

PHYSICAL PROPERTIES OF THERMALLY MODIFIED SELECTED TROPICAL WOOD SPECIES AFTER USING DIFFERENT COOLING MEDIA

Oluwatayo S. AKINOLA*

Department of Forestry and Wood Technology
The Federal University of Technology, Akure, Nigeria
E-mail: tayoakinola64@gmail.com
0009-0000-3402-5562

Jacob M. OWOYEMI

Department of Forestry and Wood Technology
The Federal University of Technology, Akure, Nigeria
E-mail: jmowoyemi@futa.edu.ng
0000-0002-9524-8169

Titus O. AKINWAMIDE

Department of Forestry and Wood Technology
The Federal University of Technology, Akure, Nigeria
E-mail: akinwamideto@futa.edu.ng
0000-0002-0163-9266

Abstract:

*Thermal treatment of wood is a possible option for enhancing the dimensional stability of wood. This study investigated the physical properties of thermally modified *Pterygota macrocarpa*, *Terminalia ivorensis*, and *Alstonia congensis* wood cooled in castor oil, radiator coolant, and air immediately after heating. The samples were sourced from a wood processing mill and oven-dried at $103\pm 2^\circ\text{C}$ for 24 hours till constant weight was achieved after which they were thermally treated in an oven at a constant temperature of 190°C at varying time durations of 60 mins, and 120 mins, following heat treatment; the samples were cooled in castor oil, radiator coolant, and air (35°C room temperature) for 6 hours. Volumetric swelling, water absorption, and weight loss due to leaching value were taken. The results showed that with an increase in treatment time using the same temperature, the values were drastically reduced. The density was increased after cooled in castor oil and radiator coolant. Visual observation of treated samples showed that wood color changes with an increase in temperature time. The treatments led to enhanced dimensional stability, making it appropriate for outdoor use due to decreased hygroscopicity of the wood.*

Key words: Castor oil; cooling process; Physical properties; Thermal Treatment; Radiator coolant.

INTRODUCTION.

The rapid growth in world population has been the major cause of the increasing exploitation of matured and durable tree species coupled with poor utilization of wood resources. This has shifted attention to less durable wood species like *Pterygota macrocarpa*, *Alstonia congensis*, and *Leucaena leucocephala* to meet the growing demand for wood resources (Sundar *et al.* 2017). Wood modification has become an alternative way of reducing the hygroscopic nature of wood material thereby enhancing its dimensional stability (Kocaeft *et al.* 2015). Heat treatment overcomes some of the drawbacks of low-durable wood, such as dimensional instability and low durability, to increase its competitiveness in an environmentally responsible manner (Hill 2006). Thermal modification involves heating wood to temperatures between 170°C and 220°C in an oxygen-deprived environment, these changes reduce the wood's equilibrium moisture content, increase its biological resistance, and improve its dimensional stability (Candelier *et al.* 2016). Thermal modification has recently attracted interest in post-heating treatment using oils and other cooling mediums, which represents a promising advancement, offering enhanced durability, moisture resistance, and overall performance, making it a valuable technique for industries that rely on long-lasting, high-quality materials. The application of oil as a post-heat-treatment cooling agent has been found to deposit hydrophobic substances onto the wood surface, which enhances its water-repellent properties (Oyeleye *et al.* 2024). Coconut oil, rapeseed, palm, soya, and Linseed are among the vegetable oils utilized in heat treatments in the industry (Manalo and Acda 2009; Welzbacher and Rapp 2005; Wang and Cooper 2005). Oils not only act as a way to transfer heat but also prevent oxygen from reaching the treated specimens, reducing the thermal breakdown of certain wood components. (Lee *et al.* 2018). Castor oil has a high boiling point, making it stable under the high temperature required (Momoh *et al.* 2012). It is naturally degradable,

*Corresponding author

has low ecological toxicity and is safe for humans, made from sustainable sources, and has a minimal impact on carbon dioxide levels in the atmosphere. The integration of heat treatment and plant oil infusion shows great promise in protecting wood. The resistance of poplar wood against termites was greatly enhanced by utilizing a blend of neem and sesame oils with heat treatment reaching temperatures up to 200°C (Fatima *et al.* 2021). Nanofluids radiator coolant has improved thermal properties and heat transfer efficiency, making it a promising option for various devices to enhance energy, heat transfer, and overall performance (Bhogare and Kothawale 2013). This study was carried out to improve the properties of three fast-growing, most commonly available and low durable wood species (*Pterygota macrocarpa*, *Terminalia ivorensis* and *Alstonia congensis*) this choice of wood selection will positively lift the restriction in the area of usage and expand the areas of utilization to improve the wood supply chain globally.

MATERIALS AND METHODOLOGY
MATERIALS

Sawn Timber of *Pterygota macrocarpa* (Oporoporo), *Terminalia ivorensis* (Idigbo), and *Alstonia congensis* (Ahun) were sourced from a wood processing mill in Akure, Ondo State, Nigeria and machined into the required dimensions 20x20x60mm for physical properties test according to ASTM – D2395 (2014). The samples were oven-dried at 103±2°C. Castor oil was purchased from an agricultural processing factory, while the radiator coolant was purchased from ABRD factory.

THERMAL TREATMENT PROCESS

The heat treatment was carried out in an enclosed muffle furnace, a temperature-controlled heating chamber. Five replicates of each species were used as a treated and untreated group. The samples were put in an oven with a securely shut door to prevent heat loss throughout the modification process. The samples were heated in the oven at 190°C for 60 and 120 minutes, respectively. After heat treatment, they were withdrawn from the oven and subjected to varying cooling mediums in Castor oil, Radiator Coolant and air cooling for 6 hours to assess the effect of different cooling mediums on thermally modified species. The air cooling of the thermally modified samples under a laboratory condition of 35°C (Normal room temperature). All modified samples were conditioned for a week before the properties assessment.

DETERMINATION OF PHYSICAL PROPERTIES

Physical properties investigated were absorption, density increment, water absorption, volumetric swelling and weight loss due to leaching. The determination of the physical properties of wood samples was carried out according to American Society for Testing and Materials - ASTM – D2395 (2014).

TREATMENT UPTAKE

The coolant uptake of the selected wood samples during the cooling process was calculated using this formula:

$$\text{Absorption (\%)} \left(\frac{T_3 - T_2}{T_2} \right) \times 100 \dots \dots \dots \text{(Equation 1)}$$

where: T_3 is the weight of the sample after cooling in cooling medium in grams and T_2 is the weight of the sample before cooling.

DENSITY INCREMENT

The weight percentage gain (DI) of the control and modified specimens was obtained according to Hill (2006) using the following formula:

$$\text{DI (\%)} = \frac{M_m - M_u}{M_u} \times 100 \dots \dots \dots \text{(Equation 2)}$$

where: M_m is the mass (g) of the cooled sample, and M_u is the oven-dry weight of the sample before cooling.

WATER ABSORPTION

The water absorption of both treated and untreated wood samples following a 72-hour immersion in water was calculated using the formula below:

$$\text{WA (\%)} = \frac{W_2 - W_1}{W_1} \times \frac{100}{1} \dots \dots \dots \text{(Equation 3)}$$

where: WA = water absorption; W2 = weight of specimen post water soaking, W1 = weight of specimen prior to water soaking.

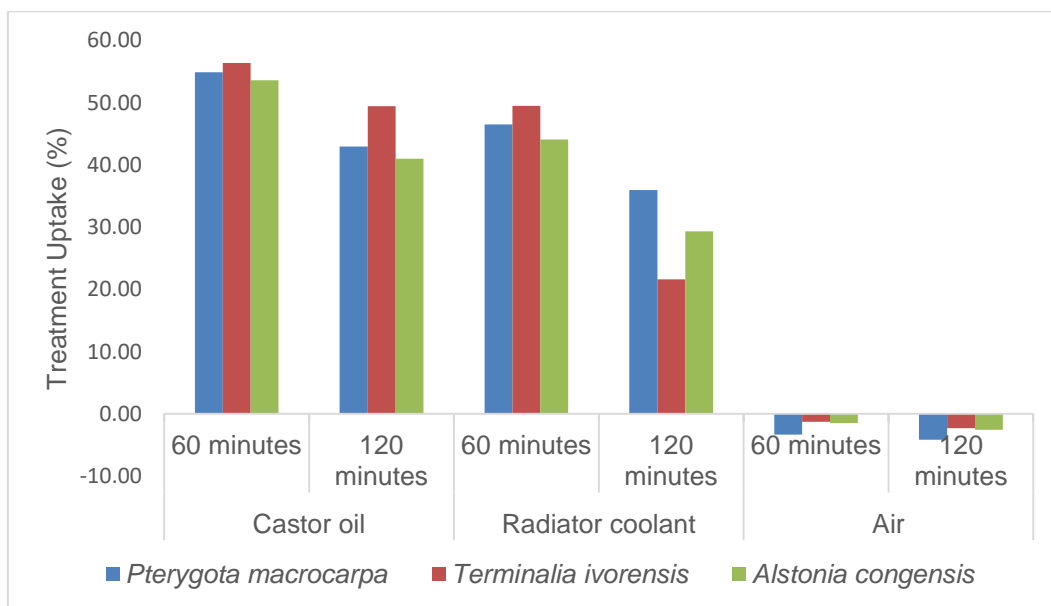


Fig. 1.
Cooling treatment uptake of the thermal-modified wood species.

Table 1

Duncan Multiple Range Test for Treatment Uptake

Species	Absorption (%)	Cooling medium	Absorption (%)
<i>Alstonia congensis</i>	27.32 ^a	Air	-2.53 ^c
<i>Pterygota macrocarpa</i>	28.80 ^a	Radiator coolant	37.83 ^b
<i>Terminalia ivorensis</i>	28.89 ^a	Castor oil	49.70 ^a

Mean with the same letter does not exhibit any significant variation, whereas mean with different letters demonstrates a noteworthy difference.

DENSITY

The results of the density before and after treatment in Fig. 2 show that for *P. macrocarpa* the mean density value ranged from 441-496kg/m³; *Terminalia ivorensis* had a range value of 395-452kg/m³ while for *A. congensis* ranged from 491-546kg/m³. The results showed that *Terminalia ivorensis* recorded the highest density increment among the species when modified for 60 minutes respectively in castor oil and radiator coolant. This suggests that the wood density could have increased due to the cooling medium absorbed by the wood. The quantity of cooling medium taken in might result from the anatomical characteristics of the wood variety such as its porosity and the speed at which the castor oil and coolant flows i.e. wood with high porosity would absorb more oil and this will increase the density (Yang *et al.* 2020). (Wright 1977) stated that the viscosity of a liquid increases as temperature rises (Owoyemi *et al.* 2017) noted a rise in specimen weight caused by oil absorption during heat treatment and a reduction in weight as time increased. The cooling treatment influences the wood density to a small extent as can be seen in Fig. 2. The thermally modified samples cooled in air recorded a density loss among the species respectively having *P. macrocarpa* recorded the highest mass loss of about -4.19%. (Ninane *et al.* 2021) achieved outcomes related to this research and claimed the reduction in density of heat-treated wood was a result of the diverse compositions and structures of wood cells from different species. Research has indicated that thermally treated wood usually undergoes weight reductions of 5% to 10%, which vary based on the treatment's temperature and duration (Poncsak *et al.* 2006). This loss happens when volatile organic compounds (VOCs) evaporate, causing the structural integrity of hemicelluloses to decrease. This results in a lignin-rich matrix that is more resistant to moisture, yet lighter in weight, creating a wood that is more stable in dimensions (Srinivas and Pandey 2012). However, by immersing the wood in castor oil and radiator coolant during the cooling process, a mass increase occurs as it penetrates and fills the void spaces left by the thermal degradation. This mass increase compensates for the weight loss, while also enhancing the wood's water repellency, mechanical strength, and durability (Oyeleye *et al.* 2024). The combination of thermal modification and cooling provides a promising treatment method for improving wood products' performance and longevity.

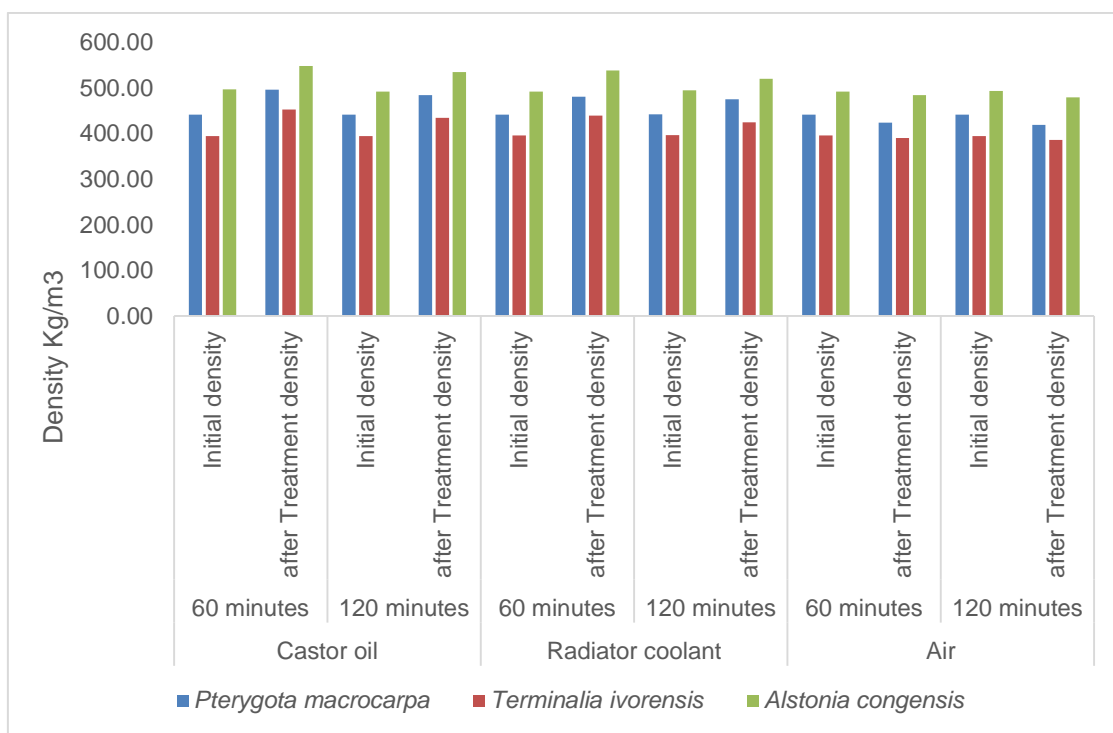


Fig. 2. Density increment of the thermal and cooling modified wood species.

Table 2

Duncan Multiple Range Test for Density of the modified wood species

Species	Density (Kg/m ³)	Cooling medium	Density (Kg/m ³)
<i>Terminalia ivorensis</i>	408.15 ^c	Air	436.59 ^b
<i>Pterygota macrocarpa</i>	452.24 ^b	Radiator coolant	461.62 ^a
<i>Alstonia congensis</i>	505.35 ^a	Castor oil	467.54 ^a

Mean with the same letter does not exhibit any significant variation, whereas mean with different letters demonstrates a noteworthy difference.

VOLUMETRIC SWELLING

The volumetric swelling value for the treated and untreated wood samples after immersion in water for 24, 48 and 72 hrs presented in Figs 3a, 3b, 3c revealed the reaction of the thermally modified wood species at varying durations after cooling in different mediums. *P. macrocarpa*, modified for 60 minutes recorded a VSW of 3.75%, 3.72% and 6.23% for Castor oil, Radiator coolant and air, respectively; samples modified for 120 minutes recorded 3.14%, 1.94% and 5.46% for Castor oil, Radiator coolant and air respectively, while the untreated samples recorded the highest value of VSW (9.86%). Likewise, for *T. ivorensis*, modified for 60 minutes recorded a VSW of 3.14%, 2.76% and 4.66% for Castor oil, Radiator coolant and air cooling respectively. Samples modified for 120 minutes recorded 2.51%, 2.10% and 4.52% for castor oil, Radiation coolant and air, respectively, while the untreated samples recorded the highest value of VSW (13.29%). *A. congensis* modified for 60 minutes recorded a VSW of 6.18%, 3.57% and 8.55% for castor oil, Radiation coolant and air, respectively. Samples modified for 120 minutes recorded 5.91%, 3.01% and 7.68% for Castor oil, Radiator coolant and air, respectively, while the untreated samples recorded the highest value of VSW (14.29%). The result revealed that modified *P. macrocarpa* cooled in radiator coolant had the lowest volumetric swelling at 120 minutes and *Alstonia congensis* had the highest VSW value. The variance analysis conducted at a 95% confidence level indicated that the treatment significantly impacted the wood species. According to (Lee *et al.* 2018), the oil absorption and accumulation within wood cell walls are other elements that contribute to improving the dimensional stability of wood. The reduced swelling is likely due to the degradation of hemicelluloses, which are highly hygroscopic and the reorganization of lignin during heat treatment, resulting in a more hydrophobic wood matrix (Esteves & Pereira 2009). Moreover, the application of oil as a cooling medium further improves the wood's water repellency by forming a hydrophobic barrier on

the wood surface, reducing water uptake (Pétrissans *et al.* 2003). (Baysal *et al.* 2014) suggested that a key reason for the improved dimensional stability of modified wood is the reduction of hemicelluloses, which are water-absorbing and hydrophilic.

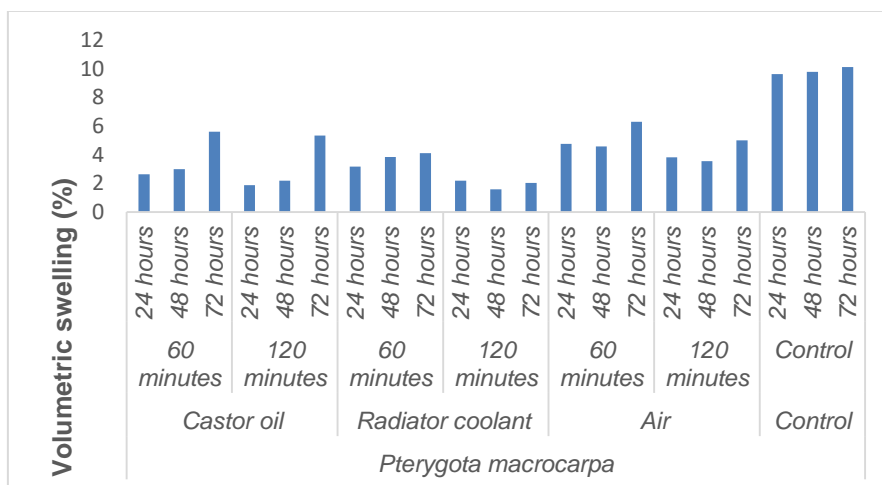


Fig. 3a.
Volumetric Swelling of both treated and untreated wood species.

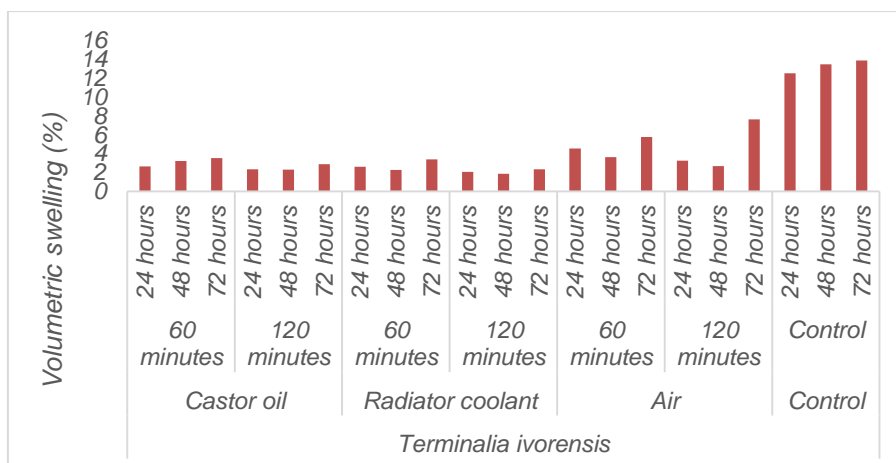


Fig. 3b.
Volumetric Swelling of both treated and untreated wood species.

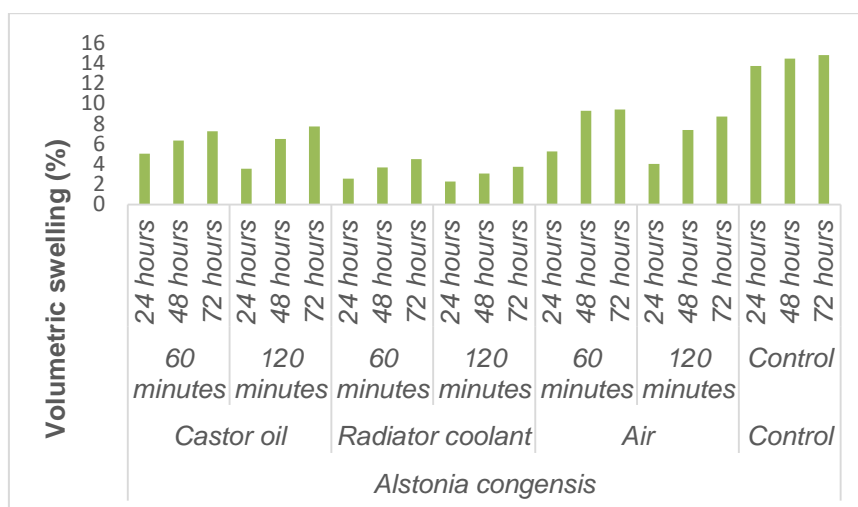


Fig. 3c.
Volumetric Swelling of both treated and untreated wood species.

The Duncan Multiple Range Test (Table 3) results showed that there are significant differences in the values obtained for the volumetric swelling across the varying species as *A. congensis* (14.29%) which recorded the highest value is significantly different from the other species. There are significant differences recorded at the different durations of thermal treatment and among the cooling media.

Table 3

<i>Duncan Multiple Range Test for Volumetric Swelling</i>							
Species	VSW (%)	Duration	VSW (%)	Medium	VSW (%)	Soaking time	VSW (%)
<i>Terminalia ivorensis</i>	4.71 ^b	120 minutes	4.03 ^b	Radiator coolant	2.85 ^d	24 hrs.	4.50 ^c
<i>Pterygota macrocarpa</i>	4.87 ^b	60 minutes	4.73 ^b	Castor oil	4.10 ^c	48 hrs.	5.31 ^b
<i>Alstonia congensis</i>	7.03 ^a	Control	12.48 ^a	Air	6.18 ^b	72 hrs.	6.80 ^a
				Control	12.48 ^a		

Mean with the same letter does not exhibit any significant variation, whereas mean with different letters demonstrates a noteworthy difference.

WATER ABSORPTION

The results presented in Fig. 4 revealed the water absorption of the thermally modified wood species at varying durations following cooling in different mediums after being submerged in water for 72 hours. The water absorption for *P. macrocarpa*, samples modified for 60 minutes recorded a VSW of 12.00%, 22.14% and 28.78% for Castor oil, Radiator coolant and air, respectively; samples modified for 120 minutes recorded 9.55%, 15.69% and 23.97% for Castor oil, Radiator coolant and air respectively, while the untreated samples recorded the highest value of VSW (41.27%). Likewise, for *T. ivorensis*, samples modified for 60 minutes recorded a VSW of 11.51%, 20.97% and 24.82% for Castor oil, Radiator coolant and air, respectively. Samples modified for 120 minutes recorded 10.41%, 15.41% and 17.47% for castor oil, Radiator coolant and air, respectively, while the untreated samples recorded the highest value of VSW (31.85%). Samples obtained from *A. congensis* modified for 60 minutes recorded a VSW of 11.55%, 21.58% and 20.40% for castor oil, Radiation coolant and air, respectively. Samples modified for 120 minutes recorded 10.39%, 13.06% and 18.16% for Castor oil, Radiator coolant and air, respectively, while the untreated samples recorded the highest value of VSW (27.52%). *P. macrocarpa* recorded notably lower water absorption rates compared to the *T. ivorensis* and *A. congensis*, which absorbed significantly less water. Thermal treatment significantly reduces the wood's capacity to absorb water, as shown by the reduction in Volumetric Swelling (VSW) values when compared to untreated wood. This reduction in water absorption can be attributed to the alteration of cellulose and lignin during the heat treatment process, which diminishes the wood's hydrophilicity and limits its ability to bond with water molecules (Olufemi *et al.* 2018). Cooling in different mediums, such as castor oil and radiator coolant, introduces different extents of hydrophobicity. Oils like castor oil can further reduce water absorption by adding a protective hydrophobic layer while cooling in air leads to comparatively higher VSW values due to lesser hydrophobic protection (Haftkhani *et al.* 2022). The wood species' cell walls and capillaries are filled with radiator coolant and oil, preventing water molecules from penetrating the wood (Ahmed *et al.* 2017). Finally, (Suri *et al.* 2021) researched how heat treatment affects wood density differently in various species. It was claimed that the length of the heat treatment and the temperature degree are the two key variables that impact the reduction of wood's water absorption. It was found that longer treatment durations and higher temperatures led to greater decreases in water absorption due to the increased breakdown of hydrophilic molecules.

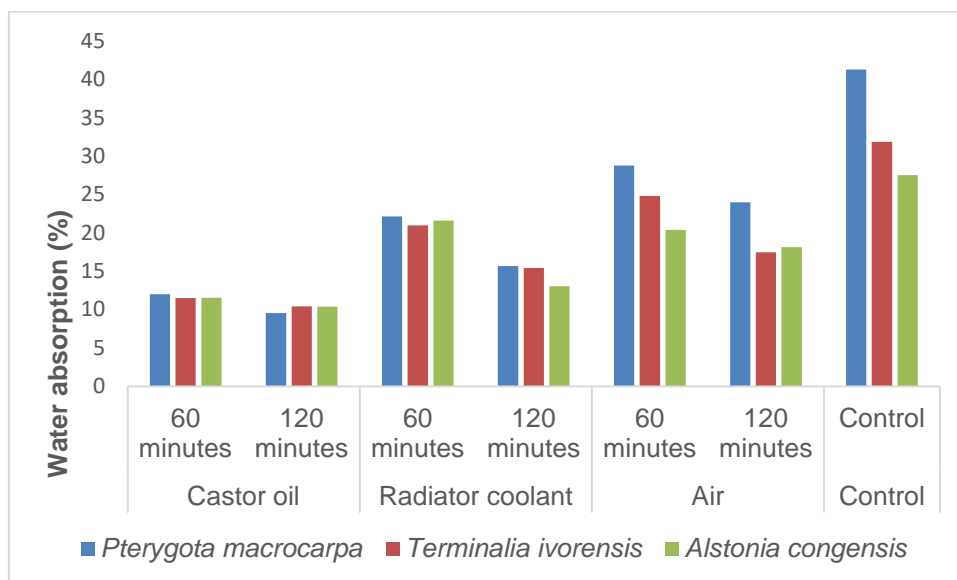


Fig. 4.
Water absorption of both treated and untreated wood species.

WEIGHT LOSS DUE TO LEACHING

The mean value for Percentage weight loss due to leaching of three different wood species thermally treated and cooled in different media. The results presented in Fig. 5 revealed the weight loss due to the leaching after soaking in water for 72 hours varied among treatments. For *P. macrocarpa*, samples modified for 60 minutes recorded a WL of 2.21%, 9.05% and 1.09% for Castor oil, Radiator coolant and air, respectively; samples modified for 120 minutes recorded 1.20%, 4.01% and 0.61% for Castor oil, Radiator coolant and air respectively, while the untreated samples recorded the WL value of (2.09%). Likewise, for *T. ivorensis*, samples modified for 60 minutes recorded a WL of 2.04%, 9.42% and 1.05% for Castor oil, Radiator coolant and air, respectively; samples modified for 120 minutes recorded 1.37%, 3.44% and 0.30 % for Castor oil, Radiator coolant and air respectively, while the untreated samples recorded the WL value of (1.37%). Samples obtained from *A. congensis* modified for 60 minutes recorded a WL of 2.30%, 10.70%, and 0.85 % for Castor oil, Radiator coolant, and air, respectively, samples modified for 120 minutes recorded 1.77%, 3.37% and 0.29% for Castor oil, Radiator coolant and air respectively, while the untreated samples recorded the WL value of (1.22%). This weight reduction is important, as it directly affects the wood's density. Samples treated for 60 minutes showed a large variation in weight loss, depending on the cooling medium. Maximum weight loss was obtained for the radiator coolant at 9.42%, while Castor oil resulted in 2.21% and air in 1.09%. The same trend was repeated for 120-minute treatments, though the weight loss values were lower. This suggests that the chemical properties of the radiator coolant interacted more aggressively with the wood structure, breaking down more internal components and leading to increased leaching. Longer modification time reduced weight loss in all cooling mediums, and across wood species indicating that extended thermal treatment stabilizes the wood structure. On the other hand, air-cooling proved to be the most effective at minimizing leaching. At the same time, Castor oil provided a moderate level of protection, likely due to its hydrophobic properties that help in sealing the wood. These results align with previous research on thermally modified wood, which shows that the type of post-treatment cooling medium significantly influences the durability and water resistance of treated wood (Priadi *et al.* 2021); (Park *et al.* 2024).

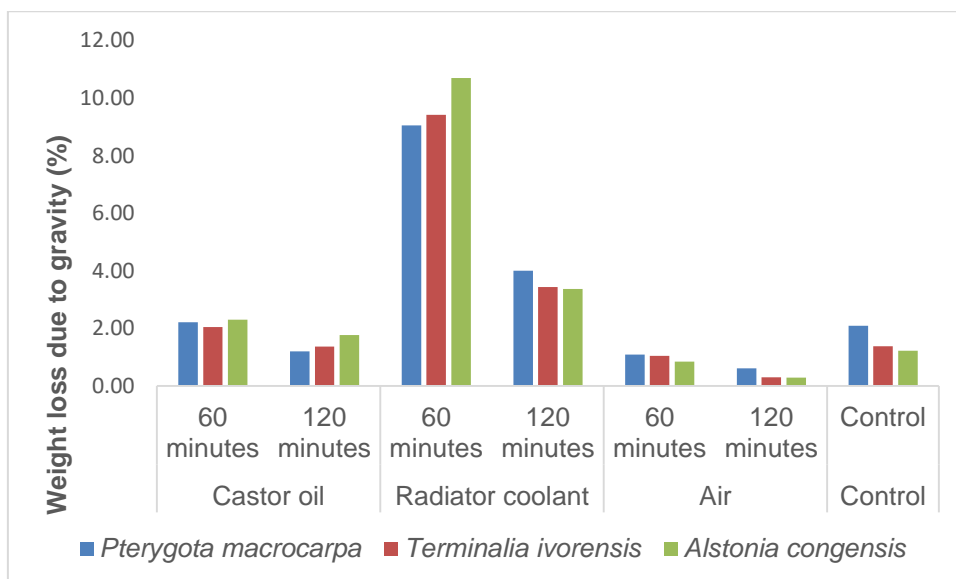


Fig. 5.
Weight loss due to leaching of both treated and untreated wood species.

The Duncan Multiple Range Test (Table 4) results showed that in terms of cooling of the samples, significantly improved their dimensional stability as samples cooled in castor oil recorded the lowest water absorption which was highly significantly different from samples cooled in air and radiator coolant. The control samples recorded the highest value. For the weight loss due to leaching, there are significant differences in the values obtained across the varying species, cooling media and duration of heating time.

Table 4

Duncan Multiple Range Test for the physical properties

Species	Water Absorption (%)	WL (%)
<i>Alstonia congensis</i>	17.52±16.40 ^c	2.93±1.83 ^a
<i>Terminalia ivorensis</i>	18.92±14.51 ^b	2.71±1.68 ^a
<i>Pterygota macrocarpa</i>	21.92±14.14 ^a	2.89±1.48 ^a

Cooling medium	Water Absorption (%)	WL (%)
Castor Oil	10.90±3.44 ^d	1.82±0.74 ^b
Radiator coolant	18.14±4.20 ^c	6.66±1.37 ^a
Air	22.27±4.25 ^b	0.70±1.37 ^d
Control	10.90±3.24 ^a	1.56±1.49 ^c

Duration	Water Absorption (%)	WL (%)
120 minutes	14.90±11.45 ^c	1.82±1.37 ^b
60 minutes	19.31±12.80 ^b	4.30±0.94 ^a
Control	33.55±3.24 ^a	1.56±1.49 ^c





















Mean with the same letter does not exhibit any significant variation, whereas mean with different letters demonstrates a noteworthy difference. Duration: The time for modifying the wood samples.

COLOUR CHANGE

The color variations after thermal treatment and cooling in different media (air, radiator coolant, castor oil) showed that the wood species changed color slightly at a consistent temperature over varying time durations. The color of *Pterygota macrocarpa* samples changed from pale brown to brown, slightly red and light brown after 60 minutes and to dark brown, reddish and brown after 120 minutes in Castor oil, Radiator coolant and air, respectively. For *Terminalia ivorensis*, colour shifted from pale creamy white to brown, red

and brown at 60 minutes and to dark brown, dark red and dark brown at 120 minutes under the same conditions, while untreated samples retained a pale creamy white appearance.

Alstonia congensis samples transitioned from creamy white to brown, light red, and light brown at 60 minutes and to dark brown, red and brown at 120 minutes. These findings highlight the distinct color changes influenced by both modification duration and the medium used for each species. The alteration in color is linked to a chemical reaction that occurred during the heating and cooling process (McDonald *et al.* 2000). Nonetheless, the temperature of the treatment significantly affects the results more than the duration of the treatment (Mitsui *et al.* 2004) (Sundqvist 2004) determined that both extractive and structural elements (lignin and hemicellulose) contributed to the color transformation of wood subjected to heat treatment (Fig.6).

Wood species	Duration	Control	Castor	R. coolant	Air
<i>P. macrocarpa</i>	60 MIN				
	120MIN				
<i>T. ivorensis</i>	60 MIN				
	120MIN				
<i>A. congensis</i>	60 MIN				

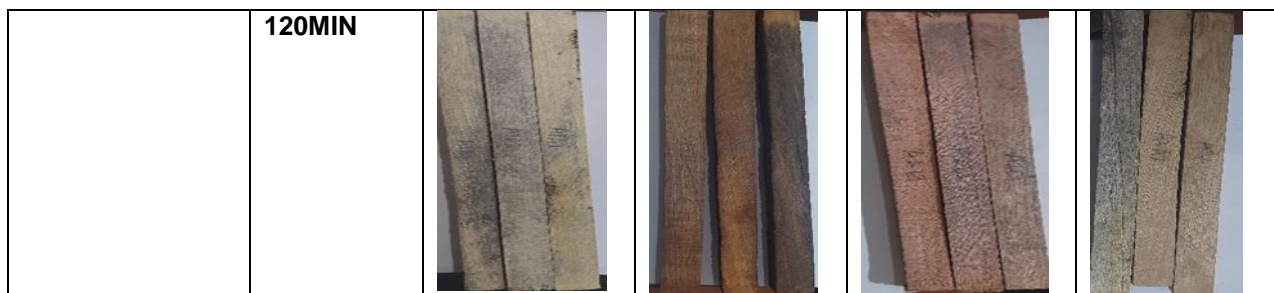


Fig. 6.

Comparison of the colour of untreated and treated wood samples.

CONCLUSION

Thermal treatments at varying time of exposure and different cooling media have generally affected the physical properties of *Pterygota macrocarpa*, *Terminalia ivorensis* and *Alstonia congensis*. Understanding the variations in the physical properties of selected less durable wood will help the wood user in exploring the suitability of these species after treatment. In general, water absorption of species was reduced significantly by heating at 190°C for 120 minutes as well as cooling in castor oil this decreased the wood's tendency to absorb moisture, resulting in better dimensional stability, especially beneficial for wood in damp conditions when compared to untreated wood. The use of radiator coolant for cooling treatment led to improved dimensional stability by lowering volumetric swelling and water absorption, and also resulted in an increase in wood density after cooling in oil and coolant. This mass increase compensates for the weight loss, while also enhancing the wood's mechanical strength and durability. The combination of thermal modification and cooling provides a promising treatment method for improving wood products' performance and longevity.

REFERENCES

- Ahmed SA, Morén T, Sehlstedt-Persson M, *et al.* (2017) Effect of Oil Impregnation on Water Repellency, Dimensional Stability and Mold Susceptibility of Thermally Modified European Aspen and Downy Birch Wood. *J Wood Sci.* 63:74-82 (2017). <https://doi.org/10.1007/s10086-016-1595-y>
- ASTM D2395-2014e1 (2014) Standard Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Material. ASTM International, West Conshohocken, PA, 2014.
- Baysal E, Kart S, Toker H (2014) Degirmentepe, S. Some Physical Characteristics of Thermally Modified Oriental-Beech Wood. *Maderas: Ciencia y Tecnologia*, 16(3):291-298, 2014. <https://doi.org/10.4067/S0718-221X2014005000022>
- Bhogare RA, Kothawale BS (2013) A Review on Applications and Challenges of Nanofluids as Coolant in Automobile Radiator. *International Journal of Scientific and Research Publications*, 3(8):1-11.
- Candelier K, Thevenon MF, Petrissans A, Dumarcay S, Gerardin P, Petrissans M (2016) Control of Wood Thermal Treatment and Its Effects on Decay Resistance: A Review. *Annals of Forest Science*, 73:571-583.
- Esteves B, Pereira H (2009) Wood Modification by Heat Treatment: A review. *BioResources*, 4(1):370-404.
- Fatima Z, Ahmed S, Hassan B (2021) Combined Effects of Neem (*Azadirachta Indica*) and Sesame (*Sesamum Indicum*) Oil as a Wood Preservative on Subterranean Termites in the Field. *Maderas. Ciencia y tecnologia* 23. 2021
- Haftkhani AR, Abdoli F, Rashidijouybari I, *et al.* (2022) Prediction of Water Absorption and Swelling of Thermally Modified Fir Wood by Artificial Neural Network Models. *Eur. J. Wood Prod.* 80:1135-1150. <https://doi.org/10.1007/s00107-022-01839-x>
- Hill CAS (2006) Wood Modification - Thermal Modification of Wood - A Review: Chemical Changes and Hygroscopicity. *Journal of Materials Science*, 56:6581-6614, 2021. <https://doi.org/10.1007/s10853-020-05722-z>
- Jones D, Hill C, Peters C (2019) Thermal Modification of Wood-Effects on Global Wood Industry Practices. *Journal of Materials Science*, 54(2):435-449.
- Karan CP, Rengasamy RS, Das D (2011) Oil Spill Cleanup by Structured Fibre Assembly. *Indian Journal of Fibre & Textile Research*, 36(2):190-200.

- Kocaefe D, Huang X, Kocaefe Y (2015) Dimensional Stabilization of Wood. *Current Forestry Reports*, 1:151-161.
- Lee SH, Ashaari Z, Lum WC, Halip JA, Ang AF, Tan LP, Tahir PM (2018) Thermal Treatment of Wood Using Vegetable Oils: A review. *Construction and Building Materials*, 181:408-419.
- Luan Y, Fang CH, Ma YF, Fei BH (2022) Wood Mechanical Densification: A Review on Processing. *Materials and Manufacturing Processes*, 37(4):359-371.
- Manalo RD, Acda MN (2009) Effects of Hot Oil Treatments on Physical and Mechanical Properties of Three Species of Philippine Bamboo. *Journal of Tropical Forestry Sci* 21(1):19-24
- Mandraveli E, Mitani A, Terzopoulou P, Koutsianitis D (2024) Oil Heat Treatment of Wood-A Comprehensive Analysis of Physical, Chemical, and Mechanical Modifications. *Materials*, 17(10):2394. <https://doi.org/10.3390/ma17102394>
- McDonald AG, Fernandez M, Kreber B, Laytner F (2000) The Chemical Nature Of Kiln Brown Stain in Radiata Pine.
- Militz H, Altgen M (2014) Processes and Properties of Thermally Modified Wood Manufactured in Europe in Deterioration and Protection of Sustainable Biomaterials, pp. 269-285. American Chemical Society.
- Mitsui K (2004) Changes in the properties of light-irradiated wood with heat treatment: Part 2. Effect of light-irradiation time and wavelength. *Holz als Roh-und Werkstoff*, 62:23-30.
- Momoh AO, Oladunmoye MK, Adebolu TT (2012) Evaluation of the Antimicrobial and Phytochemical Properties of Oil from Castor Seeds (*Ricinus communis* Linn). *Bulletin of Environment, Pharmacology and Life Sciences*, 1(10):21–27.
- Ninane M, Pollet C, Hébert J, Jourez B (2021) Physical, Mechanical, and Decay Resistance Properties of Heat-Treated Wood by Besson® Process of Three European Hardwood Species. *Biotechnology, Agronomy and Society and Environment*, 25(2):129-139, <https://doi.org/10.25518/1780-4507.19050>
- Olufemi B, Ayanleye S, Iyiola E (2018) Influence of Thermal and Chemical Modification on the Physical and Mechanical Properties of *Leucaena leucocephala* Wood. *Asian Journal of Advanced Research and Reports*. <https://doi.org/10.9734/AJARR/2018/V2I229744>.
- Owoyemi JM, Oyeleye IO (2017) Sorption and Strength Properties of Thermally Modified Plantation Grown *Leucaena Leucocephala* (Lam) Wood Using Paraffin Wax. Dubey MK, Pang S, Walker J (2011) Effect of oil heating age on colour and dimensional stability of heat treated *Pinus radiata*, *Eur. J. Wood Prod.* 69:255-262.
- Oyeleye IO, Owoyemi JM, Oluwasina OO, Olaniran SO (2024) Potentials of Thermo-Oil Treatment Process for Improved Properties of Lesser Utilized Wood Species in Nigeria. *Journal of Research in Forestry, Wildlife and Environment*, 16(2):92-102.
- Park Y, Han Y, Choi YS, Lee HM, Yoon SM, Yeo H, Eom CD (2024) Correlation Analysis between Mass Loss of Wood due to Thermal Modification and Equilibrium Moisture Content of Thermally Modified Wood. *BioResources*, 19(1).
- Pétrissans M, Pétrissans A, Gérardin P (2003) Influence of Oil on the Properties of Heat-Treated Wood. *Holz als Roh- und Werkstoff*, 61(2):152-153.
- Poncsak S, Kocaefe D, Boluk Y, Pichette A (2006) Effect of Thermal Modification of Wood on the Adhesion Strength of Coatings. *Journal of Adhesion Science and Technology*, 20(8):847-859.
- Priadi T, Lestari MD, Cahyono TD (2021) Post-treatment Effects of Castor Bean Oil and Heating in Treated Jabon Wood on Boron Leaching, Dimensional Stability, and Decay Fungi Inhibition. *Journal of the Korean Wood Science and Technology*, 49(6):602-615.
- Srinivas K, Pandey K (2012) Effect of Heat Treatment on Color Changes, Dimensional Stability, and Mechanical Properties of Wood. *Journal of Wood Chemistry and Technology*, 32:304-316. <https://doi.org/10.1080/02773813.2012.674170>.
- Sundar S, Swaroop N, Naresh R (2017) Modeling the Effect of Population and Population Augmented Industrialization on Forestry Resources. *European Journal of Engineering and Technology Research*. <https://doi.org/10.24018/EJERS.2017.2.1.247>.

Sundqvist B (2004) Colour Changes and Acid Formation in Wood during Heating (Doctoral Dissertation, Luleå Tekniska Universitet).

Suri IF, Purusatama BD, Lee S, Kim N, Hidayat W, Ma'ruf SD, Febrianto F (2021) Characteristic Features of the Oil-Heat Treated Woods from Tropical Fast Growing Wood Species. *Wood Research*, 66(3):365-378.

Wang JY, Cooper PA (2005) Effect of Oil Type, Temperature and Time on Moisture Properties of Hot Oil-Treated Wood. *Holz Roh- Werkst* 63(6):417-422.

Welzbacher CR, Rapp AO (2005) Durability of Different Heat Treated Materials from Industrial Processes in Ground Contact. International Research Group on Wood Protection. Document No IRG/WP 05-40312.

Wright P (1977) The Variation of Viscosity with Temperature. *Physics Education*, 12:323-325. <https://doi.org/10.1088/0031-9120/12/5/012>.

Yang R, Cao Q, Liang Y, Hong S, Xia C, Wu Y, Li J, Cai L, Sonne C, Le Q, Lam S (2020) High Capacity Oil Absorbent Wood Prepared Through Eco-Friendly Deep Eutectic Solvent Delignification. *Chemical Engineering Journal*, 401, 126150. <https://doi.org/10.1016/j.cej.2020.126150>.