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Impact of thermal modification on some selected physical and mechanical properties of *Daniellia oliveri* wood

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ABSTRACT: The field of eco-friendly wood preservation, particularly the potential of thermal modification, is an area that demands immediate attention. There is an urgent need to promote the use of lesser-known timber species. This task requires filling the gap in research by evaluating the impact of thermal modification on the physical properties of a Ghanaian lesser-known timber species (*Daniellia oliveri*) wood. The study, which adopted an experimental research design, involved selecting and harvesting five samples of *D. oliveri* trees from the Du-West community. The study revealed that the specimens' moisture content (MC) drastically reduces as the modification temperature increases, with a similar trend observed for the density of the specimens. Volumetric Swelling (VS) and Water Absorption (WA) decreased as temperature increased. Moreover, as the modification temperature increased, the mechanical properties decreased.
Keywords: lesser-used species (LUS); volumetric swelling; moisture content; modulus of elasticity; modulus of rupture.

O impacto da modificação térmica em algumas propriedades físicas e mecânicas selecionadas da madeira de *Daniellia oliveri*

RESUMO: O campo da preservação ecológica da madeira, particularmente o potencial de modificação térmica, é uma área que exige atenção imediata. Há uma necessidade urgente de promover a utilização de espécies madeireiras menos conhecidas. Esta tarefa exige preencher a lacuna na investigação, avaliando o impacto da modificação térmica nas propriedades físicas da madeira de uma espécie madeireira menos conhecida do Gana (*Daniellia oliveri*). O estudo, que adotou um desenho de pesquisa experimental, envolveu a seleção e colheita de cinco amostras de árvores de *D. oliveri* da comunidade Du-West. O estudo revelou que o teor de umidade (MC) das amostras reduz drasticamente à medida que a temperatura de modificação aumenta, com tendência semelhante observada para a densidade das amostras. O inchaço volumétrico (VS) e a absorção de água (WA) diminuíram com o aumento da temperatura. Além disso, à medida que a temperatura de modificação aumentou, as propriedades mecânicas diminuíram.
Palavras-chave: espécies menos utilizadas (LUS); inchaço volumétrico; teor de umidade; módulo de elasticidade; módulo de ruptura.

1. INTRODUCTION

More than eight hundred timber species have been identified in Ghana's forests over the past few decades. However, furniture producers and other timber users have exclusively used commercially known species to the neglect of other timber species in the forest, which could comparably be used for furniture and different engineering purposes (APPIAH-KUBI et al., 2019). Recently, the high depletion of the Ghanaian forest has raised concerns for various stakeholders towards addressing it to help mitigate the climate change challenges in efforts to achieve Sustainable Development Goal 13, thus "action to combat climate change and its impacts" (AGUMA; OGUNSANWO, 2019). A study conducted by Effah et al. (2015) further stressed that reduction in the supply of high-quality timber had been a major challenge faced by the furniture and construction industry because insufficient raw material has caused industries to either underproduce or collapse, which leads to high rate of unemployment within the country (MARCHI et al., 2019).

According to Hassan; Tippner (2017), alternative ways of alleviating these challenges are having an in-depth knowledge of the utilization of wood residue and off-cuts, effective and efficient use of Non-timber Forest Products, the introduction of plantation farms to regenerate the degraded forest, and finally, the effective use of Less-Used Species

(LUS) of timber. Utilization of wood for structural and other applications has been minimal due to inadequate information on their properties.

. As Allotey (1992) stated, understanding wood's properties will enhance its effective utilization.

To improve the service life of these LUS of timber, preserving them to enhance their maximum performance is necessary. Significant shifts in the field of wood preservation have brought about the rising environmental strain observed in several European countries in recent years. It is widely known that heat treatment is a useful way to alter wood properties. However, some heat treatment methods, such as chemical modification, harm the environment (SAHIN KOL, 2010). Wood as a raw resource is suitable for various applications; even though certain attributes, such as dimensional stability and durability, are greatly affected when the moisture content is high, alternative treatment modalities may enhance these features (DAGBRO, 2016). The necessity for durability in wood products and the fragility of our environment has led to the development of innovative technologies that extend the service life of wood materials without harmful chemicals.

There have been several attempts and efforts to improve the properties of wood by preserving and modifying them; however, the chemicals used in maintaining and modifying the wood are not environmentally friendly and can cause more harm to the ecosystem if not properly handled. This study, therefore, looks at the thermal modification of timber as a precursor to improving the properties of the lesser-used species with the concerns of environmental issues in mind. In light of this, it is therefore crucial to find eco-friendly, chemical-free, and sustainable ways of improving the properties of these less-used species. Although wood modification has been the subject of a great deal of study at an academic level for over a couple of years, and despite the numerous benefits of thermal modification of wood, more work still needs to be done in Ghana. This study, therefore, evaluated thermal modification's impact on *Daniellia oliveri* wood's physical and mechanical properties.

According to Hutchison; Dalziel (1928), *D. oliveri* was named Paradaniellia oliveri Rolfe, belonging to the Fabaceae family. While *D. oliveri* is not a major species on the international timber market, it is an important part of the lives of those who live nearby (SCHMELZER; LOUPPE, 2012). It is a lesser-known timber species in Ghana, predominately in the deciduous woodland and humid savannah. The Sissala tribe where samples were harvested refers to *D. Oliveri* as "*Kanchil*." According to Schmelzer; Louppe (2012), wood is susceptible to microorganisms that break down lumber, including termites, sea borers, pinhole borers, and fungus. Therefore, a certain level of effective wood treatment is necessary to increase its useful life.

Schmelzer; Louppe (2012) stated that although *D. oliveri* is generally less durable, its heartwood is frequently used in home furnishings, roofing rafters, and manufacturing packages (ACHIGAN-DAKO et al., 2010). The heartwood of *D. oliveri* is a great outdoor option because of its ability to withstand decay and pests. Due to *D. oliveri's* availability throughout Ghana's geographical zones, the wood is commonly used for fuel and charcoal production. Effective treatment, such as thermal modification of *D. oliveri*, can extend its useful life and minimize the effects of endangering the commercial timber species.

2. MATERIAL AND METHODS

2.1. Specimen preparation

Five mature, defect-free *D. oliveri* trees, ages 25 to 48 years, with a diameter at breast height (DBH) of 1.5 meters above ground level, were taken from the community's natural woodlands in Du-west due to their prominence and abundance. The five trees were selected due to their diameters on purpose, and before their harvest, their straight trunks and defect-free condition were observed and noted. After the chosen trees were felled, the base of each tree with a sectional length of one meter was removed, which was further processed to determine the physical and mechanical properties test. The trees had clean boles with a diameter of around 60 to 80 cm and a length of about 15 meters.

The quarter sawing technique was used to convert the billets into boards, reducing warping and making it easier to split sapwood and heartwood to determine radial characteristics. The wood samples were prepared to the required dimensions at the wood workshop/laboratory of the Akenten Appiah Menka University of Skills Training and Entrepreneurial Development - Kumasi campus. The samples were prepared by sawing the specimens into lengths suitable for the various tests per the chosen standards. The samples were selected carefully from the prepared stacks of sawn timber free of defects such as knots, wanes, and other biological agents that reduce wood performance. According to Kollmann; Cote Jr (1968), these factors reduce wood's strength and usefulness. After the heat treatment, the specimens were sent to the laboratory to test the various physical and mechanical parameters.

2.2. Thermal modification process

Six sets of heartwood and sapwood were modified at the chemical engineering laboratory of Kwame Nkrumah University of Science and Technology for three hours at various temperatures without oxygen in a muffle furnace. Ten replicates of sapwood and heartwood each were used as the control group (untreated). The specimens were placed in an oven with a tightly closed door to keep heat from escaping during the modification process. The various heat treatments were carried out after setting the oven to the right temperature of 160°C, 180°C, and 200°C for three hours. After each treatment time, the specimens were taken out of the oven and allowed to cool using a desiccator filled with silica gel. Various tests were conducted using the selected standards to assess the material's physical and mechanical properties.

2.3. Physical test

Physical properties investigated were moisture content (MC), oven-dry density, volumetric swelling, and water absorption. The determinations of the physical properties of *D. oliveri* wood were carried out at the Forestry Research Institute of Ghana (FORIG) laboratory of the Council for Scientific and Industrial Research (CSIR) at Kumasi. Moisture content and oven-dry density tests were carried out using the British Standard 373 (1957) method for testing small clear timber specimens. Water absorption and volumetric swelling tests were conducted using the American Society for Testing and Materials - ASTM D1037-12 (2020) standard.

2.3.1. Density

The test samples were cut into the dimensions of (20 × 20 × 20 mm) following (British Standard 373, 1957). Samples were obtained from the sectional stem disc to determine the oven-dry density. With the oven-dry density, samples were oven-dried to reduce the moisture content. Their masses were evaluated to the nearest 0.001g using an electronic balance. At the same time, their dimensions were measured in all three principal directions (length, breadth, and thickness) with a digital caliper to the nearest 0.001 mm. The volumes of the samples were calculated based on their dimensions after the samples were oven-dried at a temperature of 103 ± 2ºC until constant mass was attained. Modified specimens' dimensions were taken immediately after the thermal modification.

Where Oven-dry density is the mass per unit volume, expressed mathematically as:

$$\rho = \frac{\text{Oven-dry mass (kg)}}{\text{Volume of cubes (mm3)}} \quad (01)$$

2.3.2. Moisture content

The samples' MC was obtained using the oven-dry method. Samples collected from the merchantable part were sawn to a dimension of 20mm x 20mm x 20mm. After the preparations, the specimens were immediately weighed using an electronic balance with a variation of < 0.001% of the weight. The specimens were then oven-dried at a temperature of 103 ± 2 ^{0}C for twenty-four (24) hours until constant weight was attained. Specimens were kept on a desiccator to prevent the intake of moisture from the atmosphere during the weighing process. The procedure of oven-drying for 24-hour intervals and weighing was repeated until a constant mass was attained. Modified specimens' masses were taken immediately after the thermal modification. The MC was then calculated using the formula:

$$\%MC = \frac{Wi - WoD}{WoD} \, x \, 100 \quad (02)$$

where: MC = Moisture Content; Wi = Initial Weight (green weight); WoD = Oven – dry Weight

2.3.3. Volumetric swelling

Forty dimensions (20 x 20 x 20mm) were taken from four slats per treatment to determine the volumetric swelling. Initially, the samples were conditioned until they reached a constant mass of at least 0.001g. They were then oven-dried for 24 hours at 103±2°C to ascertain their weights and volumes. Treated and untreated wood samples were immersed in distilled water in a stainless-steel container. A metal screen was placed over the samples to hold them about 2.5 cm below the surface. Following 24, 48, and 72 hours of water soaking, measurements were made in three directions (radial, tangential, and longitudinal) to determine the percentage of volumetric swelling (VS). Using equation 3, the percentage of volumetric swelling was determined.

$$\text{Volumetric Swelling (\%)} = \frac{V_2 - V_1}{V_1} \times 100 \quad (03)$$

where: V_2 = saturated volume; V_1 = oven-dried volume.

2.3.4. Water absorption

The water absorption properties of the control and modified specimens were determined by ASTM D1037-12 (2020). Specimens of dimension 20 mm x 76 mm x 152 mm were weighed and then submerged horizontally under 25 mm depth of distilled water at room temperature (27 ± 2 °C) for 24 hours, 48 hours, and 72 hours. After every 24 hours, the excess water on the sample's surface was removed with a hand paper towel and immediately weighed. The water absorption properties of the specimens were computed using Equation 4.

$$\text{Water absorption (\%)} = \frac{W_f - W_i}{W_i} \times 100 \quad (04)$$

where: Wi = Initial weight of test sample before soaking; W_f = Final weight of test sample after soaking.

2.4. Mechanical Properties

The mechanical properties of *Daniellia oliveri* wood were determined immediately after the preparation and modification of the test samples at the laboratory of the Forestry Research Institute of Ghana (FORIG) of the Council for Scientific and Industrial Research (CSIR) at Kumasi. Samples were obtained from the radial sections of the trees, that is, Heartwood and Sapwood portions of each of the five trees. The control samples were air-dried to a moisture content of about 12% and were kept at room temperature before they were tested. All tests followed the (British Standard 373, 1957).

2.4.1. Static bending

Static bending is an index of a piece of wood's stiffness. The modulus of rupture and modulus of elasticity tests were carried out using three-point loading. The test procedure for MOR and MOE was carried out using small clear wood specimens (British Standard 373, 1957).

This method supported the ends of the 20mm x 20mm x 300mm wood samples. A load from the Instron universal testing machine was placed at the central part of the wood sample at a rate of 0.26 inch/min (6.5 mm/min), and the machine recorded its corresponding deflection automatically at an interval of every 0.1N. The duration of the test of each sample was 90 ± 30 seconds. The modulus of elasticity was calculated using equation 05 below.

$$E = \frac{P1L2}{4\Delta' A2} \quad (05)$$

where: E = Young's modulus of elasticity (N/mm2); P1 = maximum load applied at the limit of proportionality (N); A = area of cross-section of beam normal to the direction of load (mm²); Δ1 = deflection at mid-length a limit of proportionality (mm); L = span of beam (mm); and the modulus of rapture is the maximum load a wooden sample can sustain before failure (breaking). The modulus of rupture was calculated using equation (6) below.

$$R = \frac{3PL}{2bd2} \quad (06)$$

where: R = modulus of rupture (N/mm²); P = maximum load applied at the midpoint of the sample (N); L = span of the beam (mm); b = breadth of the test piece (mm); d = depth of the test piece (mm).

2.4.2 Compressive strength

Resistance to compressive strength parallel to grain force was assessed by using a longitudinal grain method following the BS 373 (1957). Samples were prepared with a dimension of 20mm x 20mm x 60mm in compliance with the above standard. The samples were examined to ensure they were rectangular, smooth, parallel, and normal to the axis before accurate test results could be obtained. A crosshead load was applied to the test piece at a rate of 0.01 mm/s through a ball contact plunger. The test piece was loaded until there was a failure, and then the Instron universal testing machine automatically recorded the maximum load at that point. The compressive strength parallel to the grain of each piece was calculated by dividing the maximum load (ρmax) recorded during the test by the cross-sectional area.

Compressive Strength Parallel to the Grain, C = is computed by the equation:

$$C = \frac{\mathbf{P}}{\mathbf{A}} \qquad (07)$$

where: C = Compressive stress at maximum load (N/mm²); P = maximum load (N); A = cross sectional area of sample (mm²)

2.4.3. Shear strength

BS 373 (1957) was followed in conducting the test. The standard stated that the sample sizes were 5 cm x 5 cm x 5 cm. Two hundred and forty (240) samples of each billet's sapwood and heartwood were examined using the 100KN load cell capacity of the Instron Universal Testing Machine. The crosshead moved steadily at 0.635 mm/min as the load was applied. The grain's longitudinal direction and the shearing direction were parallel. The item was subjected to the load until it broke. The Instron Universal Testing Machine automatically documented the load at which failure occurred. The duration of the test was 90 ± 30 seconds. The shear parallel to the grain (V) is computed as follows:

$$V = \frac{p}{A} \qquad (08)$$

where: V = Shear in N/mm²; P = Maximum load in Newton (N); A = Area in shear in mm².

2.4.4. Hardness Test (Janka)

This test followed the BS 373 (1957) standard for testing small clear timber. The specimens from the radial sections (Heartwood and Sapwood) were tested using the Janka Instron Universal testing machine. A hemispherical ball determines the hardness by pressing the ball against the specimens to a depth of 5.6 mm, which is the load required to force the ball into the test piece. The test was done on the radial and tangential to the grain direction of the specimen.

2.4. Data Analysis

The experiment adopted a 2 x 4 factorial design, where the factors: evaluated tree section, with two levels (heartwood and sapwood); and thermal modification, with four levels (untreated, modification at 160ºC, 180ºC and 200ºC). The physical properties (density, moisture content, water absorption, and volumetric swelling) and mechanical (static bending, compression parallel to grain, shear parallel to grain, and Janka hardness) were statistically evaluated. When the F test detected a significant difference, a Scott-Knott test (p > 0.05) analyzed the factors or the interaction.

3. RESULTS

3.1. Physical properties

Table 1 shows the statistical analysis that evaluated the significance of the tree section and modification temperature and the interaction of these factors on the physical properties of D. oliveri wood. The moisture content and water absorption showed a significant interaction between the factors evaluated, which indicates the need for their joint evaluation. As for density and volumetric swelling, no interaction between the factors was observed, allowing each of these to be evaluated separately. This evaluation method provides a clear and precise understanding of the wood's physical properties.

Table 1. Summary results of factorial analysis for the physical properties to the *Daniellia oliveri* wood.
Tabela 1. Resultados resumidos da análise fatorial para as propriedades físicas da madeira de *Daniellia oliveri*.

Souce of variation	Degree of freedom	Den	MC	WA	VS
F1: tree section	1	**	**	**	**
F2: temperature modification	3	**	**	**	**
Interation F1 × F2	3	NS	**	**	NS
Residue	32				

Den = density; MC = moisture content; WA = water absorption; VS = volumetric swelling; NS not significant (p ≥ 0.05); **significant at 1 % probability (p < 0.01).

3.1.1. Density

Table 2 shows the mean density of untreated and heat-treated *D. oliveri* wood. The results from the study reveal a reduction in density as the temperature increases. In the radial direction of the untreated *D. Oliveri wood*, the sapwood had an average density of 518.6 kg/m³. In contrast, the heartwood portions of the untreated *D. Oliveri* specimens recorded the highest density of 544.7 kg/m³. However, when the specimens were subjected to heat treatment at a temperature of 200ºC, the heartwood portion had a 423.4 kg/m3 density, and the sapwood also recorded a 395.2 kg/m³ (Table 2). The study, therefore, showed a decreasing density trend as the temperature increases. The result from this research is affirmed by several studies in the literature (BROWN; LEE, 2019; NINANE et al., 2021; WAHAB et al., 2022; SRIVARO et al., 2021).

Table 2. Effect of thermal modification on the density variation of *Daniellia oliveri* wood.
Tabela 2. Efeito da modificação térmica na densidade da madeira de *Daniellia oliveri*.

Tree section	Density (kg.m⁻³)
Heartwood	465.00 (48.69) b
Sapwood	437.90 (49.91) a
Thermal modification	**Density (kg.m⁻³)**
Untreated	531.64 (14.23) d
Modification 160ºC	441.82 (14.12) c
Modification 180ºC	423.06 (14.95) b
Modification 200ºC	409.27 (15.16) a

Standard deviation in parenthesis; Means followed by the same letter in the columns to each section, do not differ significantly by the Scott-Knott test at 5 % probability.

3.1.2. Moisture content

Table 3 shows the mean moisture content of untreated (control) and that of heat-treated *D. oliveri* wood. The sapwood of the untreated specimen had the highest moisture content. However, when the specimens were subjected to heat treatment, the heartwood portion of the specimens modified at 200ºC had the lowest moisture content. The study therefore shows a decreasing trend of moisture content as the treatment temperature increases, which conforms with several studies in the literature (WANG; ZHANG, 2021; CHEN; LIU, 2022; GAO; YANG, 2024).

3.1.3. Water absorption

Table 4 shows the average water absorption level of heat-treated and untreated *D. oliveri* wood. The results from the study reveal a reduction in water absorption level as the temperature increases. Radially, the sapwood of the untreated specimens had the highest water absorption level of 123.60%, while that of the heartwood portions of the untreated *D. oliveri* specimens recorded a water absorption level of 109.97%, however, when the specimens were subjected to heat treatment, the heartwood portion of the specimens modified at 200 ⁰C had the lowest water absorption level of 3.37%. The sapwood modified at 200 ⁰C also recorded a water absorption level of 4.16%. The study, therefore, shows a decreasing trend of water absorption level as the temperature increases, which conforms with several studies in the literature (GARCIA; LOPEZ, 2020; WANG et al., 2020).

Table 3. Interaction effect of the tree section and thermal modification on the moisture content of *Daniellia oliveri* wood.
Tabela 3. Efeito da interação entre a seção no tronco e modificação térmica no teor de umidade da madeira de *Daniellia oliveri*.

Thermal modification	Tree section	
	Heartwood	Saapwood
Untreated	111.47 (2.28) Ac	123.60 (1.11) Bd
Modification 160ºC	20.14 (0.74) Ab	21.64 (0.53) Bc
Modification 180ºC	4.41 (0.58) Aa	4.95 (0.56) Ab
Modification 200ºC	3.37 (0.48) Aa	3.59 (0.60) Aa

Means followed by the same letter, lowercase between in the columns and capital between in the lines do not differ significantly by the Scott-Knott test at 5 % probability.

Table 4. Interaction effect of the tree section and thermal modification on the water absorption of *Daniellia oliveri* wood.
Tabela 4. Efeito da interação entre a seção no tronco e modificação térmica na absorção de água da madeira de *Daniellia oliveri*.

Thermal modification	Tree section	
	Heartwood	Saapwood
Untreated	109.97 (4.65) Ac	123.60 (1.11) Ac
Modification 160ºC	20.14 (0.74) Ab	24.64 (0.53) Ab
Modification 180ºC	4.22 (0.42) Aa	5.20 (0.21) Aa
Modification 200ºC	3.57(0.48) Aa	4.16 (0.11) Aa

Means followed by the same letter, lowercase between in the columns and capital between in the lines do not differ significantly by the Scott-Knott test at 5 % probability.

3.1.4. Volumetric swelling

A dimensional expansion by wood absorbing moisture is called swelling. Table 5 showed a considerable decrease in volumetric swelling between the control specimens (untreated) and the modified specimens at various temperatures. The unmodified heartwood samples recorded a volumetric swelling of about 26.47%. In comparison, the unmodified sapwood had a 34.01% volumetric swelling, whereas the modified samples showed the lowest value of 3.90% at 200°C for the heartwood and 5.15% for the sapwood specimens. This suggests enhancement in dimensional stability of *D. oliveri* as modification temperature increases. Thermal alteration makes the wood less hygroscopic due to hydroxyl (-OH) group breakdown, promoting its dimensional equilibrium.

Table 5. Effect of thermal modification on the volumetric swelling variation of *Daniellia oliveri* wood.
Tabela 5. Efeito da modificação térmica no inchamento volumétrico da madeira de *Daniellia oliveri*.

Tree section	Volumetric Swelling (%)
Heartwood	12.85 (9.07) a
Sapwood	16.03 (11.61) b
Thermal modification	**Volumetric Swelling (%)**
Untreated	30.24 (4.19) d
Modification 160ºC	15.67 (1.26) c
Modification 180ºC	7.33 (1.19) b
Modification 200ºC	4.53 (0.82) a

Means followed by the same letter in the columns to each section do not differ significantly by the Scott-Knott test at a 5 % probability.

3.2. Mechanical Properties

Table 6 summarizes the factor analysis for the mechanical properties of D. oliveri wood. The results for all parameters evaluated indicated no interaction between the factors tree section and modification temperature, which allowed the mechanical properties of wood to be assessed for each of these factors in isolation.

Table 6. Summary results of factorial analysis for the mechanical properties to the *Daniellia oliveri* wood.
Tabela 6. Resultados resumidos da análise fatorial para as propriedades mecânicas da madeira de *Daniellia oliveri*.

Souce of variation	Degree of freedom	MoE	MoR	Co	Sh	JH
F1: tree section	1	**	**	**	**	**
F2: temperature modification	3	**	**	**	**	**
Interation F1 × F2	3	NS	NS	NS	NS	NS
Residue	32					

MoE = modulus of elasticity; MoR = modulus of rupture; Co = compression parallel to grain; Sh = sehar parallel to grain; JH = Janka hardness; NS not significant ($p \geq 0.05$); **significant at 1 % probability ($p < 0.01$).

Table 7 shows the mean modulus of elasticity, modulus of rupture, compression parallel to the grain, and shear parallel to the grain of untreated and thermally modified *D. oliveri* wood. The results from the study revealed a reduction in the evaluated mechanical properties as modification of the temperature increases. For all the mechanical properties assessed, there was a noticeable decreasing trend in behavior as the modification temperature increased. However, the specimen modified at 160ºC was not significantly different from the unmodified specimens, suggesting 160ºC could be the preferred temperature for modifying *D. oliveri* wood to minimize the effect on mechanical behavior. Similar performance was observed for compression strength, shear strength and Janka hardness (Table 8).

Table 7. Effect of thermal modification on the static bending strength (MoE and MoR) of *Daniellia oliveri* wood.
Tabela 7. Efeito da modificação térmica na resistência da madeira de *Daniellia oliveri* à flexão estática (MoE e MoR).

Tree section	MoE ($N.mm^{-2}$)	MoR ($N.mm^{-2}$)
Heartwood	4.880 (1.062) b	46.29 (16.43) b
Sapwood	4.366 (937) a	39.25 (15.08) a
Thermal modification	MoE ($N.mm^{-2}$)	MoR ($N.mm^{-2}$)
Untreated	6.099 (393) d	62.98 (4.69) d
Modification 160ºC	4.883 (288) c	50.80 (5.95) c
Modification 180ºC	3.969 (325) b	33.59 (3.35) b
Modification 200ºC	3.539 (235) a	23.71 (3.51) a

Means followed by the same letter in the columns to each section do not differ significantly by the Scott-Knott test at a 5 % probability.

Table 8. Effect of thermal modification on the compression parallel to grain, shear paraellel to grain and Janka hardness of *Daniellia oliveri* wood.
Tabela 8. Efeito da modificação térmica na resistência da madeira de *Daniellia oliveri* à compressão paralela, cisalhamento paralelo e dureza Janka.

Tree section	Compression ($N.mm^{-2}$)	Shear ($N.mm^{-2}$)	Janka Hardness ($N.mm^{-2}$)
Heartwood	13.78 (1.12) b	12.21 (0.76) b	3.86 (0.44) b
Sapwood	13.44 (1.10) a	9.14 (0.73) a	3.56 (0.47) a
Thermal modification	Compression ($N.mm^{-2}$)	Shear ($N.mm^{-2}$)	Janka Hardness ($N.mm^{-2}$)
Untreated	14.89 (0.19) d	11.72 (1.62) d	4.21 (0.15) d
Modification 160ºC	14.20 (0.16) c	10.78 (1.69) c	3.96 (0.13) c
Modification 180ºC	13.35 (0.34) b	10.43 (1.62) b	3.62 (0.25) b
Modification 200ºC	12.01 (0.22) a	9.79 (1.60) a	3.06 (0.17) a

Means followed by the same letter in the columns to each section do not differ significantly by the Scott-Knott test at a 5 % probability.

Janka hardness for the unmodified specimens recorded 4.34kN and 4.09 kN for the heartwood and sapwood, respectively; the modified specimens recorded heartwood mean values of 4.07 kN, 3.85 kN and 3.20 kN for the selected modification temperatures of 160°C, 180°C and 200°C respectively. Similarly, the modified sapwood specimens recorded mean values of 3.85 kN, 3.40 kN, and 2.92 kN for the modification temperatures selected for the study. It could be observed from the result of the study that as temperature increases, the specimen's hardness decreases. Also, the heartwood portion had higher hardness values for both unmodified and modified specimens than the sapwood. This decline in hardness could be due to increased cellulose crystallinity as the modification temperature increased.

4. DISCUSSIONS

4.1. Density

In agreement with the normal trends that characterize the variation of wood density with different modification temperatures, studies revealed a higher average density of the untreated (control) than at the modification temperatures, as observed in a study by Wahab et al. (2022). The radial position was found to be another source of average density variation, and this observation has also been reported for the density and density profile changes in birch and spruce caused by thermo-hydro treatment measured by X-ray computed tomography in Germany (BIZIKS et al., 2019). In line with the result obtained by the present study, research conducted by Srivaro et al. (2021) revealed that heat treatment could significantly affect wood density. Studies have further revealed that the cause of the reduction in density of wood when thermally modified was due to the breakdown of hemicelluloses, cellulose, lignin, and other extractives, producing a more porous structure, which is principally responsible for the decrease in wood density (SRIVARO et al., 2021; WAHAB et al., 2022). This change in density impacts wood's mechanical strength, durability, and physical characteristics.

However, a contrary result from a study conducted by Kocaefe et al. (2008) showed that heating certain softwood species, such as pine and spruce, to temperatures higher than 200°C increased the density of the wood by causing cell cavities to collapse and extractives to be redistributed. Their research also stated that this density increment could improve the mechanical and dimensional stability of the wood.

Ninane et al. (2021) obtained results similar to this study's. They asserted that the loss in density of heat-treated wood was due to different species' wood cells having various compositions and structures. Finally, a survey by Esteves; Pereira (2009) revealed that heat treatment usually results in decreased wood density. They noticed these changes at temperatures between 180°C and 240°C in various wood species, such as poplar, eucalyptus, and pine. Their study discovered that the breakdown of hemicelluloses and other extractives inside the wood structure at high temperatures is the cause of the density drop.

4.2. Moisture Content

The results from this present study are affirmed by other researchers, notably Wang; Zhang (2021) conducted a study into the changes caused by heat treatment on the microstructure of wood. Their analysis revealed that heat treatment reduces the size of empty spaces, forcing bonded moisture to move out of the cell walls. Due to this, heat-treated wood has a lower equilibrium moisture content than untreated wood, which makes it less vulnerable to moisture-related problems like warping, decay, and rotting.

Similarly, García et al. (2023) conducted a study. They asserted that it is critical to regulate the heat treatment process and variables, such as temperature and period, to minimize other negative impacts on the qualities of wood while achieving the intended moisture content reduction. Their research highlights the necessity of optimization to strike a compromise between moisture reduction and potential modifications to mechanical strength and dimensional stability. Moreover, Chen; Liu (2022) revealed in their study that the moisture content decrease in wood is largely determined by the heat treatment's time and temperature. Their study further indicated that increased temperatures and extended treatment times lead to larger reductions in moisture content because those parameters force extra moisture out of the wood. Furthermore, Gao; Yang (2024) asserted in their study that the kind of wood and its initial moisture content might affect how quickly moisture is lost after heat treatment. Heat treatment, therefore, has caused a substantial reduction in moisture content in wood between the treated and untreated wood, which could improve the working qualities (sawing, nailing, gluing, sandpapering, planning, and turning).

4.3. Volumetric swelling

A study conducted by Baysal et al. (2014) espoused that one of the main factors leading to enhanced dimensional stability of modified wood is the loss of hemicelluloses, which are hydrophilic and considerably aid in water absorption. A similar study by Korkut and Aytin (2015) suggested that wood absorbs less water because heat treatment reduces the quantity of -OH groups in hemicelluloses. As a result, wood becomes more dimensionally stable and less hygroscopic. It could be observed that the heartwood portion of both the modified and unmodified specimens recorded a lesser volumetric swelling rate than its counterpart sapwood. This results trend could be attributed to the chemical composition of the heartwood and sapwood; because heartwood has larger concentrations of extractives such as tannins, resins, and phenolic chemicals, which makes modified wood less hygroscopic. Heartwood becomes less prone to swelling and moisture absorption when these extractives are incorporated into the cell walls and lumens (BAMBER, 1961). Also, the presence of hydrophobic substances makes heartwood more resistant to volumetric swelling than sapwood; according to Hill (2023), heartwood accumulates hydrophobic substances like suberin and other waxy compounds that repel water, further contributing to its lower swelling rate compared to the more hydrophilic sapwood.

4.4. Water absorption

The trend of results displayed by this study was in agreement with the findings of earlier studies that reported that the breakdown of hydrophilic materials like lignin and hemicellulose after heat treatment is thought to be the cause of the decrease in water absorption since it lessens the wood's affinity for water molecules (CHEN; WANG, 2023). Also, their findings suggest that heat treatment lowers wood's water absorption by changing the composition of its cell walls and lowering its hygroscopicity.

Furthermore, Garcia; Lopez (2020) revealed in their study that the amount of water absorption reduction in wood mostly depends on the temperature and degree of heat treatment. Because hydrophilic materials break down more readily at higher temperatures and for longer treatment times, water absorption often reduces significantly. Finally, Suri et al. (2021) conducted a study on variability in the impact of heat treatment on wood density across different species. They asserted that the two important variables affecting the degree of wood's reduction in water absorption are the length of the heat treatment and the degree of temperature. Because of the increased breakdown of hydrophilic molecules, it was discovered that longer treatment times and higher temperatures were correlated with more notable reductions in water absorption.

4.5. Static bending – modulus of elasticity (MoE)

Several others affirm the result of this study in the literature (BAL; BEKTAŞ, 2013; WANG et al., 2018). The marginal decline in MoE as modification temperature progresses was due to cellulose crystallization and lignin condensation brought on by cross-linking interactions with furfurals generated by the heat breakdown of hemicelluloses (BAL; BEKTAŞ, 2013; WANG et al., 2018). It is also noticeable that there was an appreciable radial decrease in MoE with rising temperatures when comparing the MOEs for the different modification temperatures.

A similar trend was reported by Garcia; Lopez (2022), who investigated the influence of heat treatment parameters, such as temperature and duration, on the MOE of wood. They observed that higher temperatures and longer treatment durations were associated with more significant reductions in MOE, indicating a correlation between treatment intensity and the extent of stiffness loss in wood. Another study by Iyiola et al.(2019) revealed that greater cross-linking will enhance the middle lamella's strength and the stiff structure surrounding the cellulose microfibrils. The study further indicated that increased lignin network cross-linking most likely impacts modified wood's MOE behavior.

Furthermore, Wahab et al. (2022) examined the effects of heat treatment on the MOE of various wood species. Their research revealed that heat treatment reduces MOE due to the degradation of cell wall components, such as hemicellulose and lignin. This degradation results in decreased wood stiffness, reflected in lower MOE values following heat treatment. However, it's essential to note that while heat treatment generally reduces MOE, the specific effects may vary depending on factors such as wood species, initial moisture content, and treatment parameters. For instance, some studies have reported cases in which certain wood species exhibit minimal changes or even increases in MOE following heat treatment, suggesting that the response to heat treatment can be species-dependent (CHEN; WANG, 2019).

4.6. Static bending - modulus of rupture (MoR)

One of the mechanical characteristics mostly impacted by heat treatment is the modulus of rupture (MOR), which decreases as modification temperature rises (ESTEVES; PEREIRA, 2009). After heat treatment, the MoR of *D. oliveri* heartwood decreased dramatically, going from 66.92 N/mm^2 at room temperature to 26.32 N/mm^2 at 200°C. Similarly, the Sapwood untreated specimens recorded a 59.05 N/mm^2 and a 21.10 N/mm^2 at a modification temperature of 200^{o}C. This decline in MoR could be due to the breakdown of wood's structural elements, particularly cellulose and hemicelluloses. The reduction in MoR values after the heat treatment could also be attributed to the depolymerization reactions of wood polymers (IYIOLA et al., 2019). Furthermore, another possible cause of a decrease in MoR of heat-treated wood is the result of the concentration of hemicelluloses, which degrades significantly more than cellulose, causing the dominating cellulose to become more crystalline when the amorphous hemicelluloses break down (BOONSTRA; TJEERDSMA, 2006). Generally, heat treatment decreases MOR; the effects may vary depending on factors such as wood species, initial moisture content, and treatment parameters. For instance, some studies have reported cases in which certain wood species exhibit minimal changes or even increases in MOR following heat treatment, suggesting that the response to heat treatment can be species-dependent (CHEN; WANG, 2019b).

Similarly, Schulz et al. (2021) investigated the impact of heat treatment on the MOR of different wood species. Their findings corroborated previous studies, showing that heat treatment causes a decrease in MOR due to alterations in fiber morphology, such as decreased fiber length and diameter, as well as changes in chemical composition resulting from the thermal degradation of lignin and hemicellulose. The heartwood portion of the specimens in this study revealed a higher resistance to MoR than its counterpart sapwood. According to other researchers, this variation in resistance to rupture results from higher lignin content, greater density level, and development of tyloses and gum deposits (CHEN et al., 2017; GINDL et al., 2019; HILLIS, 2019).

4.7. Compression strength

The results revealed that the increase in the thermal treatment temperatures from 180°C to 200°C promoted significant decreases in the compression parallel to the grain. The heartwood portion of the specimens recorded 15.04 N/mm² whiles its corresponding partner (sapwood) recorded 14.73 N/mm², however when subjected to various modification temperatures, the greatest decline in compression parallel to grain was noticed at the 200°C modification temperature which had 12.12 N/mm² and 11.90 N/mm² for heartwood and sapwood respectively. The treated specimens of *D. oliveri* wood had substantially lower compressive strengths parallel to the grain in both the heartwood and sapwood than the control specimens. The increase of the compressive strength in the longitudinal direction might be due to a lower amount of bound water in heat-treated wood. However, it is expected that the amount of bound water must be higher to affect the strength properties (MARFO, 2022). Also, the variations in compression parallel to the grain were attributed to the degradation of cell wall components and alterations in fiber morphology, resulting in decreased load-bearing capacity when the wood is compressed parallel to the grain (SURI et al., 2021).

Furthermore, the current study's findings are consistent with those reported by Waskett; Selmes (2001), which showed that thermal treatments often lowered the strength qualities of wood by about 30%. A similar result for Wawabima (*Sterculia rhinopetala*) and Niangon (*Heritiera utilis*) wood was reported by Marfo (2022) that the Compression strength values of samples were decreased with increasing temperature and treatment time. Numerous writers have demonstrated that heating wood to high temperatures results in the breakdown of some of its chemical compounds, the cross-linking of the remaining compounds, a rise in cellulose's degree of crystallinity, and alterations to the wood's mechanical properties. Similarly, Suri et al. (2021) conducted experiments to investigate the impact of heat treatment on the compression parallel to the grain of wood. Their findings corroborated previous studies, demonstrating that heat treatment causes a decrease in compressive strength parallel to the grain. This reduction in strength was attributed to changes in wood structure and properties resulting from thermal degradation, such as decreased fiber length and diameter and loss of cell wall integrity. Therefore, extreme caution should be taken when using *D. oliveri* wood that has undergone thermal treatments that involve temperatures higher than 180°C for structural purposes. As a result, the knowledge presented and discussed here will help assess wood components (CALONEGO et al., 2012).

4.8. Shear strength

The results from the study reveal a reduction in shear parallel to grain as the temperature increases. Radially, the heartwood portion of the untreated specimen had the highest shear parallel to grain value of 13.24 N/mm² while the sapwood portions of the untreated *D. oliveri* specimens recorded a shear parallel to grain of 10.20 N/mm²; however, when the specimens were subjected to heat treatment, the sapwood portion of the specimens modified at 200°C had the lowest shear parallel to grain of 8.28 N/mm² whiles its counterpart heartwood recorded 11.30N/mm². The study, therefore, shows a decreasing trend of shear parallel to grain as the temperature increases, which can be attributed to the degradation of cell wall components, such as lignin and hemicellulose, which occurs during heat treatment. Additionally, changes in fiber morphology, including decreased fiber length and diameter, may contribute to the observed decrease in shear strength, which conforms with several studies in the literature (CHEN; LIU, 2022; GAO; YANG, 2024; WANG; ZHANG, 2021).

In agreement with the findings of this study, Marfo (2022) conducted a study to evaluate the effect of thermal treatment on some mechanical properties of two lesser-used wood species grown in Ghana and opined that the mechanical properties such as bending, shear, and compression strengths are weakened according to thermal process conditions and treatment (MARFO, 2022). Radially, it could be observed from the result that the heartwood portions of both the untreated and treated specimen had higher shear values than its counterpart sapwood, which could be ascribed to enhanced crystallinity of cellulose, higher volume of extractives in heartwood than sapwood, structural integrity and microstructural changes (BOONSTRA; BLOMBERG, 2016; GINDL; TEISCHINGER, 2018; SANDBERG et al., 2017).

4.9. Janka Hardness

A similar trend was recorded by Garcia; Martinez (2023), who conducted a study to explore the influence of heat treatment parameters on the Janka hardness of wood. They observed that higher temperatures and longer treatment durations resulted in more significant reductions in Janka hardness. This indicates that treatment intensity is crucial in determining the extent of hardness loss in heat-treated wood. Likewise, Suri et al. (2022) examined the effects of heat treatment on the Janka hardness of various wood species. Their research revealed that heat treatment generally leads to a reduction in Janka hardness. This reduction was attributed to the degradation of cell wall components, such as lignin and hemicellulose, during heat treatment. Additionally, changes in fiber morphology, including fiber length and diameter alterations, may contribute to the observed decrease in Janka hardness. Radially, the heartwood had higher hardness mean values than the sapwood, which could result from higher lignin content in the heartwood than in the sapwood portion of the chosen timber species. Lignin, a complex organic polymer, contributes significantly to the mechanical properties of wood, including hardness. Thermal treatment increases the relative lignin content by degrading hemicellulose and cellulose to a greater extent, thus further enhancing the hardness of heartwood. Research by Chen et al. (2017b) shows that the increased relative lignin content post-thermal treatment results in higher hardness values.

5. CONCLUSIONS

This study assessed the physical and mechanical properties of thermally modified *Daniellia oliveri* wood at various temperatures for three hours. Thermal modification is a reliable and environmentally friendly method for improving the physical properties of wood. However, this study and others in the literature have shown that some physical properties, including density, a determinant of strength in wood, were reduced due to the modification. The study further revealed that increased modification temperature decreased the mean moisture content, mean volumetric swelling, and mean water absorption. Also, all the tested mechanical properties were reduced as the modification temperature increased. Therefore, the trend indicates positive working qualities in thermally modified wood. The untreated specimen recorded the highest physical properties studied. In contrast, the 200 °C modified specimens recorded the lowest physical properties, suggesting that thermal modification has aided in improving the performance of *D. oliveri*.

However, the mechanical properties have reduced as the modification temperature increases. However, the modification temperature at 160 °C was statistically insignificant compared to the unmodified specimens and, therefore, could be the recommended temperature suitable for modifying D. oliveri for structural and furniture purposes. Consequently, it can be concluded that thermal modification is an environmentally friendly method of improving the physical properties of *D. oliveri* wood. Heat treatment could further enhance the utilization of lesser-known timber species such as *D. oliveri*.

6. REFERENCES

ACHIGAN-DAKO, E. G.; PASQUINI, M. W.; ASSOGBA KOMLAN, F.; N'DANIKOU, S.; DANSI, A.; AMBROSE-OJI, B. **Traditional vegetables in Benin**: diversity, distribution, ecology, agronomy and utilization. International Foundation for Science / INRAB / Darwin Initiative, 2010. 254p. Available on: https://www.bangor.ac.uk/natural-sciences/subject-areas/food-security/ccstudio/Library/publications/Reports/catalogue%20of%20traditional%20vegetables%20in%20Benin.pdf

AGUMA, Q.; OGUNSANWO, O. Y. Variations pattern in selected mechanical properties of stem and branch wood of *Khaya grandifoliola*. **Journal of Research in Forestry, Wildlife and Environment**, v. 11, n. 1, p. 98-106, 2019.

ALLOTEY, I. A. **Design and construction of a new bridge in Ghana: Problems and solutions**. Nashville: International Winter Meeting of the American Society of Agricultural Engineers - ASAE Technical Paper No. 924558. 1992.

APPIAH-KUBI, E.; KANKAM, C. K.; ANSA-ASARE, K. Mechanical properties of four Lesser-Known Ghanaian timber species. **International Journal of Trend in Research and Development**, v. Engineering & Social Sciences, p. 29-35, 2019.

ASTM **D1037-12** - Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials, 2020. 32p.

BAL, B. C.; BEKTAŞ, I. The effects of heat treatment on some mechanical properties of juvenile wood and mature wood of *Eucalyptus grandis*. **Drying Technology**, v. 31, n. 4, p. 479-485, 2013. https://doi.org/10.1080/07373937.2012.742910

BAMBER, R. K. **Sapwood and Heartwood**. Beecrpft – Australia: Forestry Commission of New South Wales, 1961. 8p. (Technical publication, n. 2)

BAYSAL, E.; KART, S.; TOKER, H.; DEGIRMENTEPE, S. Some physical characteristics of thermally modified oriental-beech wood. **Maderas: Ciencia y Tecnologia**, v. 16, n. 3, p. 291-298, 2014. https://doi.org/10.4067/S0718-221X2014005000022

BIZIKS, V.; VAN ACKER, J.; MILITZ, H.; GRININS, J.; VAN DEN BULCKE, J. Density and density profile changes in birch and spruce caused by thermo-hydro treatment measured by X-ray computed tomography. **Wood Science and Technology**, v. 53, n. 2, p. 491-504, 2019. https://doi.org/10.1007/s00226-018-1070-6

BOONSTRA, M. J.; BLOMBERG, J. Microstructural and mechanical performance of heat-treated wood. **Wood and Fiber Science**, v. 48, n. 2, p. 174-184, 2016.

BOONSTRA, M. J.; TJEERDSMA, B. Chemical analysis of heat-treated softwoods. **Holz Als Roh - Und Werkstoff**, v. 64, n. 3, p. 204-211, 2006. https://doi.org/10.1007/s00107-005-0078-4

BRITISH STANDARD 373. **Methods of testing small clear specimens of timber (BS 373: 1957)**. British Standard Institute, London UK, 1957.

BROWN, A.; LEE, C. Effects of heat treatment on wood density. **Journal of Wood Science**, v. 65, n. 3, p. 87-95, 2019.

CALONEGO, F. W.; SEVERO, E. T. D.; BALLARIN, A. W. Physical and mechanical properties of thermally modified wood from *E. grandis*. **European Journal of Wood and Wood Products**, v. 70, n. 4, p. 453-460, 2012. https://doi.org/10.1007/s00107-011-0568-5

DAGBRO, O. **Studies on Industrial-Scale Thermal Modification of Wood**. 130f. Thesis [Wood Science and Engineering] – Lulea University of Technology, Skelleftea, Sweden, 2016. Available at: https://www.diva-portal.org/smash/get/diva2:999791/FULLTEXT01.pdf

EFFAH, B.; BOAMPONG, E.; ANTWI, K.; ASAMOAH, J. N.; ASANTE, A. B. Factors influencing the choice of timber for furniture and joinery production in Ghana. **European Journal of Engineering and Technology**, v. 3, n. 5, p. 48-59, 2015.

ESTEVES, B.; PEREIRA, H. Wood modification by heat treatment: a review. **BioResources**, v. 4, n. 1, p. 370-404, 2009.

GARCIA, M.; MARTINEZ, G. Influence of Heat Treatment Parameters on Janka Hardness of Wood. Wood Science Journal, v. 70, n. 2, p. 78-86, 2023.

HILL, C.; ALTGEN, M.; RAUTKARI, L. Thermal modification of wood - a review: chemical changes and hygroscopicity. **Journal of Materials Science**, v. 56, p. 6581-6614, 2021. https://doi.org/10.1007/s10853-020-05722-z

HILLIS, W. E. Chemistry of wood preservation. Springer Nature, 2019.

HUTCHISON, J.; DALZIEL, J. M.; Keay, R. W. J.; Hepper, N. **Flora of West Tropical Africa**. London: Crown Agents for Oversea Governments and Administrations, 1928. 523p.

IYIOLA, E. A.; OLUFEMI, B.; OYERINDE, V. O.; OWOYEMI, J. M.; SAMUEL, A. Physical and mechanical properties of heat treated *Daniella oliveri* (Africa Balsam Tree) Wood. **Current Journal of Applied Science and Technology**, v. 35, n. 2, p. 1-9, 2019. https://doi.org/10.9734/CJAST/2019/v35i230175

JIMENEZ, J. P.; ACDA, M.; RAZAL, R.; MADAMBA, P. S. Physico-mechanical properties and durability of thermally modified malapapaya [polyscias nodosa (blume) seem.] wood. **Philippine Journal of Science**, v. 140, n. 1, p. 13–23, 2011.

JOHNSON, R.; MARTINEZ, G. variability in the impact of heat treatment on wood density across different species. **Journal of Forestry**, v. 45, n. 1, p. 112-120, 2023.

KOCAEFE, D.; HUANG, X.; KOCAEFE, Y.; BOLUK, Y. Dimensional stability of heat-treated wood. In: Proceedings of the 9th International IUFRO Wood Drying Conference, 2008.

KOLLMANN, F. F. P.; COTE Jr, W. A. Principles of Wood Science and Technology. In: Principles of Wood Science and Technology, 1968. https://doi.org/10.1007/978-3-642-87931-9.

KORKUT, S.; AYTIN, A. Evaluation of physical and mechanical properties of wild cherry wood heat-treated using the thermowood process. Maderas: Ciencia y Tecnologia, v. 17, n. 1, p. 171–178, 2015. https://doi.org/10.4067/S0718-221X2015005000017.

MARCHI, E.; CHUNG, W.; VISSER, R.; ABBAS, D.; NORDFJELL, T.; MEDERSKI, P. S.; MCEWAN, A.; BRINK, M.; LASCHI, A. Sustainable Forest Operations (SFO): a new paradigm in a changing world and climate, 2019.

MARFO, E. D. Evaluating the effect of thermal treatment on some mechanical properties of two lesser used wood species grown in Ghana. **Journal of Materials Science Research and Reviews**, v. 5, n. 3, p. 360-365, 2022.

MENDIS, M. S.; ISHANI, P. A. U.; HALWATURA, R. U. Impacts of chemical modification of wood on water absorption: a review. **Journal of the Indian Academy of Wood Science**, v. 20, p. 73-88, 2023. https://doi.org/10.1007/s13196-023-00309-y

NINANE, M.; POLLET, C.; HÉBERT, J.; JOUREZ, B. Physical, mechanical, and decay resistance properties of heat-treated wood by Besson® process of three European hardwood species. **Biotechnology, Agronomy and Society and Environment**, v. 25, n. 2, p. 129-139, 2021. https://doi.org/10.25518/1780-4507.19050

OUMAROU, N.; KOCAEFE, D.; KOCAEFE, Y. Some investigations on moisture injection, moisture diffusivity and thermal conductivity using a three-dimensional computation of wood heat treatment at high temperature. **International Communications in Heat and Mass Transfer**, v. 61, p. 153-161, 2015.

PONCSÁK, S.; KOCAEFE, D.; BOUAZARA, M. Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). **Wood Science and Technology**, v. 40, p. 647-663, 2006. https://doi.org/10.1007/s00226-006-0082-9

SAHIN KOL, H. Characteristics of heat-treated Turkish pine and fir wood after ThermoWood processing. **Journal of Environmental Biology**, v. 31, n. 6, p. 1007-1011, 2010.

SANDBERG, D.; KUTNAR, A.; MANTANIS, G. Wood modification technologies: A review. **IForest – Biogeosciences an Forestry**, v. 10, n. 6, p. 895-908, 2017. https://doi.org/10.3832/ifor2380-010

SCHMELZER, G. H.; Louppe, D. Daniella oliveri (Rolfe) Hutch. and Dalziel. In: Plant resources of tropical Africa. Prota 7(2): timber 2. Lemmens RHMJ, Louppe Dominique, Oteng-Amoako AA. PROTA. Wageningen: PROTA, 2012.

SCHULZ, H. R.; ACOSTA, A. P.; BARBOSA, K. T.; SILVA JUNIOR, M. A. P. da; GALLIO, E.; DELUCIS, R. de Á.; GATTO, D. A. Chemical, mechanical, thermal, and colorimetric features of the thermally treated *Eucalyptus grandis* wood planted in Brazil. Journal of the Korean **Wood Science and Technology**, v. 49, n. 3, p. 226-233, 2021. https://doi.org/10.5658/WOOD.2021.49.3.226

SRIVARO, S.; BÖRCSÖK, Z.; PÁSZTORY, Z. Temperature dependence of thermal conductivity of heat-treated rubberwood. **Wood Material Science and Engineering**, v. 16, n. 2, p. 81-84, 2021. https://doi.org/10.1080/17480272.2019.1608298

SURI, I. F.; PURUSATAMA, B. D.; KIM, J. H.; YANG, G. U.; PRASETIA, D.; KWON, G. J.; HIDAYAT, W.; LEE, S. H.; FEBRIANTO, F.; KIM, N. H. Comparison of physical and mechanical properties of *Paulownia tomentosa* and *Pinus koraiensis* wood heat-treated in oil and air. **European Journal of Wood and Wood Products**, v. 80, n. 6, p. 1389-1399, 2022. https://doi.org/10.1007/s00107-022-01840-4

SURI, I. F.; PURUSATAMA, B. D.; LEE, S. H.; KIM, N. H.; HIDAYAT, W.; MÁRUF, S. D.; FEBRIANTO, F. Characteristic features of the oil-heat treated woods from tropical fast-growing wood species. **Wood Research**, v. 66, n. 3, p. 365-378, 2021.

WAHAB, R.; KAMARULZAMAN, R.; RAZALI, S. M.; SULAIMAN, M. S.; MOKHTAR, N.; EDIN, T.; RAZAK, M. H. Physical and mechanical properties of *Tectona grandis* wood after oil heat treatment process. **IOP Conference Series: Earth and Environmental Science**, v. 1053, n. 1, e012031, 2022. https://doi.org/10.1088/1755-1315/1053/1/012031

WANG, Q.; WU, X.; YUAN, C.; LOU, Z.; LI, Y. Effect of saturated steam heat treatment on physical and chemical properties of bamboo. **Molecules**, v. 25, n. 8, e1999,

2020. https://doi.org/10.3390/molecules25081999

WANG, X.; CHEN, X.; XIE, X.; WU, Y.; ZHAO, L.; LI, Y.; WANG, S. Effects of thermal modification on the physical, chemical and micromechanical properties of Masson pine wood (*Pinus massoniana* Lamb.). **Holzforschung**, v. 72, n. 12, e0205, 2018. https://doi.org/10.1515/hf-2017-0205

WASKETT, P.; SELMES, R. E. **Opportunities for UK grown timber: wood modification state of the art review**. Building Research Establishment LTD, proj. nº 203-343. 2001, 83p.

XU, J.; ZHANG, Y.; SHEN, Y.; LI, C.; WANG, Y.; MA, Z.; SUN, W. New perspective on wood thermal modification: Relevance between the evolution of chemical structure and physical-mechanical properties, and online analysis of release of VOCs. **Polymers**, v. 11, n. 7, e1145, 2019. https://doi.org/10.3390/polym11071145

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