Evaluating Vegetable Oil Epoxidation Efficiency on Properties of Eucalyptus Wood: Thermal and Thermo-chemical Processing

Seyed Javad Hejazi, Raoufeh Abedini ,* Maryam Ghorbani, and Foroogh Dastoorian

The applications of wood are limited by its hygroscopicity and resulting dimensional changes, which reduce its service life for outdoor conditions. Modification methods develop the usages of wood-based products by altering the structure. This study compared the effect of oil heat treatment (OHT) with raw (SO) and epoxidized soybean oil (ESO) at different temperatures relative to the practical properties of eucalyptus wood. Fourier transform infrared spectra confirmed hemicellulose degradation with increasing temperatures of ESO-treated specimens. With increasing temperature, ESO darkened the specimens compared to SO. Thermal modification at the highest temperature in ESO resulted in a weight loss of modified specimens and the lowest density, with more hydrophobicity and dimensional stability compared to the SO-modified specimens. Based on bending data, unlike modulus of elasticity (MOE), modulus of rupture (MOR) did not show a statistical difference between the two types of oils, except at 150 °C. At 200 °C, the specimens modified with ESO exhibited lower hardness than SO. The impact resistance of 150 and 175 °C/ESO modified specimens was higher than SO specimens. In summary, functionalized vegetable oil significantly improved physical characteristics compared to SO, with obvious improvement in impact strength at 150 °C.

DOI: 10.15376/biores.20.2.4450-4463

Keywords: Chemical structure; Color change; Epoxidized soybean oil; Mechanical properties; Oil heat treatment; Physical properties; Thermal modification

Contact information: Department of Wood and Cellulosic Product Engineering, Faculty of Natural Resources, Sari Agricultural Sciences and Natural Resources University, Sari, Iran;
** Corresponding author: r.abedini@sanru.ac.ir*

INTRODUCTION

Wood as a natural and renewable material with various applications, despite its distinctive features such as aesthetic features, high specific mechanical properties, and insulation against heat and sound, is highly hygroscopic, dimensionally unstable, and biodegradable, which reduce its service life (Lee *et al.* 2018; Baar *et al.* 2021). Protective procedures that effectively reduce these inherent limitations expand the utilization of wood products. Thermal modification of wood under high temperatures in various mediums, such as water, vapor, nitrogen, and oil, is a practical and environmentally friendly method that can overcome its disadvantages without the use of toxic chemicals (Hill 2006; Nejad *et al.* 2013; 2019; Sandberg *et al.* 2017). The oil heat treatment (OHT) process using vegetable oils through hemicellulose degradation at high temperatures and the presence of non-polar oil (without chemical reaction) makes the cell wall hydrophobic (Esteves *et al.* 2013; Sandberg *et al.* 2017). Oil heat treatment with hemp oil enhances the density and

dimensional stability of European beech (Baar *et al.* 2021). Oil uptake during OHT increases the weight of wood and subsequently the density (Lee *et al*. 2018). However, degradation of wood cell wall components at high temperatures reduces the final density of the product (Düzkale Sözbir *et al*. 2021).

Unlike the physical properties and biological resistance, thermal modification has been shown to reduce the mechanical strengths of wood (Gaff *et al.* 2019; Baar *et al.* 2021; Yang and Jin 2021). The effect of OHT on the mechanical behavior of wood depends on the type of strength and processing temperature. Unlike modulus of elasticity (MOE) and compression strength parallel to the grain, elevating temperature reduces modulus of rupture (MOR), toughness, and hardness of modified wood (Haseli *et al.* 2024). To control the loss of strength, OHT under modified oils can be used (Tjeerdsma *et al.* 2005). According to the literature, the reaction of functional groups in modified oils with the hydroxyl groups of wood improved some physical and mechanical properties (Tjeerdsma *et al.* 2005; Jebrane *et al.* 2015a,b). Soybean oil with high epoxidation capacity is one of the most important vegetable oils (Tan and Chow 2010). The reaction of epoxy groups in epoxidized soybean oil forms chemical bonds with the hydroxyl groups of wood (Jebrane *et al.* 2015b). Impregnation of Scot pine samples with epoxidized linseed oil (ELO) decreased the moisture uptake, dimensional changes, and mechanical properties of ELO-treated wood (Jebrane *et al.* 2015b). The curing of ESO in the range 175 to 190 °C increased hardness of resulted polymer. However, the increase of temperature to 205 °C decreased it due to the thermal degradation of the cured polymer (Khoklang and Srithep 2022).

Simultaneous chemical and thermal modification of wood with functionalized oil has rarely been studied in literature (Tjeerdsma *et al.* 2005). It is assumed that OHT in the epoxidized soybean oil can improve physical characteristics and reduce the mechanical loss of wood. In addition to the method, the type of environment and the process schedule, wood species is also an important factor that influence the property alteration extent after wood modification (Mandraveli *et al*. 2024). Tomak *et al*.'s (2011) research showed that thermally treated beech wood had higher water absorption than Scots pine and resulted that changes in dimensional stability depend on the species.

Eucalyptus (*Eucalyptus camaldulensis*), which is a fast-growing species that is widely planted, has an important role in forestry, environmental restoration, as well as industrial applications such as papermaking and flooring. The unfavorably high dimensional changes of eucalyptus wood under different conditions (Poonia and Tripathi 2016) could be decreased *via* thermal modification methods such as OHT. In this study, the effects of OHT modification under epoxidized and raw soybean oil on some of the practical properties of eucalyptus wood were investigated.

EXPERIMENTAL

Materials

The defect-free and straight-grained heart wood of fast-growing eucalyptus (*Eucalyptus camaldulensis*) was harvested from the north of Iran and cut into 3 cm thick lumber pieces. After outdoor drying, they were cut to standard size for physical and mechanical tests according to ASTM D4442-92 (2003) and ASTM D143-14 (2014), in 10 replicates for each treatment.

Specimens with similar average dry density of 0.6 g/cm^3 were selected and oven-dried at 103 ± 2 °C for 24 h. Raw (molecular weight: 874 g/mol) and epoxidized soybean oil (molecular weight: 1000 g/mol) were obtained from Sepahan Fanavaran Shimi Company (Isfahan, Iran).

Table 1. The Condition and Code of Treatments

Treatments Code	Oil Type	Temperature (°C)
C	-	-
SO150	Raw soybean oil	150
SO175	Raw soybean oil	175
SO200	Raw soybean oil	200
ESO150	Epoxidized soybean oil	150
ESO175	Epoxidized soybean oil	175
ESO200	Epoxidized soybean oil	200

Methods

For OHT, oil immersion of specimens was done in a cubic steel container, and a mesh plate was placed on them to ensure full soaking. Consequently, the container was heated in an oven at 150, 175, and 200 °C for 4 h. After treatment, the specimens were left out of oil for one day to remove excess oil. Then the specimens were dried in an oven at 103 ± 2 °C for 24 h, weighed, and dimensions were measured. The various treatments and the code of specimens are presented in Table 1.

Physical Properties

The density of specimens, before and after OHT, and weight percent gain (WPG) of modified specimens was evaluated according to equations 1 and 2,

$$\text{Density} = m / v \quad (1)$$

where m is the weight (g) and v is the volume of specimens (cm^3) before and after modification.

$$\text{Weight gain} = W_1 - W_0 / W_0 \times 100 \quad (2)$$

In Eq. 2, W_0 and W_1 are weight of specimens before and after modification (g).

The efficiency of thermal modification was examined by calculating the water absorption (WA), water repellent efficiency (WRE), volumetric swelling (VS), and anti-swelling efficiency (ASE) of the specimens during soaking in water for 216 h according to equations 3 to 6. For long term immersion, the weight and dimension of specimens were measured during soaking in distilled water at room temperature until 216 h.

$$WA = W_2 - W_1 / W_1 \times 100 \quad (3)$$

where W_1 and W_2 are the weight of the specimens before and after soaking in water (g), respectively. The water repellent efficiency is given by,

$$WRE = WA_c - WA_t / WA_c \times 100 \quad (4)$$

where WA_c and WA_t represent water absorption of control and treated specimens. The volumetric swelling is calculated using,

$$VS = V_1 - V_0 / V_0 \times 100 \quad (5)$$

where V_1 and V_0 are the volume after and before soaking in water (cm^3). The anti-swelling efficiency is calculated as,

$$ASE = S_1 - S_2 / S_1 \times 100 \quad (6)$$

where S_1 is the volume swelling of unmodified specimens (%), and S_2 is the volume swelling of the modified specimens (%).

Mechanical Properties

Mechanical properties, including bending strength (MOR) and bending modulus (MOE), hardness, and impact resistance, were tested according to ASTM D143-14 (2014). Bending strength and hardness were tested using a SANTAM STM-20 machine (Santam Co., Iran). Impact resistance was tested using the SANTAM SIT-100 Pendulum Impact Tester machine (Santam Co., Iran).

Attenuated Total Reflection Fourier Transform Infrared (ATR-FTIR) Spectroscopy

For evaluating the chemical structure, the FTIR Spectroscopy was conducted on the surface of samples using an Agilent cary630 FTIR spectrometer (Agilent Co., USA) in the attenuated total reflectance (ATR) mode. The resulting spectra were recorded in the range of 400 and 4000 cm^{-1} with a resolution of 4 cm^{-1}.

Color Measurement

The color of specimens before and after thermal modification was assessed using a ZB-A Colorimeter (Hangzhou Zhibang Automated Technology Co., China) on three points of tangential surface in the CIELAB color system. This instrument provided the numerical value of L^* (lightness intensity from zero: black to 100: white), a^* (the color coordinate in pure green: -120 –pure red: +120), b^* (the color chroma on the pure yellow: +120 –pure blue axis: -120). To compare the color changes after OHT, three factors, ΔL^* as the lightness change, Δa^* and Δb^* as the color coordinates changes, and ΔE^* as the overall color change due to modification were calculated using Eqs. 7-10.

$$\Delta L = L_i - L_f \quad (7)$$

$$\Delta a = a_i - a_f \quad (8)$$

$$\Delta b = b_i - b_f \quad (9)$$

$$\Delta E = [\Delta L^2 + \Delta a^2 + \Delta b^2]^{1/2} \quad (10)$$

where i is the index after modification and f is the index before modification (control specimens).

Statistical Analysis

A complete randomized design and Duncan grouping were used to evaluate the effect of different conditions of Thermal modification on the properties of Eucalyptus wood. Statistical analysis was conducted using SPSS software program, version 17.0 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Chemical Structure

Figure 1 illustrates the Fourier transform infrared spectroscopy of the control and modified specimens. Compared to the control samples, the peak around 3350 cm^{-1} corresponding to the hydroxyl groups was reduced in the SO-OHT samples, due to the degradation of hemicellulose (Haseli *et al.* 2024). By the deacetylation reactions of hemicellulose, acetic acid was formed, which catalyzed the degradation of polysaccharides (Hill 2006; Kučerová *et al*. 2016; Mandraveli *et al*. 2024). The increase of hydroxyl groups in ESO-modified specimens can be attributed to the successful opening of the epoxy ring, which declined with rising temperatures (Jebrane *et al.* 2015b; Li *et al.* 2021).

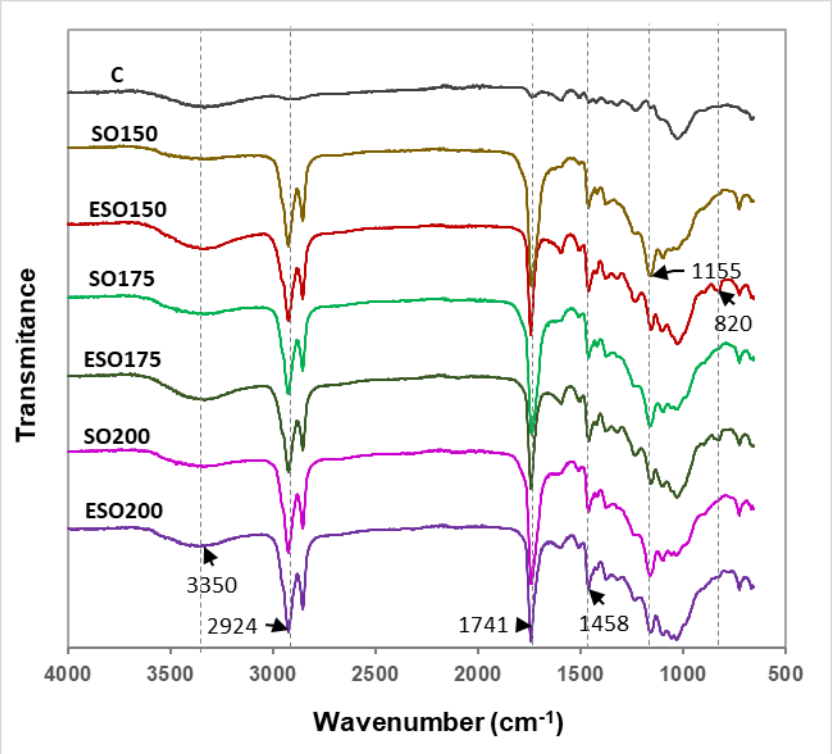

Fig. 1. Fourier transform infrared spectra of control and treated wood at different conditions (C: untreated control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C)

In both SO and ESO-treated specimens, the stretching vibrations of the methyl groups (CH_3) at the end of the triglyceride chain and the methylene part (CH_2) of the main saturated fatty acid chain were observed at 2924 cm^{-1} and 2854 cm^{-1}, respectively (Li *et al.* 2021). Compared to control specimens, the peak of carbonyl groups (C = O) at 1735 cm^{-1} increased for both OHT modifications (SO and ESO), which can be attributed to the presence of these groups in the oils. Heat treatment up to 200 °C decreased carbonyl groups intensity, which was more obvious for the ESO-treated specimens, similar to previous studies (Demirel *et al.* 2018; Li *et al.* 2021). Previous literature also confirmed decreasing the carbonyl peak intensity by thermal modification *via* the degradation of hemicellulose (Esteves *et al.* 2013; Cheng *et al.* 2016; Suri *et al.* 2021). The higher intensity of the C-H

bond at 1458 cm^{-1} for modified specimens can be attributed to the presence of hydrocarbon groups in oil structures (Esteves *et al.* 2013; Haseli *et al.* 2024). The intensity of peaks around 1100 and 1155 cm^{-1} correspond to the C-O-C bond of glucans (Werner *et al*, 2014), main glucosic structure of cellulose (Apaydın Varol and Mutlu, 2023), and ether bond of oils, were higher for SO-treated specimens than ESO-treated ones. At higher temperature, these peaks slightly decreased due to the more degradation of hemicellulose or amorphous parts of cellulose (Mburu *et al.* 2007; Suri *et al.* 2021). Indeed, glucan remained mostly unchanged up to 180 °C, and it degraded at higher temperature (Borrega *et al*. 2011). The intensity of the peak at 820 cm^{-1} associated with epoxy groups decreased for ESO-modified specimens at higher temperatures, owing to the side reactions and the opening of the oxirane ring, the destruction of epoxy rings, and the consumption of epoxy groups (Demirel *et al.* 2018; Meadows *et al.* 2016).

Color Appearance

The changes in the color of the specimens were measured by the colorimetric test (Table 2). Thermal modification darkened the specimens, which was more obvious at higher temperatures (Fig. 2) (Bak and Nemeth 2012; Freitas *et al.* 2018; Výbohová *et al.* 2018; Baar *et al.* 2021; Yang and Jin 2021).

C	Oil Type	150 °C	175 °C	200 °C
	SO			
	ESO			

Fig. 2. Color of the control and thermal modified wood at different temperatures

Higher temperatures decreased *L** index compared to the control. At all temperatures, the color change of the modified samples with ESO was more than SO modified ones, and the maximum total color change was observed on the ESO modified samples at 200 °C, which it has previously been confirmed in the literature (Tjeerdsma *et al.* 2005). Change of color by OHT depends on temperature, amount of oil uptake, and type of oil (Tjeerdsma *et al.* 2005). Thermal treatment alters the chromophore groups of lignin (Yang and Jin 2021). In oxygen-free mediums like oil, caramelization of soluble sugars in frying oil is a more probable reason for the darkening effect (Lee *et al.* 2018).

Table 2. Parameters of Wood Samples Color Change after Oil Heat Treatment

Treatment	*L**	*a**	*b**	ΔE*
C	62.09 (2.42)	15.16 (3.26)	25.41 (1.59)	-
SO150	42.42 (1.29)	20.69 (2.2)	22.08 (0.52)	20.76 (1.78)
ESO150	29.02 (1.54)	16.9 (0.99)	12.05 (3.39)	35.84 (1.17)
SO175	32.12 (1.28)	15.85 (2.41)	18.41 (0.93)	30.86 (1.12)
ESO175	32.81 (1.77)	22.24 (2.87)	20.22 (3.32)	30.75 (2.36)
SO200	25.39 (0.58)	8.4 (0.49)	12.37 (0.89)	39.53 (0.64)
ESO200	23.72 (2.11)	5.76 (2.9)	6.18 (1.87)	44.04 (1.71)

Note: Standard deviation in parenthesis

Physical Properties

According to the results, thermal modification in ESO/200 °C resulted in a weight loss of modified specimens (Fig. 3). This phenomenon could be attributed to less uptake of ESO with higher molecular weight into the wood structure than SO. Proportional with increasing temperature, the ESO modification showed lower WPG compared to SO and even led to a reduction of weight at 200 °C. Decrease in WPG of ESO200 could be attributed to: cell wall degradation at high temperature (Tjeerdesma *et al*. 2005; Mandraveli *et al*. 2024), and less uptake of ESO with higher molecular weight. Because of the simultaneous loss of wood substance and oil uptake during the OHT, wood mass loss could not be exactly measured (Tjeerdesma *et al*. 2005). The density of OHT specimens significantly increased at 150 °C for SO/ESO and SO175 compared to control specimens because weight gain from oil uptake was more than weight loss due to cell wall degradation; however, the weight decreased with increasing of the temperature to 200 °C (Fig. 3) (Tjeerdesma *et al.* 2005; Boonstra *et al.* 2007; Düzkale Sözbir *et al*. 2021; Yang and Jin 2021). According to thermal analysis of ESO, functionalization with epoxy groups increases thermal stability of oil up to 240 to 260 °C (Kim and Sharma 2012; Sun *et al*. 2013). Thus, weight loss and subsequently, decrease of density for ESO200 could be attributed to the more cell wall degradation that could not be compensated with oil uptake.

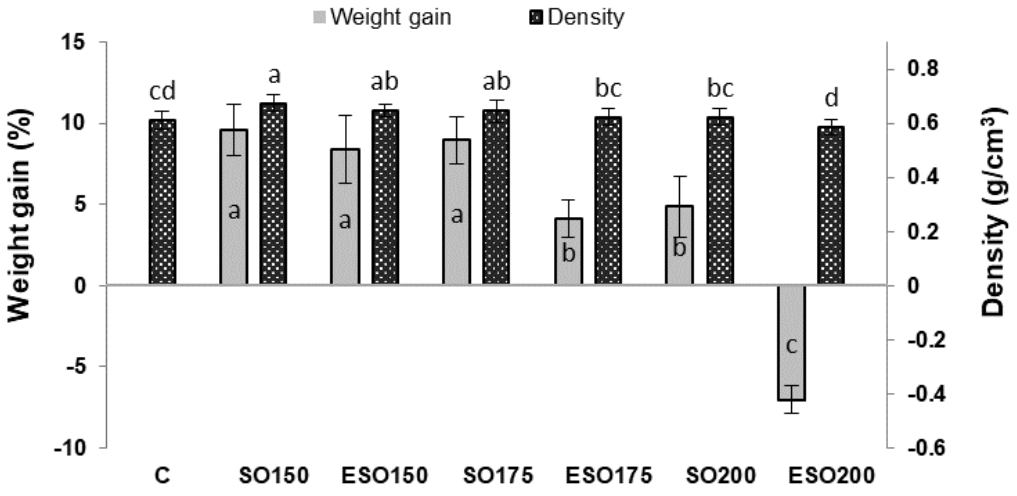

Fig. 3. Density and weight percent gain (WPG) of control and modified specimens. C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C. Different letters on columns indicate Duncan grouping at 95% significant level.

Figure 4 illustrates the water absorption (WA) and water repellency efficiency (WRE) of the control and modified specimens. WA of control specimens ranged from 18% after two hours soaking in water to 94% after 9 days (216 hours). WA of oil heat-treated specimens reduced significantly. At the end of soaking time, the reduction in WA was 23% for SO150 and about 77% for ESO200 compared to the control. At all temperature conditions, ESO-modified samples with higher WRE absorbed less water compared to the SO-modified samples in spite of higher WPG, and this difference became more obvious by increasing temperature. This result confirms the higher efficiency of ESO (WRE: 82% after 9 days) through chemical reaction of epoxy groups with free hydroxyl groups of wood cell wall and reducing water absorption sites, which confirms with FTIR results (Meadows *et al.* 2016; Demirel *et al.* 2018). Typically, hydrophobicity of OHT-modified samples occurred through two mechanisms: (1) the hydrophobic nature of the oil absorbed into the wood cavities and (2) the reduction of hydroxyl groups by degradation of hemicelluloses (Lee *et al.* 2018; Baar *et al.* 2021). In ESO heat treated specimens the simultaneous chemical/thermal modification could also intensify the effect of this procedure on WRE.

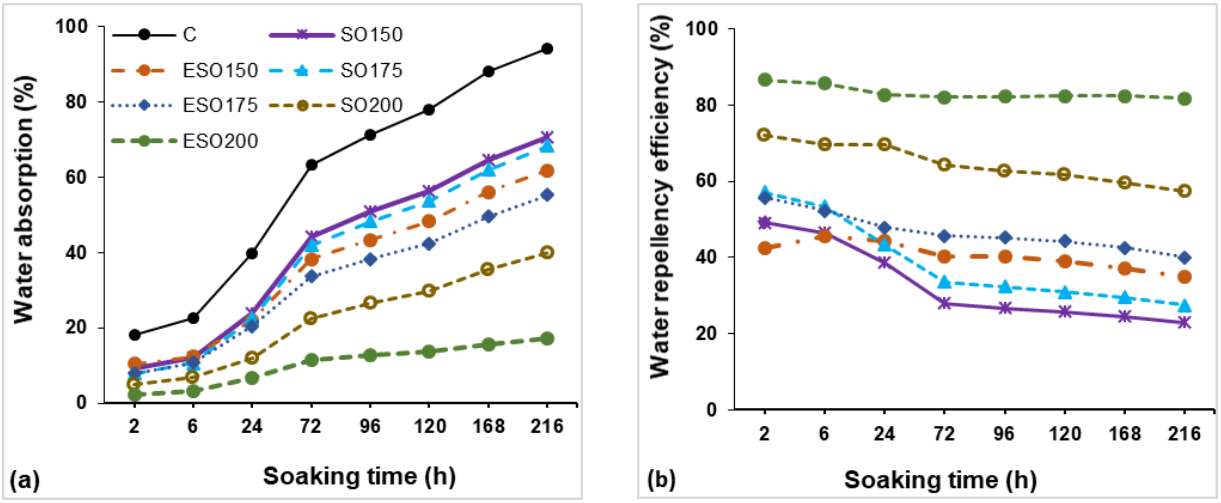

Fig. 4. Water absorption (a) and water repellency efficiency (b) of different treatments. Legends are the same for (a) and (b). C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C, respectively.

According to Fig. 5, OHT resulted in the dimensional stability of modified specimens, which was higher for ESO than SO-modified specimens. At the end of soaking time, the highest ASE results (79%) were obtained from ESO200 and the lowest from SO150 (10%). The least thermal modification occurred at lower temperature (150 °C). It has been proposed that the main reason for hydrophobicity is a mechanical barrier effect of nonpolar oil in wood cell lumens (Baar *et al*. 2021). ASE and also WRE of SO modified specimens were reduced rapidly with outgoing of oil in SO150, while chemical bound of ESO with wood maintained these two factors relatively constant in ESO150. ASE was enhanced prominently with increasing temperature. Degradation of hemicelluloses by declining hydroxyl groups during heat treatment has been stated as being the reasons for dimensional changes (Lee *et al.* 2018). Chemical reaction of epoxy groups in functionalized oil with the hydroxyl groups of wood at higher temperatures also further reduced the swelling of ESO-modified specimens. The reduction of the intensity of epoxy groups with increasing temperature, indicating the reaction of epoxy groups with wood,

has been confirmed by the FTIR spectra (Fig. 1). These results were in agreement with those of other researchers, who have reported ASE increases of 70% for ESO and 12.7% for SO modified Scots pine wood (Demirel *et al*. 2018). Several publications reported increases of WRE or ASE with chemical modification of wood with epoxidized vegetable oils (Temiz *et al*. 2013; Jebrane *et al*. 2015a; Demirel *et al*. 2018) and synchronic thermal/chemical modification with chemically modified vegetable oil (Tjeerdesma *et al.* 2005).

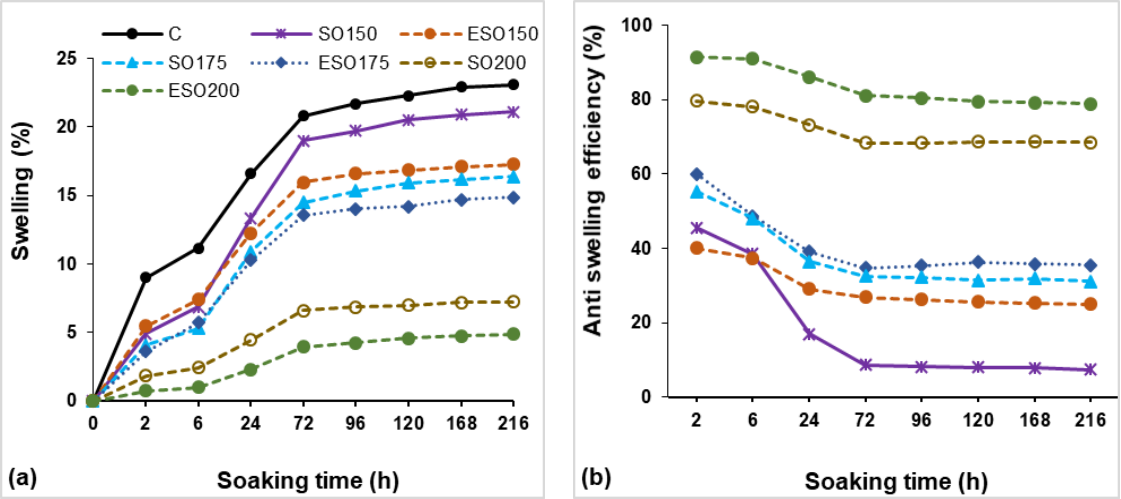

Fig. 5. Volume swelling (a) and anti-swelling efficiency (b) of different treatments. Legends are the same for (a) and (b). C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C, respectively

Mechanical Properties

The bending strength of treated and untreated specimens is presented in Fig. 6. Heat treatment with both types of oil increased MOE. This improvement was not significant at 200 °C compared with control specimens. This increment could be attributed to (1) the degradation of the amorphous part of cellulose and increasing relative crystallinity (Kocaefe *et al.* 2008; Lee *et al.* 2018; Baar *et al.* 2021; Haseli *et al.* 2024), (2) the transformation of lignin (from a glassy state to a plastic state at glass-transition temperature and cross link formation with more rigidity) (Araújo *et al.* 2016; Lee *et al.* 2018; Baar *et al.* 2021), and (3) the filling of cell lumens by oil as incompressible fluid (Megnis *et al.* 2002; Baar *et al.* 2021). Gaff *et al.* (2019) reported a slight increase in MOE of European oak wood modified under low temperature (160 °C), which declined with increasing temperature.

Based on the results, SO/thermal modification at 150 °C, unlike ESO, did not cause a significant change in MOR compared to the control specimens. However, any statistical difference was not observed between the two types of oils at higher temperatures (Fig. 6). According to the literature, oil uptake improved the MOR of wood specimens, which could compensate for the negative effect of structural degradation of SO/OHT modified wood (Baar *et al.* 2021). The lower uptake of ESO likely resulted in loss of MOR in modified specimens at 150 °C. The lowest value of MOR was observed at 200 °C, due to the increased degradation of the cell wall components proportional with increasing temperature (Boonstra *et al.* 2007; Araújo *et al.* 2016; Baar *et al.* 2021).

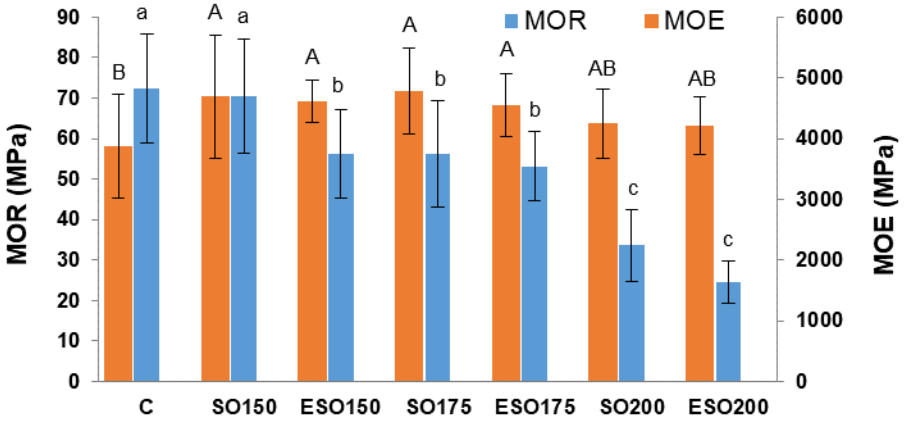

Fig. 6. Modulus of elasticity and MOR of control and modified Eucalyptus wood. C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C. Different letters on columns indicate Duncan grouping at 95% significant level.

Oil heat treatment at 150 °C resulted in an increase in hardness for both oil types (Fig. 7) due to the transformation of lignin, which was not significant for ESO ones (Gaff *et al.* 2019; Juizo *et al.* 2020). At 200 °C, the specimens modified with ESO exhibited lower hardness than those modified with SO. According to Jebrane *et al.* (2015b), chemical modification of Scot pine wood with epoxidized linseed oil also decreased the hardness. The reduction of hardness proportional to increasing temperature can be attributed to the degradation of cell wall components (Fang *et al.* 2012; Khoklang and Srithep 2022).

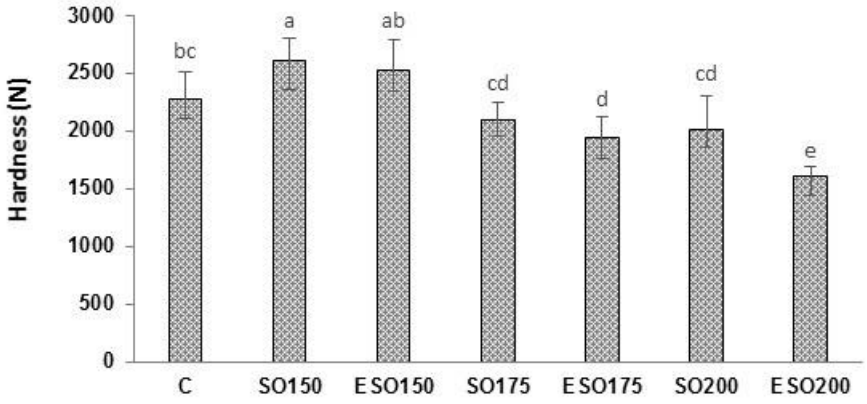

Fig. 7. Hardness of control and oil heat treated specimens. C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C. Different letters on columns indicate Duncan grouping at 95% significant level.

The results showed that thermal modification significantly reduced impact bending resistance (Fig. 8). The highest impact resistance was measured for the control specimens, and this strength declined by increasing temperature for both oils, which could be related to the increasing brittleness resulting from degradation of the cell wall and enhancing rigidity due to the formation of cross-linkages in heat treated specimens (Gaff *et al.* 2019; Yang and Jin 2021; Zheng *et al.* 2023). In comparing two types of oil, the impact resistance

of 150 and 175 °C/ESO modified specimens was higher than SO ones, without significant difference at 175 °C. Wood modification in ESO by replacing long chains of oil between cellulose microfibrils, likely increased flexibility due to the weakening of the bond between the cell wall components, which enhanced impact resistance of 150 °C/ESO modified specimens, without obvious degradation in this temperature.

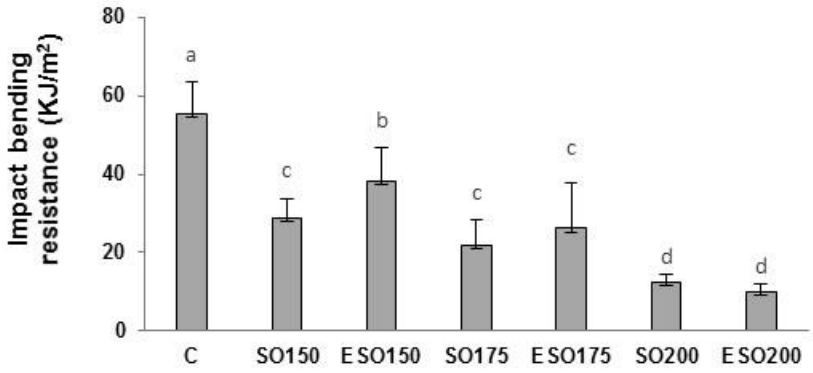

Fig. 8. Impact bending resistance of control and modified specimens. C: control; SO150, SO175, SO200: thermally modified with soybean oil at 150, 175 and 200 °C; ESO150, ESO175, ESO200: thermally modified with epoxidized soybean oil at 150, 175 and 200 °C. Different letters on columns indicate Duncan grouping at 95% significant level.

Thermal modification with ESO at a lower temperature, in the presence of catalysts, may retain the mechanical strength accompanied by the desirable color and dimensional stability, which needs to be investigated in future research.

CONCLUSIONS

1. The results showed the change in the chemical structure of the oil heat treated eucalyptus wood. Thermal modification in epoxidized soybean oil (ESO) with increasing temperature resulted in a darker color, loss of weight and density, and more hydrophobicity and dimensional stability compared to the raw soybean oil (SO)-modified specimens.
2. Bending strength did not show a statistical difference between the two types of oils in the case of oil heat treatment (OHT) specimens, except at 150 °C.
3. At 200 °C, ESO-modified specimens showed lower hardness than SO-modified specimens.
4. The impact resistance of 150 and 175 °C/ESO modified specimens was higher than SO specimens.
5. Functionalized vegetable oil significantly improved physical properties and impact strength at 150 °C compared to SO.

ACKNOWLEDGEMENTS

The authors would like to thank the Vice Chancellor for Research at Sari Agricultural and Natural Resources University in I. R. Iran for financial support.

REFERENCES CITED

Apaydın Varol, E., and Mutlu, Ü. (2023). "TGA-FTIR analysis of biomass samples based on the thermal decomposition behavior of hemicellulose, cellulose, and lignin," *Energies* 16(9), 1-19. DOI: 10.3390/en16093674

Araújo, S. O., Vital, B. R., Oliveira, B., Carneiro, A. C. O., Lourenço, A., and Pereira, H. (2016). "Physical and mechanical properties of heat treated wood from *Aspidosperma populifolium*, *Dipteryx odorata* and *Mimosa scabrella*," *Maderas. Ciencia y Tecnología* 18(1), 143-156. DOI: 10.4067/S0718-221X2016005000015

ASTM D4442-92 (2003). "Standard test methods for direct moisture content measurement of wood and wood-base materials," ASTM International, West Conshohocken, PA, USA.

ASTM D143-14 (2014). "Standard test methods for small clear specimens of timber," ASTM International, West Conshohocken, PA, USA.

Baar, J., Brabec, M., Slávik, R., and Čermák, P. (2021). "Effect of hemp oil impregnation and thermal modification on European beech wood properties," *European Journal of Wood and Wood Products* 79, 161-175. DOI: 10.1007/s00107-020-01615-9

Boonstra, M., Acker, J., Tjeerdsma, B., and Kegel, E. (2007). "Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents," *Annals of Forest Science* 64(7), 679-690. DOI: 10.1051/forest:2007048

Borrega, M., Nieminen, K., and Sixta, H. (2011). "Degradation kinetics of the main carbohydrates in birch wood during hot water extraction in a batch reactor at elevated temperatures," *Bioresource Technology* 102(22), 10724-10732. DOI: 10.1016/j.biortech.2011.09.027

Demirel, G. K., Temiz, A., Jebrane, M., Terziev, N., and Gezer, E. (2018). "Micro-distribution, water absorption and dimensional stability of wood treated with epoxidized plant oils," *BioResources* 13(3), 5124-5138. DOI: 10.15376/biores.13.3.5124-5138

Esteves, B., Velez Marques, A., Domingos, I., and Pereira, H. (2013). "Chemical changes of heat treated pine and eucalypt wood monitored by FTIR," *Maderas. Ciencia y Tecnología* 15(2), 245-258. DOI: 10.4067/S0718-221X2013005000020

Fang, C., Cloutier, A., Blanchet, P., and Koubae, A. (2012). "Densification of wood veneers combined with oil-heat treatment. Part II: Hygroscopicity and mechanical properties," *BioResources* 7(1), 925-935. DOI: 10.15376/biores.7.1.925-935

Freitas, F. P. D., Carvalho, A. M. M. L., Carneiro, A. D. C. O., Vital, B. R., Gonçalves, L. M. S., Jesus, M. S. D, and Xisto, M. F. (2018). "Influence of time and heat treatment temperature on permeability of *Eucalyptus grandis* wood," *Revista Árvore* 43(3), 1-7. DOI: 10.1590/1806-90882019000300001

Gaff, M., Kačík, F., Sandberg, D., Babiak, M., Turčani, M., Niemz, P., and Hanzlík, P. (2019). "The effect of chemical changes during thermal modification of European oak and Norway spruce on elasticity properties," *Composite Structures* 220, 529-538, DOI: 10.1016/j.compstruct.2019.04.034

Hill, C. A. S. (2006). *Wood Modification: Chemical, Thermal, and Other Processes*, John Wiley & Sons, Hoboken, NJ, USA.

Jebrane, M., Fernández-Cano V., Panov, D., Terziev, N., and Daniel, G. (2015a). "Novel hydrophobization of wood by epoxidized linseed oil. Part 1. Process description and anti-swelling efficiency of the treated wood," *Holzforschung* 69(2), 173-177. DOI: 10.1515/hf-2014-0029

Jebrane, M., Fernández-Cano V., Panov, D., Terziev, N., and Daniel, G. (2015b). "Novel hydrophobization of wood by epoxidized linseed oil. Part 2. Characterization by FTIR spectroscopy and SEM, and determination of mechanical properties and field test performance," *Holzforschung* 69(2), 179-186. DOI: 10.1515/hf-2014-0030

Juizo, C. G. F., Pereira da Rocha, M., Nogueira Xavier, C., Moreira Moraes, A., Bezerra de Oliveira, M., and Moreira da Silva, J. R. (2020). "Thermal modification of eucalyptus wood and use for floors of low traffic environment," *FLORESTA* 51(2), 457-465. DOI: 10.5380/rf.v51i2.69860

Khoklang, N., and Srithep, Y. (2022). "Preparation of epoxidized soybean oil for use as bio-based epoxy for coating application," *KKU Science Journal* 50(1), 1-12.

Kim, J. R., and Sharma, S. (2012). "The development and comparison of bio-thermoset plastics from epoxidized plant oils," *Industrial Crops and Products* 36, 485-499.

Kocaef, D., Poncsak, S., and Boluk, Y. (2008). "Effect of thermal treatment on the chemical composition and mechanical properties of birch and aspen," *BioResources* 3, 517-537. DOI: 10.15376/biores.3.2.517-537

Kučerová, V., Lagana, R., Vybohova, E., and Hýrošová, T. (2016). "The effect of chemical changes during heat treatment on the color and mechanical properties of fir wood," *BioResources*, 11, 9079–9094.

Lee, S. H., Ashaari, Z., Lum, W. C. H., Halip J. A., Ang, A. F., Tan, L.P., Chin, K. L., and Tahir, P. M. (2018). "Thermal treatment of wood using vegetable oils: A review," *Construct. Building Mater.* 181, 408-419. DOI: 10.1016/j.conbuildmat.2018.06.058

Li, W., Zhang, Z., Wang, X., Mei, C., Van Acker J., and Van den Bulcke, J. (2021). "Understanding the effect of growth ring orientation on the compressive strength perpendicular to the grain of thermally treated wood," *Wood Science and Technology* 55, 1439-1456. DOI: 10.1007/s00226-021-01323-4

Mandraveli, E., Mitani, A., Terzopoulou, P., and Koutsianitis, D. (2024). "Oil heat treatment of wood—A comprehensive analysis of physical, chemical, and mechanical modifications," *Materials*, 17, article 2394. DOI: 10.3390/ma17102394

Mburu, F., Dumarcay, S., Huber, F., Petrissans, M., and Gerardin, P. (2007). "Evaluation of thermally modified *Grevilla robusta* heartwood as an alternative to shortage of wood resource in Kenya: Characterisation of physicochemical properties and improvement of bio-resistance," *Bioresource Technology* 98, 3478-3486. DOI: 10.1016/j.biortech.2006.11.006

Meadows, A. L., Hawkins, K. M., Tsegaye, Y., Antipov, E., Kim, Y., Raetz, L., and Tsong, A. E. (2016). "Rewriting yeast central carbon metabolism for industrial isoprenoid production," *Nature* 537(7622), 694-697. DOI: 10.1038/nature19769

Megnis, M., Olsson, T., Varna, J., and Lindberg, H. (2002). "Mechanical performance of linseed oil impregnated pine as correlated to the take-up level," *Wood Science Technology* 36(1), 1-18. DOI: 10.1007/s002260100120

Nejad, M., Shafaghi, R., Ali, H., and Cooper P.A. (2013). "Coating performance on oil-heat treated wood for flooring," *BioResources* 8(2), 1881-1892. DOI: 10.15376/biores.8.2.1881-1892

Nejad, M., Dadbin, M., and Cooper, P. (2019). "Coating performance on exterior oil-heat treated wood," *Coatings* 9(4), 1-11. DOI: 10.3390/coatings9040225

Nemeth, R., and Bak, M. (2012). "Changes in swelling properties and moisture uptake rate of oil- treated poplar (*Populousx euramericana* cv. Pannonia) wood," *BioResources* 7(4), 5128-5137. DOI: 10.15376/biores.7.4.5128-5137

Poonia, P. K. and Tripathi, S. (2016). "Moisture-related properties of eucalyptus tereticornis after thermal modification," *J. Tropical Forest Science* 28(2): 153–158.

Sandberg, D., Kutnar, A., and Mantanis, G. (2017). "Wood modification technologies - A review," *iForest Biogeosciences Forestry* 10, 895-908. DOI: 10.3832/ifor2380-010

Düzkale Sözbir, G., Bektaş, İ., Kiliç Ak, A., and Erkan, S. (2021). "Pine wood modification *via* an antifungal oil – Heat treatment and its effect on annual wood rings," *BioResources* 16(3), 4731-4742.

Sun, B., Chaudhary, B. I., Shen, C. Y., Mao, D., Yuan, D. M., Dai, G. C., Li, B., and Co-gen, J. M. (2013). "Thermal stability of epoxidized soybean oil and its absorption and migration in poly (vinylchloride)," *Polymer Engineering and Science* 53 (8), 1645-1656. DOI: 10.1002/pen.23417

Suri, I. F., Purusatama, B. D., Lee, S. H., Kim, N. H., Hidayat, W., and Ma'ruf, S. D. (2021). "Characteristic features of the oil-heat treated woods from tropical fast growing wood species," *Wood Research* 66(3), 365-378. DOI: 10.37763/wr.1336-4561/66.3.365378

Tan, S. G., and Chow, W. S. (2010). "Biobased epoxidized vegetable oils and its greener epoxy blends: a review," *Polymer-Plastics Technology and Engineering* 49(15), 1581-1590. DOI: 10.1080/03602559.2010.512338

Temiz, A., Akbas, S., Panov, D., Terziev, N., Alma, M. H., Parlak, S., and Kose, G. (2013). "Chemical composition and efficiency of bio-oil obtained from giant cane (*Arundo donax* L.) as a wood preservative," *BioResources* 8(2), 2084-2098.

Tjeerdsma, B. F., Swager P., Horstman, B., Holleboom, and W., Homan. J. (2005). "Process development of treatment of wood with modified hot oil," *European Conference on Wood Modification* 1-10.

Tomak, E. D., Hughes, M., Yildiz, U. C., and Viitanen, H. (2011). "The combined effects of boron and oil heat treatment on beech and scots pine wood properties. Part 1: Boron leaching, thermogravimetric analysis, and chemical composition," *J. Mater. Sci.* 46, 598-607. DOI: 10.1007/s10853-010-4859-8

Výbohová, E., Kučerová, V., Andor, T., Balážová, Z., and Veľková, V. (2018). "The effect of heat treatment on the chemical composition of ash wood," *BioResources* 13(4), 8394-8408. DOI: 10.15376/biores.13.4.8394-8408

Werner, K., Pommer, L., and Broström, M. (2014). "Thermal decomposition of hemicelluloses," *J. Anal. Appl. Pyrol.* 110, 130-137. DOI: 10.1016/j.jaap.2014.08.013

Yang, L., and Jin, H. (2021). "Effect of heat treatment on the physic-mechanical characteristics of *Eucalyptus urophylla* S.T. Blake," *Materials* 14(21), 1-12. DOI: 10.3390/ma14216643

Zheng, S., Chen, M., Wu, J., and Xu, J. (2023). "Effect of heat treatment on properties and interfacial compatibility of poplar veneer/polyethylene film composite plywood," *Polymer Testing* 122, 1-8. DOI: 10.1016/j.polymertesting.2023.108006

Article submitted: July 23, 2024; Peer review completed: August 18, 2024; Revised version received and accepted: September12, 2024; Published: April 25, 2025.
DOI: 10.15376/biores.20.2.4450-4463