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Moisture content variability in kiln-dried *Gmelina arborea* wood: effect of radial position and anatomical features

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Abstract *Gmelina arborea* is one of the most important species for plantation in tropical areas. However, high variability in final moisture content (MC_f) is a problem in the drying process. This study sought to determine the variability in MC_f in relation to distance from the pith (DP), and anatomic elements. Boards of 1.2 cm in thickness obtained from bark to the pith from 15-year-old plantation trees were dried in a pilot kiln. Anatomical characteristics, initial moisture content (MC_i), and specific gravity (SG) were also determined. Pearson correlation matrix was conducted between MC_f and the other variables. DP, fiber length, and ray width were correlated negatively with MC_f, while fiber diameter was positively correlated. Other studied anatomical properties showed no statistical correlations. Other wood properties such as SG and MC_i showed some influence on MC_f. DP can be considered as a good practical predictor for MC_f in *G. arborea* because some wood properties are related to MC_f. However, other wood characteristics that are not related with DP also influence MC_f, such as the presence of sapwood, MC_i variation between and within trees, fiber diameter, and ray width. These results suggest that MC_f variation in *G. arborea* is difficult to determine.

Key words Fast-growth plantations · Kiln drying · Lumber · Anatomical variation

Introduction

Gmelina arborea (Melina) is the most important reforestation species in Costa Rica and is one of the most important species for plantation in tropical areas.[1] The wood industrialization sector has been based on the commercialization of this species, which implies a variety of industrial processes and techniques to provide a higher added value to forest products.[2] Drying is one of the important processes in wood industrialization, which helps to improve properties such as the dimensional stability, coating and adhesive compatibility, and mechanical properties. In addition, drying improves the wood workability and the thermal, acoustic, and electrical properties, as well as resistance to biodegradation.

Inconsistency is known to occur in drying of *G. arborea* wood and drying kiln operators have mentioned great differences in the final moisture gradient. On the other hand, Lauridsen and Kjaer[3] mentioned that *G. arborea* wood is slow drying. However, some research has demonstrated that the variation in final moisture content, the number of drying defects, and the drying time can be reduced with appropriate drying schedules.[4] Literature reports suggest that the variations in the final moisture content are not only related to drying schedules but also to kiln characteristics and design, as well as to the wood anatomical structure.[5,6] The presence of sapwood, vessel and fiber lumens, wall fiber, and pits are the main anatomical features that influence water flow during drying.[5] Moreover, these features also influence the final moisture content of dried wood.

The present study deals with the final moisture content (MC_f) variability in *G arborea* wood coming from fast-growing plantation trees and its relationship with initial moisture content (MC_i), distance from the pith (DP), specific gravity (SG), and anatomical features.

Materials and methods

This study was carried out at Centro de Investigación en Integración Bosque Industria (CIIBI) of Instituto Tecnológico de Costa Rica (ITCR). The material was collected from a 15-year-old *Gmelina arborea* plantation, with a site index (SI) of 27.0 m (dominant height at the age of 15) located in Puriscal, San José, Costa Rica (9° 52′ 47″ N, 84° 23′ 49″ W) at 400 m asl and corresponding to tropical wet forest.[7]

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Table 1. Diameter, height, and moisture content of *Gmelina arborea* sampled trees

Tree no.	Diameter at breast height (cm)	Total height (m)	MC_i (%)	MC_f (%)
1	28.2	19.5	168	6.5
2	26.0	18.8	144	6.7
3	30.8	20.6	184	8.3
4	35.2	22.0	182	8.5

MC_i, average initial moisture content obtained from green lumber; MC_f, average final moisture content obtained from dried lumber

The plantation was established under 3 × 3 m spacing; thinning was carried out at 4, 8, and 12 years, following the typical management applied to *G. arborea* plantations with a site index between 25 and 32 in Costa Rica.[2] Four trees were randomly selected (Table 1), and one stump log (2.5 m long) was collected from each tree. The four logs were sawn, obtaining one diametrical block (7.5 cm width) and then resawn to obtain 1.2-cm-thick samples tangential to the growth rings in the bark–pith direction. A total of 39 boards were taken from four trees (9 from tree 1, 9 from tree 2, 10 from tree 3, and 11 from tree 4). From each board (1.2 cm thick, 7.5 cm wide, 250 cm long), a 50-cm-long sample for kiln drying was taken from the central part of the board. The ends of these samples were cut to obtain two small samples, measuring 1.2 cm thick, 7.5 cm wide, and 2.5 cm long, and the SG was calculated according to ASTM D-143.[8] All the boards were maintained in plastic bags until they were piled in the kiln.

The SG was calculated as oven-dry weight (24 h at 105°C until constant weight) divided by green volume. Another smaller piece (1.0 cm wide, 1.2 cm thick) was used for anatomical studies. Using Franklin's method, macerations were prepared using glacial acetic acid and hydrogen peroxide (1:1, v/v) to determine the fiber dimensions. Permanent slides were prepared following the methodology proposed by Johansen[9] and Sass.[10] The anatomical elements were evaluated using an Olympus light microscope and a digital camera; images were analyzed with the Image Tool software. The measurements of anatomical elements were repeated 25 times.[11] The measurements included fiber length (FL), fiber diameter (FØ), lumen diameter (LØ), cell-wall thickness (CW) obtained by subtracting LØ from FØ, vessel tangential diameter (VTØ), vessel frequency (VF) in vessels per square millimeter, ray frequency (RF) in rays per millimeter, ray height (RH), cells in ray height (CRH), ray width (RW), and cells in ray width (CRW). All properties were evaluated following standard IAWA procedures.[11] A Nardi pilot kiln with dimensions of 1.4 m high, 1.0 m wide, and 2.5 m long was used for the drying process, following a drying schedule of high temperatures and high relative humidity at the beginning of the drying process, frequently used by wood industries in Costa Rica (Table 2). The drying ended when the MC reached 8.0%, which in the present study required a total drying time of 12 days. The weight variations of 39 kiln samples were controlled on a daily basis to calculate the reduction in moisture content. Average moisture content of these kiln samples were used as reference to make changes to both temperature and relative humidity inside the kiln. MC_i was determined before drying and MC_f after drying, using Eqs. 1 and 2. MC_f variability and its correlation with MC_i, DP, SG, and anatomical properties were analyzed using Pearson's correlation matrix and linear regression.[12]

Table 2. Kiln schedule applied for drying *G. arborea* boards

Step	MC of wood (%)	EMC (%)	DBT (°C)	RH (%)
1	Above 50	19	70	96
2	50–48	18	72	94
3	48–42	17	73	92
4	42–39	16	75	90
5	39–35	15	76	88
6	35–30	14	77	86
7	30–25	13	78	84
8	25–20	12	80	81
9	20–18	11	83	78
10	18–16	10	85	74
11	16–14	9	86	70
12	14–12	8	87	66
13	12–10	7	88	60
14	10–8	6	89	53

MC, moisture content of wood; EMC, equilibrium moisture content; DBT, dry-bulb temperature; RH, relative humidity

$$MC_i = \frac{\text{green weight} - \text{oven-dry weight}}{\text{oven-dry weight}} \quad (1)$$

$$MC_f = \frac{\text{weight (day12)} - \text{oven-dry weight}}{\text{oven-dry weight}} \quad (2)$$

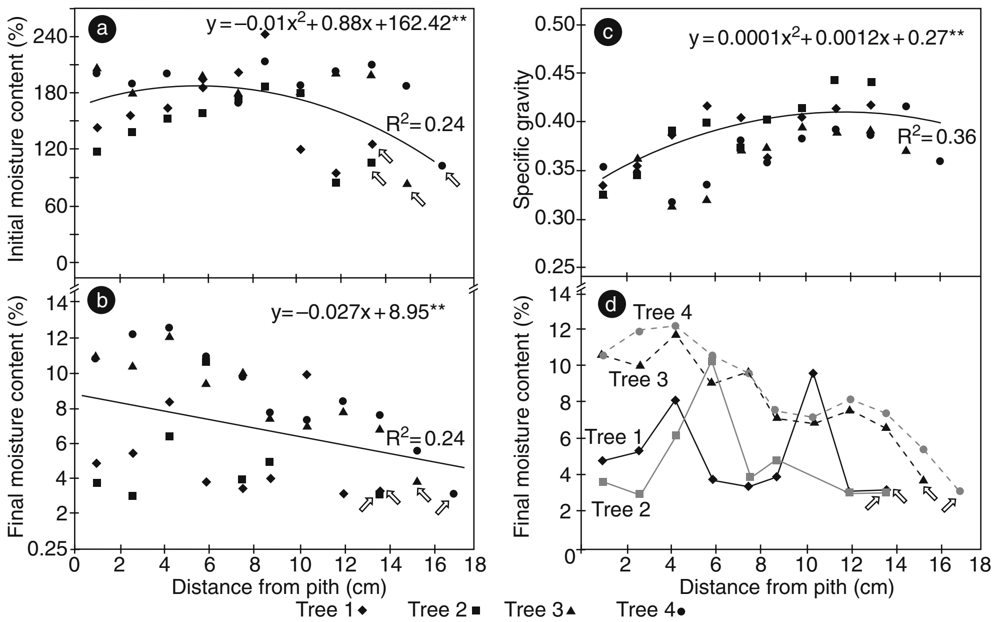
The oven-dry weight was obtained by setting the kiln samples to a temperature of 105°C during 24 h.

Results and discussion

The average MC_i was 170% for all trees but it varied between 144% and 184% (Table 1). Furthermore, it was found that MC_i varied from pith to bark (Fig. 1a). The highest values were found around 8.0 cm from the pith and the lowest near the bark in three of the four trees sampled. On the other hand, a reduction in moisture was observed in the zone near the bark, where sapwood was present. The boards with sapwood in trees 3 and 4 and the last two boards had the lowest values of MC_i in each tree (Fig. 1a). Although the sapwood boards in trees 1 and 2 did not have the lowest values of MCi, the boards near these probably had high sapwood proportions, resulting in the lowest MC for these trees. According to Ohbayashi and Shiokura,[13] the juvenile wood in *Gmelina arborea* can be identified at 4.0–9.0 cm from the pith, after which the mature wood begins to appear. The inflection that occurred in MC_i at 8.0 cm can be influenced by a transitional stage from juvenile to mature wood. Similar behavior of MC_i with DP was found in four trees. Trees with greater diameters (trees 3 and 4) showed on average 20% higher MC_i than the trees with smaller diameters (trees 1 and 2; Table 1).

The decrease of MC_i from pith to bark in wood from planted *G. arborea* trees has also been reported in other forest species such as *Cedrela odorata*, *Acacia mangium*,

Fig. 1a–d. Variation of **a** initial moisture content, **b, d** final moisture content, and **c** specific gravity with distance from pith in four *Gmelina arborea* trees. *Arrows* show sapwood samples



and *Acacia auriculiformis*.[14,15] High MC_i near the pith can be attributed to the presence of juvenile wood with high moisture content, because vessel frequency is high in this part of the tree. The lowest values of moisture content in sapwood can be attributed to the effect of large vessels and low frequency.[13] This behavior is considered to be normal for many fast-growing species; however, it depends on the growing conditions, age, and tree dimensions.[16]

The MC_f averaged 7.50%, varying between 6.5% and 8.5%. Wood near the pith had the highest MC_f, while wood near the bark showed the lowest values (Fig. 1b). It was also found that trees with small diameter and low MC_i values had a low MC_f, while trees with large diameter and high MC_i values had a high MC_f (Table 1).

A different tendency was found for each tree. A decrease of MC_f from pith to bark was found in trees 3 and 4, while no specific tendency for MC_f was found in trees 1 and 2. There were sharp increments in MC_f for tree 1 at 4 and 10 cm from the pith, and for tree 2 at 6 cm from pith (Fig. 1d). Moya and Muñoz[17] have shown that dried lumber from G. arborea heartwood contains wet pockets, which are zones with higher MC than the rest of the cross section. The average MC of dried lumber with wet pockets was 3% to 15% higher than dried lumber at 12% MC. Although we did not determine or observe wet pockets in trees 1 and 2, these may explain the sharp increments in MC_f at 4 and 10 cm from the pith for tree 1 and at 6 cm from the pith for tree 2. However, other factors can affect water flow during drying, such as sampling wood near a knot or differences in air circulation in the kiln. The real effects of these factors on MC_f were not determined in this study.

On the other hand, the lumber near the pith of trees 1 and 2 presented the lowest values of MC_i (Fig. 1a), in spite of having SG similar to the rest of the trees (Fig. 1c). However, boards from trees 1 and 2 reached the lowest values of MC_f (Fig. 1b). Boards from these trees were probably overdried because of temperature changes in kiln schedules (steps) that are controlled by the average moisture content of kiln samples.

Table 3. Pearson's matrix correlation for final moisture content and anatomical properties ($n = 39$)

	DP	MC_i	MC_f	SG
MC_i	–0.37*	1	0.50**	–0.32*
MC_f	–0.49*	0.50**	1	–0.46**
SG	0.55**	–0.32*	–0.46**	1
FL	0.49**	–0.46**	–0.46**	0.73**
FØ	–	–	0.65**	–0.37*
LØ	–	–	0.62**	–0.35*
CW	0.42**	–	–	0.49**
VTØ	0.67**	–	–	0.46**
VF	–0.57**	–	–	–
RF	–0.47**	–	–	–
RH	–	–	–	–
RW	–	–0.44**	–0.52**	0.40*
CRH	–	–	–	–
CRW	–	–	–	–

DP, distance from the pith; SG, specific gravity; FL, fiber length; FØ, fiber diameter; LØ, lumen diameter; CW, cell-wall thickness; VTØ, vessel tangential diameter; VF, vessel frequency; RF, ray frequency; RH, ray height; RW, ray width; CRH, number of cells in ray height; CRW, number of cells in ray width
* $P < 0.05$; ** $P < 0.01$

Both MC_i and MC_f showed a statistical negative correlation with DP (Table 3). Boards with sapwood had on average lower values of MC_f than boards with heartwood (Fig. 1b), probably caused by the lower MC_i at the beginning of the drying process (Fig. 1a) and easier water flow through vessels of sapwood because tyloses were not present.[18]

SG, FL, FØ, LØ, and RW showed significant statistical correlations ($P < 0.01$) with MC_f (Table 3), while CW, VTØ, VF, RF, RH, CRH, and CRW showed no significant correlation with MC_f. The increment in FL, RW, and SG decreased MC_f (Fig. 2a–c), while the increment in LØ and

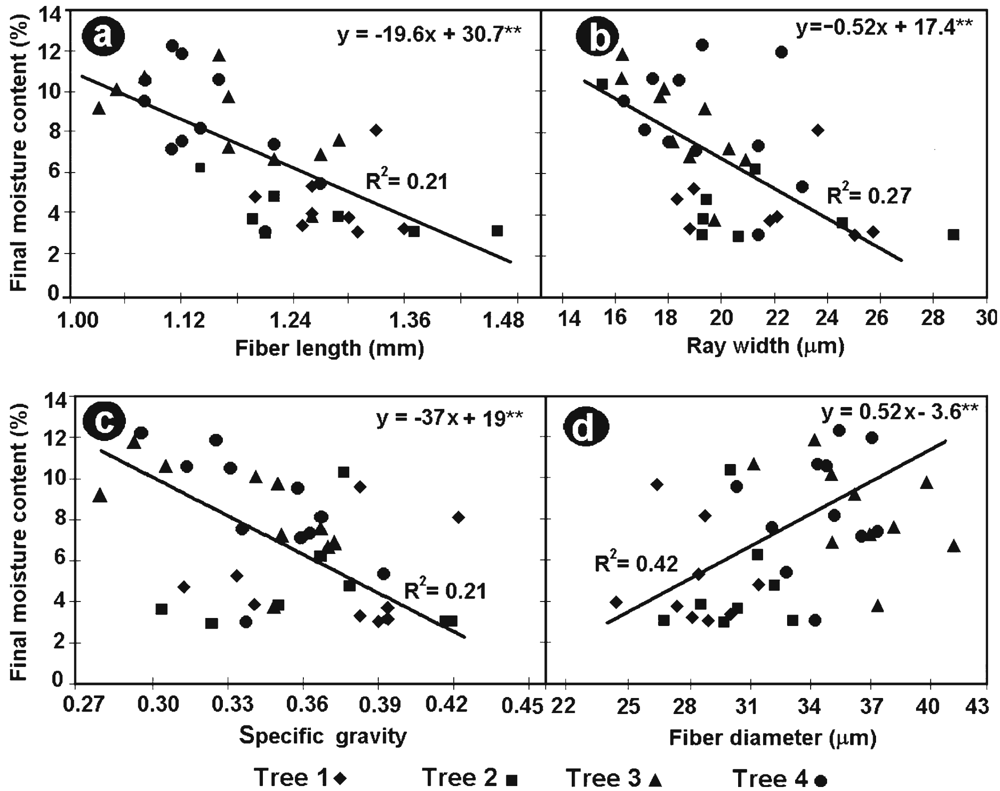


Fig. 2a–d. Relationships between final moisture content and anatomical properties in four *G. arborea* trees: **a** fiber length, **b** ray width, **c** specific gravity, **d** fiber diameter

FØ caused an increment in MC_f (Fig. 2d). The relationship between LØ and MC_f is not presented graphically. MC_f has a higher correlation with FØ ($R = 0.986$), while the relationship between LØ and MC_f shows a similar tendency. In practice, FØ is easier to measure than LØ.

The anatomical properties have been found to be correlated with DP for some wood species;[19] consequently, it is good practice to estimate MC_f from DP.[14,20] The results of this study found that the anatomical properties of FL, CW, VTØ, VF, and RF are statistically correlated to DP (Table 3). However, only FL has a strong influence on MC_f after the drying process. On the other hand, FØ, LØ, and RW showed correlations with MC_f but not with DP (Table 3). It is important to mention that the anatomical features correlated with MC_f (FL, FØ, LØ, and RW) were also statistically correlated with SG (Table 3). These results suggest that variations in MC_f are influenced by DP and SG variation and other wood properties (FØ, LØ, and RW) that show statistical relation with SG but not with DP. In addition, the presence of sapwood tends to result in a low MC_f.

The anatomical properties have an important effect on water flow during the wood-drying process.[21] The free water flow inside the wood takes place through the fiber and vessel lumens, their pits, and along the radial parenchyma,[22,23] while the fiber cell walls are important for bound water.[4] Ours results show the importance of ray width and fiber dimensions (fiber length and diameter of fiber and lumen) on MC_f, probably for its importance in the free water flow. No significant correlation between vessel diameter and MC_f can be attributed to the presence of tyloses into the hollow lumens of vessels in *G. melina*.[24]

SG showed a negative correlation with MC_f, meaning that the boards with greater SG have lower MC_f when the drying process ends (Fig. 2c). The wood sections with low SG values were located near the pith, and SG increased with increasing DP (Fig. 1c). The opposite tendency was found for variation of MC_f with DP (Fig. 1b). Then dried lumber probably gave high MC_f in boards near the pith where MC_i is high (Fig. 1a) and SG is low (Fig. 1c). Drying simulation models to predict the MC_f, used by different authors,[25,26] considered a negative influence of SG on MC_f, among other wood properties and kiln design. For example, Pang[25] developed a model to establish a drying rate and MC_f distribution between boards considering SG, green moisture content, growth ring pattern, mixture of sapwood and heartwood, thickness, and rheological properties. Pang found that SG together with rheological properties of wood play an important role in moisture content distribution and drying stress relief in the dried lumber.

Pang found large variation in drying rate of *Pinus radiata*,[6] while Chen and Lamb found the same for red oak,[26] and the variation was found to correlate with SG of dried lumber in conventional and vacuum drying. However, they attributed the variation in MC_f to the influence of extractives on SG, which differs the findings in the present study, where the SG variation was produced by cambium aging (Fig. 1c). On the other hands, Möttönen et al.[20] carried out a study on the variation of MC_f in *Betula pendula* and they suggested that moisture variation within a stem was presumably caused by SG variation, juvenile wood, and high extractives content.

The results obtained can help to reduce the difference in MC_f during a drying process. The boards taken near the pith give a higher MC_i than the boards obtained near the bark (Fig. 1a). Thus, the boards near the pith will present a high

MC_f if they are dried in a same batch with boards from near the bark. MC_i was more stable with a distance from the pith of 8 cm, this value is a good indicator to classify lumber from the inner and outer parts of the log. In doing so, lumber from the inner (near pith) and outer (near bark) parts can be separated during the sawing process. Afterward, drying schedules for each lumber position can be applied. During the separation process, the lumber with sapwood can also be separated.

Statistically significant correlation was found between SG and MC_f variation for *G. arborea*, although low correlation was found and the main effects occurred in trees 1 and 2 (Fig. 1b). We consider that SG is a good predictor for MC_f. The separation of inner and outer lumber can reduce the difference in SG as well. Furthermore, SG is correlated with other anatomical elements (FL, FØ, LØ, and RW), which also influence MC_f (Table 3).

The variation of MC_f in *G. arborea* dried wood from fast-growing plantation trees was found to be correlated with DP. However, this variation cannot be fully explained, because there exists a contribution from other wood features that influence MC_f without being related to DP, but they are related to SG. It was found that MC_f is influenced by SG, FL, FØ, LØ, and RW of wood, sapwood presence, and difference among trees. Among these properties, SG and FL are the only variables correlated with DP, while FL, FØ, LØ, and RW are correlated with SG.

Moisture content distribution in wood during drying has been explained in terms of several factors related to board position within the log or wood properties, such as anatomical features or SG. However, among these properties, board position within the tree is easily monitored. The concept of monitoring moisture content distribution in wood during drying has been developed.[27] For example, Cai and Hayashi,[28] developed a new method to determine moisture content distribution in wood by measuring temperature and pressure, which are easy variables to monitor during drying.

Given the low uniformity in MC_f of *Gmelina arborea* fast-growing plantation timber found in this study, it is important to obtain an acceptable drying process. Lumber separation from inner and outer parts of log batches or monitoring the moisture content could improve MC_f uniformity during the drying process, and resulting in raw dried material of better quality for furniture and construction. Research is needed to implement an improvement in MC_f uniformity through the study of kiln schedules at an industrial level to reduce the wood drying times and to improve the kiln design and characteristics.

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