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Anatomical, physical, and chemical changes in *Albizia carbonaria* wood subjected to thermal modification

Cambios anatómicos, físicos y químicos de la madera *Albizia carbonaria* sujeto a modificación térmica

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ABSTRACT

In Colombia, wood preservation treatments still rely on toxic and environmentally hazardous products, whereas cleaner and safer alternatives remain scarcely implemented. Thermal modification has emerged as a sustainable technology capable of enhancing wood resistance to biological degradation, improving dimensional stability, and optimizing its performance for industrial applications. Furthermore, this process enables the assessment of chemical and structural transformations associated with wood modification. *Albizia carbonaria*, a native Colombian species distributed in tropical and premontane humid forests, is commonly used in agroforestry systems associated with coffee cultivation. This study evaluated the effects of thermal treatments conducted in a closed system at 170 and 190 °C, temperatures at which significant changes are expected in low-density woods due to hemicellulose degradation and consequent alterations in the internal structure. Dimensional stability, density, chemical composition, and anatomical modifications were analyzed according to Colombian Technical Standards and Technical Association of the Pulp and Paper Industry (TAPPI) standards, using wood obtained from an agroforestry plantation. Mass loss reached 7.72 and 9.54% at 170 and 190 °C, respectively. Air-dry density (12%) was significantly higher at 190 °C, while dimensional stability improved under both treatments. In addition, holocellulose and extractives contents increased as a consequence of total mass reduction and the formation of new compounds. Anatomical alterations and cell wall thickening were also observed. However, the 170 °C treatment promoted greater density increases, higher chemical content, and lower anatomical damage, indicating that this thermal condition is more suitable for the species.

Palabras clave:
Anatómico
Composición química
Densidad
Estabilidad dimensional

RESUMEN

En Colombia, los tratamientos de preservación de la madera continúan dependiendo de productos tóxicos y ambientalmente contaminantes, mientras que las alternativas más limpias y seguras siguen siendo escasamente implementadas. La modificación térmica ha surgido como una tecnología sostenible capaz de incrementar la resistencia de la madera al deterioro biológico, mejorar su estabilidad dimensional y optimizar su desempeño para aplicaciones industriales. Además, este proceso permite evaluar las transformaciones químicas y estructurales asociadas con la modificación de la madera. *Albizia carbonaria*, especie nativa de Colombia distribuida en bosques húmedos tropicales y premontanos, es ampliamente utilizada en sistemas agroforestales asociados al cultivo de café. En este estudio se evaluaron los efectos de tratamientos térmicos realizados en un sistema cerrado a 170 y 190 °C, temperaturas en las que ocurren cambios significativos en maderas de baja densidad debido a la degradación de hemicelulosas y las consecuentes modificaciones en su estructura interna. Se analizaron la estabilidad dimensional, densidad, composición química y cambios anatómicos, de acuerdo con las Normas Técnicas Colombianas y los estándares de la Technical Association of the Pulp and Paper Industry (TAPPI), utilizando madera proveniente de una plantación agroforestal. La pérdida de masa alcanzó 7,72 y 9,54% a 170 y 190 °C, respectivamente. La densidad al 12% de humedad fue significativamente mayor a 190 °C, mientras que la estabilidad dimensional aumentó en ambos tratamientos. Asimismo, el contenido de holocelulosa y extractivos se incrementó debido a la reducción de la masa total y a la formación de nuevos compuestos. También se observaron alteraciones anatómicas y engrosamiento de la pared celular. Sin embargo, el tratamiento a 170 °C promovió mayores incrementos de densidad, mayor contenido químico y menor daño anatómico, indicando que esta condición térmica es la más adecuada para la especie.

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In Colombia, preservation treatments are still used with highly toxic and polluting products such as arsenic, chromium, and chlorine (Townsend et al. 2004), which generates environmental impacts and limits the acceptance of treated wood in different industrial sectors. In addition, population growth has steadily increased the demand for wood and wood products, creating strong pressure on natural forests and contributing to the scarcity of high-quality and durable timber (Hill 2006). This scenario highlights the urgent need to develop sustainable alternatives to improve the performance of fast-growing timber species.

In this context, *Albizia carbonaria* (galapo, pisquín, or carbonero) is a native species of Colombia widely distributed between 900 and 1,800 meters above sea level (masl), typically found in premontane humid tropical forests (Arroyave et al. 2021). This species is frequently integrated into agroforestry systems, particularly in coffee crops, where it provides shade regulation, contributes to soil fertility through nitrogen fixation, supports biodiversity conservation, and promotes ecosystem restoration (Criollo et al. 2020). It is also commonly associated with other forest species such as *Pinus patula* and *Eucalyptus* in Colombian coffee-growing regions (Ortiz et al. 2022).

Despite its ecological relevance and high availability, its industrial use remains limited. Its wood is low-density, soft, and lightweight, which facilitates its workability but also represents one of its main limitations, as it exhibits low natural durability, high hygroscopicity, dimensional instability, and susceptibility to biological degradation. These weaknesses restrict its structural use and limit it mainly to low-performance applications. These characteristics constrain its use in structural or high-performance applications, limiting its value to low-demand uses despite its abundance in agroforestry systems.

To overcome these limitations, thermal modification has emerged as a sustainable and environmentally friendly alternative to improve wood performance. This process increases resistance to fungal and insect attack, enhances dimensional stability, and modifies physical and mechanical properties (Herrera-Builes et al. 2020; Giridhar et al. 2017). Thermal treatment consists of exposing wood to high temperatures under low-oxygen conditions, which induces degradation of cell wall components mainly hemicelluloses and modifies the anatomical structure (Barlović et al. 2022). However, the magnitude of these effects strongly depends on the species and process conditions (Boonstra et al. 2006), making species-specific evaluation necessary.

Although thermal modification has been widely studied in commercial timber species, there is limited information on its effect on low-density tropical species such as *Albizia carbonaria*, especially regarding the interaction between chemical changes, anatomical alterations, and improvements in physical properties. Addressing this gap is essential to determine whether thermal treatment can effectively increase the technological value of this species and expand its industrial applications.

Therefore, this study is relevant because it seeks to contribute to the understanding of how thermal modification can transform a low-durability wood into a material with greater potential for industrial use, reducing pressure on natural forests and promoting the use of fast-growing species.

In this sense, this work aimed to analyze the effect of thermal modification on certain physical and chemical properties and the internal structure of *A. carbonaria* wood, in order to improve its properties and, consequently, increase its potential for timber use. The article describes the materials and methods used; subsequently, the results obtained in terms of physical, chemical, and anatomical properties are presented; then the findings are discussed in comparison with previous studies; and finally, the main conclusion and implications of the study for the sustainable use of forest species in Colombia are presented.

MATERIALS AND METHODS

The wood was extracted from an agroforestry coffee crop located in the municipality of La Mesa de Los Santos belonging to the Department of Santander (6°51'36.9"N 73° 02' 33.9"O) with a mean annual precipitation of 2,918 mm, mean temperature up to 21 °C, and relative humidity 68% (Figure 1).

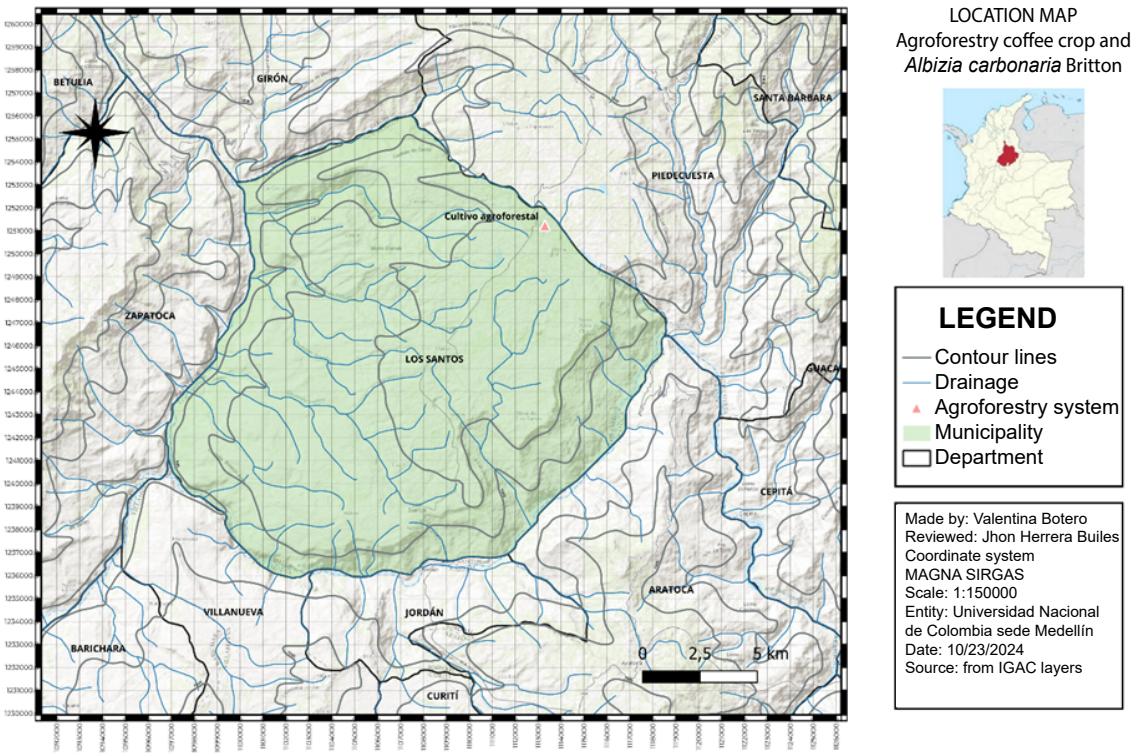


Figure 1. Map of the agroforestry coffee crop.

Ten (10) eight-year-old trees were collected randomly, with a useful shaft with a diameter of 450 mm, from which the first two logs of 2,500 mm long were taken, a central plank of 100 mm thick heartwood was cut from each log then from each plank, slats of 60x60x2,500 mm (width, thickness, and length, respectively) were cut, eliminating the pith, which were subjected to air-dry until reaching a moisture content of 12% and samples of 410 mm (Longitudinal) x 25 mm (Tangential) x 25 mm (Radial) were taken.

For the physical properties air-drying density, basic density, and dimensional stability, 10 trees of *Albizia carbonaria* were used from which 45 samples 30x30x100 mm (tangential x radial x longitudinal) were obtained. The samples for these tests were well directed growth rings and clear radial and tangential orientations. For each treatment, 15 test pieces were used. Each piece was enumerated, weighed, and its volume calculated. Additionally, measurements were taken within the longitudinal-radial plane and longitudinal-tangential plane.

Thermal modification

The thermal modification of *Albizia carbonaria* specimens at 170 and 190 °C was carried out in an oven Memmert UM100 in the "Héctor Anaya López" Forest Products Laboratory of the Universidad Nacional de Colombia, Medellín Campus. For each treatment, a total of 15 specimens were placed in the oven.

The process was initiated by adjusting the oven to 40 °C from the ambient temperature (27 °C). Once the oven reached 40 °C, the timer was initiated and the specimens were subjected to a 20-minute exposure at this temperature. When the temperature reaches 60 °C the timer is restarted for another 20 minutes. This process was cyclically repeated until reach 160 °C.

After 20 min at 160 °C, the temperature was increased to 170 °C and maintained for 150 min (2.5 h). After this time, the oven was re-adjusted to ambient temperature (27 °C) to allow the samples to cool for approximately 1,291 min (21.5 h) (Figure 2).

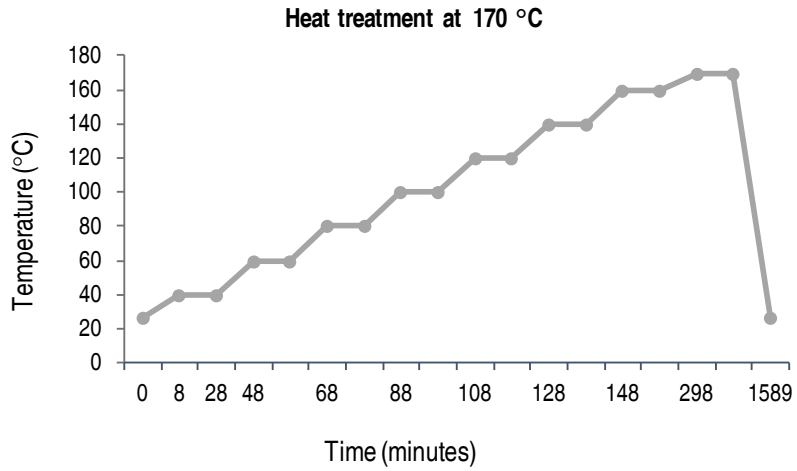


Figure 2. Evolution time of the temperatures during the thermal modification process at 170 °C.

The previous process was repeated for the treatment at 190 °C and it took around 1,053 min (17.5 h) to complete the cooling phase (Figure 3).

Physical properties

For the physical properties air-drying density, basic density, and dimensional stability, 10 trees of *Albizia carbonaria* were used from which 45 samples 30x30x100 mm (tangential x radial x longitudinal) were obtained. The samples for these tests were well directed growth rings and clear radial and tangential orientations. For each treatment, 15 test pieces were used. Each piece was enumerated, weighed, and its volume calculated. Additionally, measurements were taken within the longitudinal-radial plane and longitudinal- tangential plane.

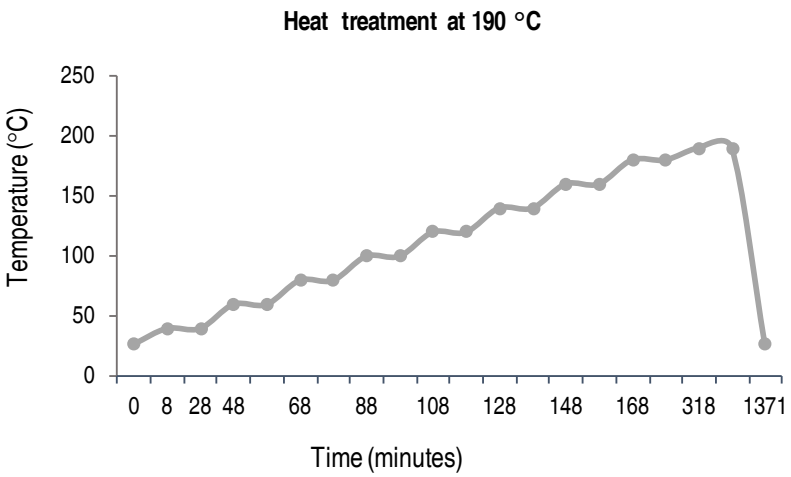


Figure 3. Evolution time of the temperatures during the thermal modification process at 190 °C.

Loss of mass was determined by measuring the difference between the initial mass and the mass after each treatment, following the calculation method applied by Kamperidou (2019). Dimensional stability was evaluated using the method described by Rowell and Youngs (1981) in a complete cycle which consisted of passing the wood from dry to wet and then wet to dry successively until three cycles were completed. The drying was carried out in an oven at 103±2 °C until reaching a constant weight, and the wet cycle was carried out by soaking the samples for 24 h and then measuring the change in dimensions of the samples.

The volumetric swelling coefficient was adapted and estimated using the shrinkages, and the Anti-swelling efficiency (ASE), it was estimated considering three cycles as a measure of the dimensional stability of the wood. The following Equations (1 and 2) were used to calculate the volumetric swelling coefficient and the anti-swelling efficiency, respectively:

$$S(\%) = \frac{100(C2 - C1)}{C1} \quad (1)$$

Where, C2 is the shrinkage of the saturated samples and C1, is the shrinkage of the oven- dried samples.

$$ASE(\%) = \frac{100(Ss - Sm)}{Ss} \quad (2)$$

Where, Ss is the average coefficient S of the unmodified samples and Sm is the average coefficient of the modified samples.

Samples of thermal unmodified and modified wood were mechanically disintegrated in sawdust. The material used for chemical analysis was classified between 40 and 60 mesh. The holocellulose content was determined using sodium chlorite according to the procedure of Wise et al. (1946). In a beaker, 150 mL of 1.5% (w/w) sodium chlorite solution was poured into 2 g of wood, and 10 drops of glacial acetic acid and the sample was placed in a water bath at 75 °C for 1 h. After 1 hour, 10 drops of glacial acetic acid and 1.5 g of sodium chlorite were added, it was cyclically repeated every hour, for a total period of 4 hours. After chlorination, the solution was filtered, washed with 200 mL of cold water, followed by 10 mL of acetone; the residue was taken to an oven at 105 °C until constant weight. All measurements were made in three replicates for each chemical composition determination. Data were presented as percentages on a dry basis.

The lignin content was determined as described by TAPPI T 222 om-02 (2002). 15 mL of sulfuric acid 72% (w/w) were added to 1 g of wood, stirring it for 10 min and letting it rest for 2 h. Then, 575 mL of distilled water were added, and it was boiled for 4 h maintaining a constant volume, if necessary distilled water was occasionally added. Lastly, it was filtered in Hirsch funnels, and the samples were washed until acid residues were removed. Finally, they were brought in oven at 105 °C, until reached a constant weight.

The extractives content was determined according to TAPPI T 204 cm-97 (1997). 100 mL of 1% NaOH were added to 2 g of wood sample, stirring it with glass rod for 10 seconds and placed it on a water bath, letting it rest in the boiled bath for 1 h (97 °C); after the bath, it was stirred again for 25 min. The digestion material was filtered and neutralized by adding 25 mL of acetic acid to 10% for 1 min, then it was washed with 100 mL of hot water. The last procedure was repeated, with a second portion of 25 mL of acetic acid to 10% for 1 min, then it was washed again with hot water letting the material free of acid. Finally, they were brought to constant weight in an oven at 105 °C.

Anatomy

Pieces of samples of thermally unmodified and modified wood were cut into lengths of 20x20x20 mm and soaked in water for 36 h. A transverse slice of 20 µm was obtained using a Spencer Model 860 microtome (AO Instrument CO, Buffalo, N.Y, USA). These sections were stained with a 1% safranin solution and mounted on a glass slide and cover glass using Canada balsam and glycerin. Anatomical measurements were performed at the Forest Products Laboratory of the Universidad Nacional de Colombia, Medellín Campus. The changes in the cellular structure of wood were examined using a Primo Star light microscope (Carl Zeiss Microscopy GmbH, Oberkochen, Germany). All measurements were made for triplicate.

Data analysis

The statistical analysis was performed using a completely randomized design for each test. Analysis of variance (ANOVA) was performed for each variable, and when the F test showed significant results, a Tukey multiple range test (P<0.05) was performed using the R statistics program and the RStudio interface (RStudio 2023). The information was processed base on the methodology described by Jeffrey (2006).

RESULTS AND DISCUSSION

The results appearing in each box are represented, following Equation 3:

$$\bar{y} \pm \frac{q}{CVt} \quad (3)$$

Where, $\bar{y}$ is the mean, ± q is the 95% confidence interval, and CVt is the total coefficient of variation.

Physical properties

The wood densities are affected by the temperature of the heat treatment (Bessala et al. 2023). The air-dry density and the anhydrous were classified as low, both for treatments and for unmodified wood, since the values are within the range suggested by ASTM (351-500 kg m^{-3}). In addition, the air-dry density presented statistically significant differences for both treatments and for unmodified wood, being higher in the unmodified wood (Table 1).

On the other hand, the anhydrous density did not show statistically significant differences between the unmodified wood and the treatments, although it was higher during modification at 190 °C (Table 1).

Table 1. Wood densities and mass loss of thermally modified *Albizia carbonaria*.

Density	Unmodified	170 (°C)	190 (°C)
Anhydrous (kg m^{-3})	384.01±18.3[a]	388.03±12.9[a]	402.22±11.0[a]
	9.4	6.6	5.44
Basic density (kg m^{-3})	343.44±13.1[a]	353.62±10.9[ab]	364.55±9.5[b]
	7.5	6.1	5.2
Air-dry density (kg m^{-3})	461.64±87.9[a]	408.13±0.2[b]	428.82±11.1[c]
	30.7	0.13	5.1
Mass loss (%)		7.72±0.1[a]	9.54±0.5[b]
		3.8	11.4

Note: The body of the table shows the average values ± at 95% confidence interval of 20 test simples per treatment. Equal letters in columns indicate no significant difference between treatments, according to Tukey´s multiple range test ($P \leq 0.05$).

According to the basic density classification of NTC 2500 (Civil Engineering and Architecture. Use of Wood for Construction) the basic density of modified and unmodified wood cannot be classified, since the values are not within any of the ranges (Table 1). In addition, the samples modified at 170 °C increased by 2.9%, but showed no statistically significant differences with the unmodified samples or with those treated at 190 °C. On the other hand, the wood treated at 190 °C increased by 6.1%, presenting statistically significant differences with the unmodified wood (Table 1). These results contradict the study made by Bessala et al. (2023) in which the density decreased proportionally to the treatment temperature; also, according to Dubey et al (2011) if there is a momentary increase in density, this decreases with the treatment temperature caused by hemicellulose degradation.

The mass loss increased with temperature. For the modification at 170 °C the losses that were obtained were 7.72% and for the treatment at 190 °C were 9.54%, this was statistically significant (Table 1). Bessala et al. (2023) states that, after the heat treatment the weight of samples generally decreases due to the induced degradation of wood components. According to Sikora et al (2018), weight loss increases with treatment temperature, mainly because of a decrease in the quantity of polysaccharides, which is mainly caused by hemicellulose degradation.

The anti-swelling efficiency (ASE) values obtained indicate that the temperature improves the dimensional stability of the wood. In the radial orientation the ASE values were higher in the treatment at 190 °C, 44.9 and 52.5%, while in the tangential orientation they were very similar between 51.5 and 51.3% at 170 and 190 °C, respectively. However, none of the orientations showed statistically significant differences (Table 2).

Determination of chemical composition

Regarding chemical composition, the results (Table 3) presented variations in the components of holocellulose, extractives and lignin, this largely coincides with the

Table 2. Anti-swelling efficiency (ASE) of thermally modified *Albizia carbonaria.*

ASE (%)	170 (°C)	190 (°C)
Radial	44.9±0.4[a]	52.5±0.5[a]
Tangential	51.5±0.5[a]	51.3± 0.7[a]

Note: The body of the table shows the average values ± at 95% confidence interval of 20 test simples per treatment. Equal letters in columns indicate no significant difference between treatments, according to Tukey´s multiple range test ($P \leq 0.05$).

studies of Sikora et al. (2018) and Dubey et al. (2011), who evaluated the thermal treatment in *Pinus radiata* and *Fagus sylvatica* species. Both investigations showed that the degradation of polysaccharides, especially the hemicelluloses increase as heat treatment temperature increases.

Table 3. Chemical composition of thermally modified and unmodified *Albizia carbonaria* wood.

Treatment	Holocellulose (%)	Extractives (%)	Lignin (%)
Unmodified	56.7±0.9[a]	33.82±3.14[a]	60±1.5[a]
	1.4	8.2	2.23
170 °C	67.4±3.6[b]	31.34±2.35[b]	59.2±5.3[a]
	4.8	6.6	8.0
190 °C	41.0±3.3[c]	39.5±4.9[b]	64.2±4.4[a]
	7.2	11.1	6.0

Note: The body of the table shows the average values ± at 95% confidence interval of 20 test simples per treatment. Equal letters in columns indicate no significant difference between treatments, according to Tukey´s multiple range test ($P \leq 0.05$).

In relation to holocellulose, increments in the content were noticed after the treatment at 170 °C (67.40), followed by a significant decrease after the heat treatment at 190 °C (41.07%). This is consistent to the results found by Sikora et al. (2018), which reported for *F. sylvatica* an increase in holocellulose at 160 °C (62.1%) and a considerable reduction at 200 °C (43.5%). The temporary increase at moderate temperatures may be due to the redistribution of polysaccharides during the early stages of thermal modification, as suggested by Dubey et al. (2011), who found that in *P. radiata* at 180 °C, the hemicellulose content also increases slightly before decreasing at higher temperatures.

The extractives content shows a decrease to 170 °C (31.3%) and a noticeable increase to 190 °C (39.5%). In previous studies, Sikora et al. (2018) found a similar behavior in *F. sylvatica* where extractives initially decreased to 160 °C (27.6%) and then increased to 200 °C (35.2%). This increase is attributable to the concentration at higher temperatures of volatile compounds not removed during intermediate-stages volatilization, as also documented by Herrera-Builes et al. (2021) and Dubey et al. (2011) in their analyses on the increase of extractives in conifers, where they observed that, at 190 °C, in *Pinus oocarpa*, the extractives reached 30%, showing a similar behavior to that of *Albizia carbonaria*.

As for lignin, a slight variation is observed with the increase of the treatment temperature: 60% in unmodified wood, 59.2% at 170 °C and 64.2% at 190 °C. These results show that although there is an initial slight decrease at 170 °C, lignin tends to stabilize and even increases at higher temperatures. This contrasts with what was reported by Herrera-Builes et al. (2021), who observed that in *P. oocarpa*, lignin increased from 58.3% in untreated wood to 56.1% at 190 °C. In both cases, lignin is more stable at high temperatures than other components, although it begins to show a slight increase in its content at temperatures above 170 °C.

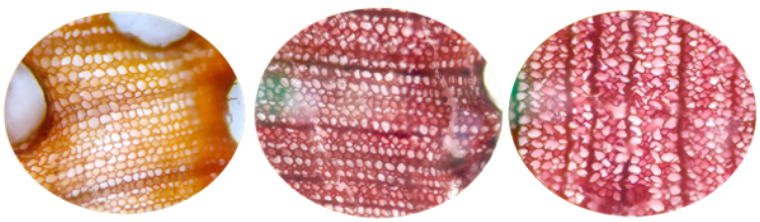
The results obtained on the chemical composition of *A. carbonaria* raise questions about how heating affects the species. In particular, the treatment at 170 °C seems

to be the most appropriate, since it allows the retention of a greater number of structural components such as holocellulose and lignin, without excessively increasing the extractive contents. However, the comparison with other species such as *P. radiata* and *F. sylvatica* suggests that degradation of components at 190 °C is more pronounced. This indicates that the differences between latifoliate and coniferous species, although notable, suggest that each species responds only to heat treatment, emphasizing the importance of adjusting thermal modification parameters according to wood characteristics as proposed by Herrera-Builes et al. (2021) and Dubey et al. (2011).

Anatomy

The thermal modification produced a significant increase in the cell wall thickness of *A. carbonaria* wood (Table 4), increasing to 266.6% at 170 °C. However, at 190 °C, this increase was smaller, reaching only 188.8%. This suggests that the treatment at higher temperatures may reduce the effectiveness of this thickening. As for the lumen diameter, the reduction was constant, with a decrease of 55.0% at 170 °C and 56.8% at 190 °C, without significant differences between both treatments. In both cases, the lumen was classified as "small", in contrast to unmodified wood, which was classified as "medium".

In addition, damages in the cell wall of the treated wood as distortions and cracks were observed, especially at 190 °C (Figure 4C), suggesting that these damages increase with temperature. In the tropics, these data have not been reported for latifoliate species, only for pines. Previous studies in *Pinus oocarpa* (Herrera-Builes et al. 2021) and *Pinus radiata* (Cabezas-Romero et al. 2021) reveal a different trend, where the thickening of the cell wall decreased with the increasing temperature, although a reduction in lumen diameter was also observed. However, this decrease was less pronounced compared to that recorded for the species under analysis.



A. Unmodified B. Treatment at 170 °C C. Treatment at 190 °C

Figure 4. Morphological changes in the anatomical structure of the wood *Albizia carbonaria*.

Table 4. Anatomical measurements of the lumen diameter of thermally modified and unmodified *Albizia carbonaria* wood.

Treatment	Cell wall thickness (µm)	Lumen diameter (µm)	Classification
Unmodified	1.3±0.2[a] 49.6	86.0±10.2[a] 27.2	Medium
170 °C	3.6±0.4[b] 26.1	47.3±2.8[b] 13.4	Small
190 °C	2.5±0.2[c] 20.0	48.9±2.8[b] 13.4	Small

Note: The body of the table shows the average values ± at 95% confidence interval of 20 test simples per treatment. Equal letters in columns indicate no significant difference between treatments, according to Tukey´s multiple range test ($P \leq 0.05$).

CONCLUSION

This study provides new insights into the behavior of *Albizia carbonaria* wood under thermal modification, a poorly characterized tropical species widely used in Colombian agroforestry systems, and improves the understanding of temperature-dependent changes in its physical, chemical, and anatomical properties.

From a scientific standpoint, 170 °C was identified as the optimal treatment condition, offering the best balance between property enhancement and structural preservation, with lower mass loss (7.72%), stable density, higher retention of holocellulose and lignin, and improved anatomical integrity. In contrast, 190 °C caused greater degradation, higher mass loss (9.54%), and more severe structural damage.

From an industrial perspective, thermal treatment at 170 °C represents a promising strategy to improve the performance of this underutilized species, increasing its value and potential use in non-structural and semi-structural applications within agroforestry-based value chains in Colombia.

These findings also confirm that tropical hardwoods may respond differently to thermal modification than conifers, highlighting the need for species-specific studies under tropical conditions.

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CONFLICT OF INTERESTS

The authors declare no potential conflicts of interest.

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