and conditioning wood for use. *Economy Botany* 21:46–50. doi: 10.1007/BF02897174
- Zelinka SL, Altgen M, Emmerich L, Guigo N, Keplinger T, Kymäläinen M, Thybring EE, Thygesen LG (2022) Review of wood modification and wood functionalization technologies. *Forests* 13(7):1004. doi: 10.3390/f13071004
- Zobel BJ, Van Buitenen JP (1989) Wood variation and wood properties. In: *Wood Variation*. Springer Series in Wood Science. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-74069-5_1