Floresta Ambient., Rio de Janeiro, 2025; 32(3): e20250013
https://doi.org/10.1590/2179-8087-FLORAM-2025-0013
ISSN 2179-8087 (online)

Floram
Floresta e Ambiente

ORIGINAL ARTICLE – Forest Products Science and Technology

Thermal Modification Improves the Durability of *Daniellia oliveri* Wood

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Abstract

Wood has long been one of the most widely utilized natural building materials. This study investigated the effect of thermal modification on the durability of *Daniellia oliveri* wood through laboratory and field decay tests. Five mature trees were selected and felled for the experiment. Wood samples were prepared and subjected to thermal treatment at 160, 180, and 200 °C for three hours. The heartwood recorded a mass loss of 25.58% for the untreated wood, while the sapwood showed a slightly higher mass loss of 26.23%. Specimens treated at 200 °C had the highest resistance to mass loss, with 7.08% for the heartwood and 8.73% for the sapwood. Similar trends were observed in the mass loss measured after exposure in the field, where mass loss decreased as the temperature increased. Thermal modification enhanced the resistance of *D. oliveri* wood, thereby increasing its durability and broadening its applications.

Keywords: Thermally modified heartwood, sapwood, fungi, wood decay test, mass loss.

1. INTRODUCTION

Wood is a renewable and sustainable natural material, valued for its high strength-to-weight ratio, ease of processing, and aesthetic appeal, which make it a superior alternative to materials such as plastics and metals (Ramage et al., 2017). According to Evans et al. (2022)8(2, wood serves as a carbon sink, sequestering carbon from the atmosphere, making it an environmentally friendly material. Additionally, the natural aesthetic appearance of wood, including texture, color, and grain, makes it a preferred material compared to others in the furniture and construction industries.

Despite the numerous benefits associated with wood, it has some notable shortfalls, including vulnerability to termite and fungal attacks (Brischke and Alfredsen, 2020). Although wood is a renewable and biodegradable resource, it remains susceptible to biological degradation caused by bacteria, fungi, insects, and marine borers (Brischke et al., 2023). Therefore, thermal modification has been proposed as an effective solution to enhance the natural resistance of wood to biological degradation (Sahin, 2017). Wood's attributes, such as durability, determine its value for a particular end use (Traoré and Cortizas, 2023b).

Wood's material resistance to diverse biotic decay agents varies between species and can be altered by cell wall modification, chemical impregnation, oil heat treatment, and thermal modification (Brischke and Alfredsen, 2023). The primary drawback of wood exposed to external conditions is connected to biodeterioration by termites (Anish et al., 2022). According to Meena (2022), preservation is crucial for extending the lifespan of wood. Wood preservatives such as copper sulfate, zinc chloride, mercuric chloride, and creosote have traditionally been used to protect wood from degrading agents. However, chemicals drained from the wood can threaten the ecosystem, soil health, the environment, and biodiversity (Shukla and Kamdem, 2023).

Due to their toxicity and environmental persistence, several of these compounds are now heavily regulated or banned. In 2003, the US Environmental Protection Agency (EPA) banned chromated copper arsenate (CCA). Similarly, in 2021, the agency announced a ban on the use of chlorpyrifos due to concerns about its impact on human health, particularly children. It is worth appreciating that Lindane was banned by the German government in 2007 due to its toxic effects on the environment and human health. Creosote has been banned in China since 2004 due to its carcinogenic properties (Miranji et al., 2022). Therefore, researchers are exploring ways to preserve wood through strategic techniques and eco-friendly media (Brischke, 2020).

In recent years, modern alternatives have emerged, focusing on reducing both ecological and human health risks. These include micronized copper formulations, tannin and lignin-based biopreservatives (Leng et al., 2024), and nanomaterial systems such as nanosilver or nanocellulose composites (Borges et al., 2018), which aim to enhance durability while minimizing leaching and toxicity (Hasanagić et al., 2023). Nonetheless, even these newer preservatives raise concerns about long-term environmental impacts, reinforcing the demand for more sustainable and non-chemical solutions, such as thermal modification.

Thermal modification technology is an eco-friendly and efficient method for enhancing wood durability, developed to address the challenges posed by wood materials in outdoor exposure. Thermal modification refers to the structural, mechanical, and chemical transformations that occur in lignocellulosic materials when they are gradually heated to specific temperature ranges (Godinho et al., 2021). Heat treatment has gained worldwide attention as an environmentally friendly method for wood protection because untreated wood is hydrophilic. In contrast, the heat-treated wood is hydrophobic with increasing heat treatment temperature (Hill, 2006).

Daniellia oliveri (Rolfe) Hutch. and Dalz. wood, popularly known as African balsam wood, is a remarkable tree species with significant ecological and commercial importance throughout the African continent (Alagbe et al., 2020). *D. oliveri* is endemically found in several African nations, such as Equatorial Guinea, Gabon, Nigeria, Cameroon, Ghana, and the Democratic Republic of Congo (Rowell, 2002). Rowell (2002) stated that this wood is locally used for packing cases, drainage boards, cattle troughs, veneers, plywood production, hardboard, and particleboard; it is also used for light flooring, joinery, interior trim, furniture, boat building, toys, and curiosities.

D. oliveri is a neglected tropical species that benefits the local economy and people's health (Atolani and Olatunji, 2016). Bark extract from *D. oliveri* trees is used to treat gastrointestinal parasites. Its resin is used as a mosquito repellent during the rainy season in nations like the Gambia (Biddinger et al., 2019). The wood of the *D. oliveri* tree is highly valued for its suitability in carving, furniture production, building, and construction purposes, among others. However, its use is limited by its limited resistance to xylophage action. Hence, enhancing its durability properties using an eco-friendly approach will significantly interest the wood industry. Therefore, the present research aims to assess the efficacy of thermal treatment on the natural durability of *Daniellia oliveri* wood.

2. MATERIAL AND METHODS

2.1. Sample collection and preparation

Five mature Daniellia oliveri trees, aged 25 years, 33 years, 38 years, 41 years, and 48 years. Due to their prominence and abundance within the locality, the trees were cut down in the community's woodland in Du-west (10.77365° W, -2.44666° S). After the trees chosen had been felled, a sectional length of 1 meter was taken from each tree at the bottom part. The trees had approximately 12 m long clear boles and a diameter of 60–80 cm at breast height, 1.5 m above ground level. The quarter-sawing technique was used to transform the billets into boards (Figure 1).

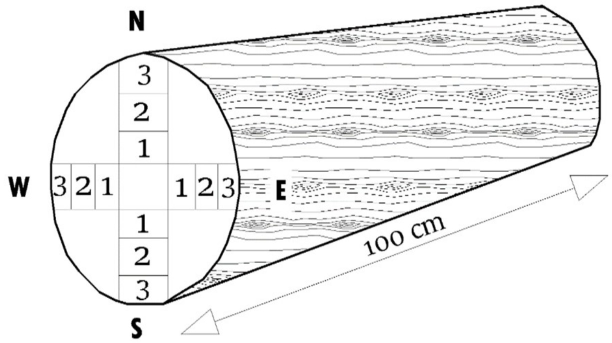

Figure 1. Schematic diagram of radial extraction of samples from the billet used for the study.

The trees were bucked into 100 cm lengths, following ASTM D2017 standards guidelines. The boards were free from defects such as knots, wane, and other biological deterioration agents or fire damage. Wood samples were carefully prepared from the selected boards.

2.2. Thermal modification process

Radially, one set of ten heartwood replicates and another set of ten sapwood replicates were used as the control (untreated). In contrast, six sets of heartwood and sapwood specimens underwent heat treatment. The specimens were heated in a muffle furnace for three hours at varying temperatures in an oxygen-free environment at 160, 180, and 200 °C. After cooling, the specimens' weights were measured and subjected to the decay tests.

2.3. Laboratory accelerated decay test

The laboratory-accelerated method (ASTM D2017-05) was employed to evaluate the susceptibility to decay. French square bottles were filled to three-quarters with moistened, screened topsoil. *Triplochiton scleroxylon* K. Schum wood strips, soaked in distilled water for 24 hours, were placed on the soil within the bottles. The bottles were then loosely sealed with plastic screw caps and sterilized in an autoclave at 121°C and 15 psi for 20 to 30 minutes. Subsequently, 10 mm-diameter discs of actively growing *Coriolopsis polyzona* mycelium were placed on each strip (Figure 2a). The bottles and contents were incubated at 25 °C for four weeks until complete colonization of the *Triplochiton scleroxylon* strips by the fungal mycelium (Figure 2b). After incubation, the mycelial mat grown on the strips was carefully transferred onto the oven-dried, sterilized control and thermally modified *D. oliveri* specimens (14 mm x 14 mm x 14 mm).

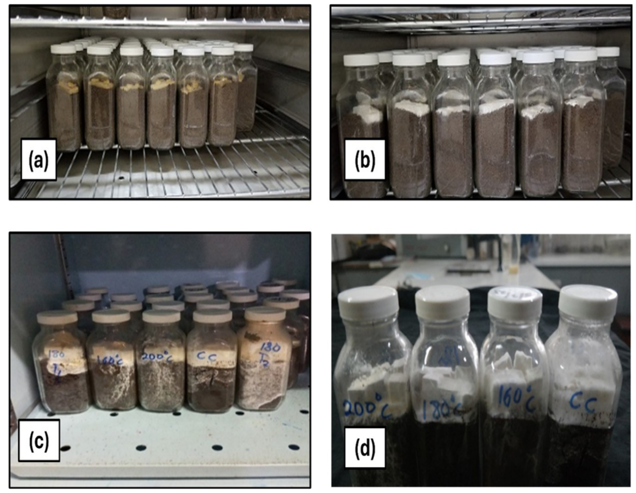

Figure 2. Images describing the laboratory decay test of *Daniellia oliveri* wood: **(a)** test specimens kept in glass jars and placed in an incubator for 2 weeks, **(b)** specimens colonized by fungi after the 6 weeks, **(c)** a closer look of mycelia on specimens after 10 weeks, (d) specimens completely colonized by mycelia after 18 weeks.

The setups were incubated for 10 weeks at 25°C and 70% relative humidity, respectively, to allow the Coriolopsis polyzona to consume the specimens (Figure 2c). At the end of the 18th week, the specimens were removed from the bottles, cleaned by removing any adhering mycelium, and oven-dried for 24 hours at 103 ± 2 °C. The percentage weight loss was calculated using Equation 1.

$$\text{Mass loss (\%)} = \frac{\text{Iw} - \text{Fw}}{\text{Iw}} \times 100 \qquad (1)$$

Where:
Iw = Initial oven-dry weight of specimens
Fw = Final oven-dry weight of specimens

The decay ratings of the test specimens, as shown in Table 1, follow the classification system outlined in ASTM D2017 (2005), where wood is considered "highly resistant" (Class I) when the mass loss is ≤10%. It is worth noting that EN 350-1 (European Committee for Standardization, 1994), a European standard, adopts a stricter criterion, where wood is classified as "very durable" only when mass loss is <5%.

Table 1. Decay resistance classification for percentage weight loss.

Average weight loss (%)	Decay resistance class
0-10	Highly resistant (Class I)
11-24	Resistant (Class II)
25-44	Moderately resistant (Class III)
45 and above	Susceptible (Class IV)

Source: Okon and Aguma (2023).

2.4. Decay-resistance field test

The test specimens were placed in the field in a 15 m x 12 m grid at a spacing of 50 cm between stakes, following the EN 252 (2014) standards. Specimens 150 mm long x 25 mm wide x 25 mm thick were oven-dried at 103 ± 2°C (EN-252, 2014). According to an entirely randomized design, the replicates were 75% partially buried into the ground (Tascioglu et al., 2012) (Figure 3).

Figure 3. Positioning of thermally-modified *Daniellia oliveri* specimens at the decay test field.

The test specimens were left in the field for 6 months. After this, they were removed from the ground, cleaned, and the mass loss was calculated using Equation 2:

$$\text{Mass loss } (\%) = \left(\frac{M1 - M2}{M2}\right) \times 100 \qquad (2)$$

Where:
M1 = Initial oven-dry mass of specimens
M2 = Final oven-dry mass of specimens after exposure

Table 2 shows the termite damage to the wood rated according to the scale proposed by Okon and Aguma (2023).

Table 2. Natural durability rating based on percentage mass loss caused by termites.

Durability class	Mass Loss (%)
Very durable	0 - 10
Durable	11 - 20
Moderately durable	21 - 30
Non-durable	31 and above

Source: Okon and Aguma (2023).

2.5. Statistical analysis

Statistical analysis included all the experimental treatments and the control. The eta square, the F-value, and the significance level were determined for the selected parameters. Differences between modification temperature, radial sections, and interactions were evaluated using a two-way analysis of variance (ANOVA) at a confidence interval of $\alpha = 0.05$; differences were considered significant at $p < 0.05$, as determined by the Statistical Package for the Social Sciences (SPSS).

3. RESULTS

3.1. Laboratory accelerated decay test

The results, as shown in Figure 4, indicate the mean mass loss of heat-treated D. oliveri wood subjected to a laboratory-accelerated fungal test.

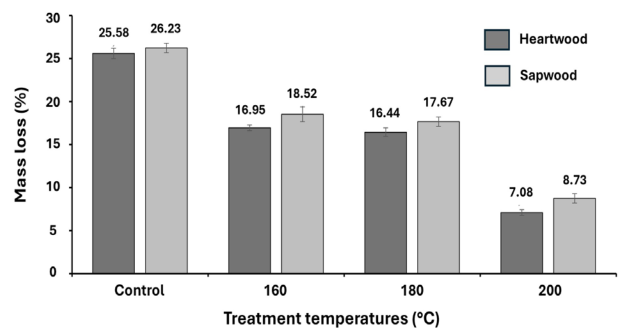

Figure 4. Mass loss percentage determined for non- and thermally-modified *Daniellia oliveri* test specimens after exposure to the laboratory decay test.

The fungi infestation and mass loss decreased as the temperature increased. Thus, thermal modification improved the durability of *D. oliveri* wood against fungi. The sapwood and heartwood portions of the untreated *D. oliveri* exhibited the highest mass loss, at 26.23% and 25.58%, respectively. The heartwood portion of the specimens modified at 200 °C had the lowest mass loss (7.08%), and the sapwood modified at 200 °C had 8.73% mass loss. The study showed radially that the sapwood portions of the modified and unmodified specimens have the highest mass losses compared to their corresponding heartwood. Table 3 indicates an analysis of variance (ANOVA) for the control and heat-treated *D. oliveri* wood specimens to verify if there was a significant difference between the durability of wood with different temperatures

(160, 180, and 200°C). Table 3 presents the main effects and interaction between temperature (T) and wood section (W) on the durability of modified wood in two settings: laboratory durability and field durability evaluation. The high F-value, small p-value, and large effect size indicated that temperature has a significant effect on durability in laboratory tests.

Table 3. Two-way ANOVA on the interaction and main effect differences in the durability properties of thermally-modified *Daniellia oliveri* wood.

Effect source	df	Mean square	Laboratory durability			Field durability			
			f	p	η^2	Mean square	f	p	η^2
Temperature (T)	3	541.630	1762.029	0.000*	0.994	2325.652	964.298	0.000*	0.989
Wood section (WS)	1	16.154	16.154	0.000*	0.622	5873.352	2435.301	0.000*	0.987
T x WS	3	0.528	1.717	0.183	0.139	231.632	96.043	0.000*	0.900
Error	32	0.307				2.412			

*Significance at alpha.

The ANOVA revealed a significant difference in the average mass loss between the control and the modification temperatures at a modification temperature of 200 °C. The wood section also plays a crucial role, although its impact is more pronounced in the field test setting compared to the laboratory accelerated test. The interaction between temperature and wood section is substantial for field durability but not significant for laboratory durability. This suggests that the interaction between the two factors is crucial for durability in real-world or more extreme environments (semi-buried in outdoor conditions). In contrast, under controlled conditions (in a laboratory), the factors may operate more independently. The effect sizes account for a substantial portion of the variance, particularly for field durability, where the main effects and interaction are highly influential. This highlights the importance of considering both temperature and wood section in assessing the durability of modified wood, particularly in more variable, real-world conditions.

3.2. Decay field test

From Figure 5, thermal modification has enhanced the biological resistance of otherwise non-durable *D. oliveri* wood (control treatment), with all treated *D. oliveri* woods exhibiting a lower percentage mass loss than the control sample (Figure 5).

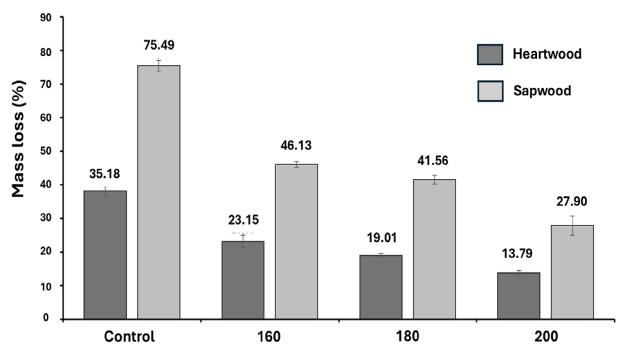

Figure 5. Mass loss percentage determined for non- and thermally-modified *Daniellia oliveri* test specimens after exposure to the decay test field.

The control sample showed a percentage mass loss of 75.49% for sapwood and 38.18% for the heartwood. However, the mass loss of the control treatment recorded here confirms that *D. oliveri* is a non-durable timber species. Based on the scale proposed by Okon and Aguma (2023), both the heartwood and sapwood of the untreated wood can be classified as non-durable. However, thermal modification of the wood at 200 °C has improved the durability status of the specimens under study to a durable class for the heartwood (13.79%) portion and moderately durable for the sapwood (27.90%) portion of the wood.

4. DISCUSSION

4.1. Decay resistance

The study revealed that mass loss improved as the temperature rose, leading to a partial loss of the nutritional medium, which is ideal for fungi and limits their activities (Birinci et al., 2022; Shmulsky and Jones, 2011). The resilience of the wood may increase when lignin deteriorates following treatment, as there would be fewer fungal attacks and fewer wood components (Shmulsky and Jones, 2011). Since fungi become dormant when wood moisture content reduces below 20% and hydrophobic wood is not conducive to fungal growth, water sorption into the material can be inhibited. This will minimize the activities of fungi in wood (Marais et al., 2020; Wang et al., 2020).

Dirol and Guyonnet (1993) investigated the impact of heat treatment on the resistance of wood to several fungi, including *Coriolus versicolor* (white rot), *Gloeophyllum trabeum*, and *Coniophora puteana* (brown rot), in three less durable species: spruce, fir, and poplar. They determined that the mass loss of the treated wood was less than 1% in each case, compared to more than 40% for the untreated samples. Additionally, *Pinus radiata* wood was tested by Kim et al. (1998) for 60 to 96 hours at temperatures of 120, 150, and 180 °C. Rot resistance improved in all cases by 35-65%. However, only treatment at 120 °C for more than 50 hours, or at 180 °C for 35 hours for dry samples and 40 hours for green samples, produced a performance comparable to that of a CCA treatment with 1% retention.

4.2. Decay field test

According to Esteves and Pereira (2009), the increased biological durability of heat-treated wood may be due to cellulose esterification following hemicellulose degradation, which results in elements that decaying agents do not recognize as food sources. The sapwood portion of both the modified and unmodified specimens has the highest mass loss compared to its corresponding heartwood, which, according to Priadi et al. (2022), results from extractives in the heart. Similarly, Militz (2002) conducted a study on the heat treatment of wood species, and the results indicated an increasing trend in resistance to these species of timber against biodegradable organisms (*Hylotrupes brajulus*, *Lyctus brunneus*, and *Annobium punctatum*).

Nunes et al. (2004) investigated the termite resistance of the *Reticulitermes grassei* species using wood treated with the German method (OHT). They found that although there was a slight increase in termite mortality in treated samples and a decrease in mass loss, the differences were not statistically significant. Termites preferred untreated wood over treated wood, and untreated wood samples were placed side by side. According to Westin et al. (2006), who modified Scots pine wood through multiple methods, there is no discernible increase in resistance to marine borers. The difference concerning mass loss was significantly lower for wood samples treated at 200 °C, as shown in Table 3, and there were differences between radial sections.

Evaluating the effect of thermal treatment of *D. oliveri* wood may have significant economic and environmental implications. Oyeleye et al. (2024) and Manhiça et al. (2023) emphasized that thermal treatment can enhance the durability and stability of lesser-used species, such as *D. oliveri*, making the species more competitive in the timber market. This could diversify the timber trade and reduce dependence on overharvested popular species. Environmentally, thermal treatment does not introduce harmful substances into ecosystems. It reduces wood's moisture content and susceptibility to decay, prolonging its usability. Utilizing lesser-known species alleviates pressure on overexploited forests, contributing to sustainable forest management, which aligns with global conservation goals (Lees, 2023; Cerutti et al., 2008).

5. CONCLUSIONS

The inherent relationships between the decay resistance, as measured through laboratory accelerated tests, and the percentage mass loss, as determined through graveyard tests, of thermally modified *Daniellia oliveri* wood were analyzed. The 200 °C was the most effective temperature in enhancing biological resistance, particularly in the heartwood, which showed better performance than the sapwood. The heat-treated *D. oliveri* wood showed a reduced percentage mass loss compared to untreated wood. Moreover, the heartwood portion of the treated and untreated *D. oliveri* wood exhibited higher resistance to mass loss for the field and laboratory decay tests. It is essential to note that thermally treated wood exhibits higher resistance to mass loss by biodegradable organisms. It is also environmentally suitable, meaning it is not harmful and does not endanger the ecosystem after its useful lifespan. However, the species showed a low density, limited stiffness, and modest bending strength, which suggests that it may not be appropriate for structural applications or direct ground contact. On the other hand, it can be viable for non-structural applications, such as indoor furniture, wall paneling, and other protected uses where mechanical resistance is less essential but durability is crucial. This information is significant in promoting the use of less commonly used timber species. Further investigation is recommended under real-world conditions to evaluate the mechanical behavior and dimensional stability of thermally modified *D. oliveri*, thereby supporting the safe, efficient, and sustainable application of this material.

ACKNOWLEDGEMENTS

The authors acknowledge the effort of Mr. Ebenezer Adom of the chemical engineering laboratory of the Kwame Nkrumah University of Science and Technology for his assistance in modifying the specimen used for the study. The authors again thank the Council for Scientific and Industrial Research-Forestry Research Institute of Ghana (CSIR-FORIG) for making their laboratories available for the studies. We are also thankful to the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Department of Construction and Wood Technology Education, for making the workshop available to process timber for the study. Dr. Pimenta and Dr. Melo thanked the National Council for Scientific and Technological Development (CNPq) for the research funding (finance code 001). Dr. Medeiros thanked the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil, for granting the post-doctoral scholarship.

SUBMISSION STATUS

Received: 19 May 2025
Accepted: 03 Aug 2025
Associate editor: Fernando Gomes

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Prosper Mensah: conceptualization (equal), data curation (equal), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), resources (equal), supervision (equal), visualization (equal), writing – original draft (equal), writing – review & editing (equal).
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DATA AVAILABILITY

The experimental data collected, compiled and evaluated in this work are available for consultation by simply requesting them from the corresponding author.

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