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# EFFECTS OF VEGETABLE OIL TYPE AND IMPREGNATION METHOD ON THE UPTAKE, LEACHING RESISTANCE, AND DIMENSIONAL STABILITY OF WOOD

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## ABSTRACT

Vegetable oils and their derivatives (VODs) were evaluated as sustainable wood treatments to improve the water resistance and dimensional stability of Japanese larch (JAC), Douglas-fir, western hemlock, and yellow poplar under saline-water exposure. Specimens were treated with castor oil (CAO), hydrogenated castor oil (HCO), soybean oil (SBO), and waste cooking oil (WCO) using coating, immersion, vacuum (VAC), and vacuum-pressure (VAC-PRES) methods. VOD uptake varied with its type, and treatment method. Leaching resistance followed the order HCO > SBO > CAO > WCO, whereas all treatments, except those using WCO, significantly improved dimensional stability compared with untreated controls. JAC specimens treated with HCO by VAC impregnation exhibited the lowest VOD concentration in leachates and the greatest dimensional stability. Overall, VOD impregnation enhanced wood performance under saline-water exposure, with VAC impregnation using HCO identified as the most effective treatment. These findings highlight the potential of HCO-treated wood for exterior and marine applications.

KEYWORDS: Vegetable oils, impregnation method, dimensional stability, moisture resistance, marine application.

## INTRODUCTION

Wood is a renewable and versatile engineering material prized for its high strength-to-weight ratio, thermal insulation, and excellent workability. Its inherent hydrophilicity, however, arising from hydroxyl groups in cell wall constituents promotes moisture adsorption and dimensional instability, which restricts use in some applications.

To mitigate these limitations, a range of physico-chemical treatments have been developed to render wood surfaces more hydrophobic and thereby improve dimensional stability (Rowell et al. 2009; Gabrielli and Kamke 2010). Chemical modifications such as acetylation and furfurylation (Westin et al. 2009; Mohebby and Militz 2010), thermal treatments (Kartal 2006), and impregnation with thermosetting resins have been used to reduce moisture uptake in harsh environments (Hazarika and Maji 2014; Augustina et al. 2023). Waxes such as paraffin and montan wax have also been shown to improve dimensional stability (Lesar et al. 2011). Despite these advances, most commercially used coatings, modification agents, and impregnation compounds are fossil-derived, raising concerns about climate change, environmental pollution, and human health. Consequently, there is growing interest in developing bio-derived water repellents as sustainable alternatives.

Plant-based hydrophobic substances including rapeseed, soybean, linseed, castor, sunflower, and safflower oils, together with natural resins, and plant- or animal-derived waxes, have been explored as eco-friendly alternatives to conventional, fossil-derived wood protectants for reducing decay and dimensional changes in exterior applications (Singh and Singh 2012; Humar and Lesar 2013). Vegetable oils can be introduced into wood by pressure impregnation, immersion, or vacuum treatments to promote penetration into cell walls and lumen (Wei et al. 2022). Natural waxes extracted from plant sources have shown particular promise. For example, Passialis and Voulgaridis (1999) reported that waxes from the needles and bark of Aleppo pine (*Pinus halepensis* M.) impart hydrophobicity to pine and beech wood, and can replace up to 50% of paraffin wax in water-repellent formulations without loss of performance. Wax impregnation has also been associated with improvements in compressive strength, hardness, bending strength, and impact resistance, depending on impregnation level, wood species, and wax characteristics (Papadopoulos and Hill 2003; Liu et al. 2011). These improvements are attributed primarily to physical mechanisms – higher density, lower equilibrium moisture content, and void-filling or plasticizing by ductile waxes – rather than to chemical bonding with wood polymers (Scholz et al. 2012). Despite these promising results, systematic investigations into the use of hydrophobic vegetable oils and plant-derived waxes for long-term dimensional stabilization are still limited. Further works, therefore, is needed to optimize impregnation methods, accurately quantify uptake and distribution, evaluate leachability under realistic environmental exposure, and assess long-term dimensional and mechanical performance.

This study evaluates castor oil (CAO) - a versatile bio-based feedstock used in cosmetic, food, pharmaceutical, plastic, and lubricants - and its hydrogenated derivative (hydrogenated castor oil, HCO) alongside soybean oil (SBO) and waste cooking oil (WCO) as bio-based wood-treatment agents. Treatments were applied to two domestic species (Japanese cedar, yellow poplar) and two imported species (Douglas fir, western hemlock) using surface coating, immersion, vacuum, and vacuum-pressure impregnation to promote penetration of the vegetable oils and its derivatives (VOD) into the porous wood structure. We quantified VOD uptake and leaching resistance, measured volumetric swelling after saline-water submersion to assess dimensional stability, and used X-ray microscopy to visualize VOD distribution after saline-water submersion. Based on these results, we identify promising VOD-treatment combinations for marine application.

## MATERIAL AND METHODS

### Preparation of wood specimens, vegetable oils and its derivatives

Wood from four species was used: Japanese cedar (*Cryptomeria japonica* D.; JAC; 430 kg/m$^3$), Douglas fir (*Pseudotsuga menziesii*; DOF; 510 kg/m$^3$), western hemlock (*Tsuga heterophylla*; HEM; 465 kg/m$^3$), and yellow poplar (*Liriodendron tulipifera* L.; YEP; 410 kg/m$^3$). For each species, wood was milled and assigned randomly without distinction between sapwood and heartwood. Specimens were prepared as blocks (2.54 cm × 2.54 cm × 2.54 cm) and strips (7.00 cm × 0.70 cm × 2.54 cm, L×R×T).

Four VODs were evaluated as impregnating agents: castor oil (CAO), hydrogenated castor oil (HCO), soybean oil (SBO), and waste cooking oil (WCO). CAO (99.9% purity., *Ricinus communis*) and HCO (flake form) were supplied by SM Green Co., Ltd. (Gimpo, South Korea) and Hebei Guanlang Biotechnology Co., Ltd. (Shijiazhuang, China), respectively. SBO (edible grade) was obtained from CJ Cheiljedang Co., Ltd. (Incheon, South Korea) via a local market. WCO was collected after frying with soybean oil, screened through a 3.17 mm (8-mesh) sieve, and provided by the cafeteria at Seoul National University, Pyeongchang campus (Gangwon-do, South Korea).

### Impregnation procedures

CAO, SBO, and WCO were used in liquid form as supplied. HCO (flake form) was liquefied by heating in an oven at 105°C until fully molten prior to use. VOD was applied by four methods, such as spreading, immersion, vacuum and vacuum-pressure. Procedures were as follows: *(1)* Spreading (SPR): specimens were dipped in the VOD for 10 s, *(2)* Immersion (IMM): specimens were fully submerged in the VOD for 24 h. *(3)* Vacuum (VAC): specimens were placed in a treatment cylinder and subjected to a vacuum of 750 mmHg for 15 min. *(4)* Vacuum-pressure (VAC-PRES): specimens underwent the same vacuum cycle (750 mmHg, 15 min) followed immediately by a pressure cycle at 40 kg/cm$^2$ for 15 min.

After treatment, excess VOD on the surface of specimens was removed by wiping with paper towels and scraping with a knife blade. Treated specimens were air-dried for 1 week to constant weight to determine treated dry weights and actual VOD retention. The percentage weight gain of each specimen was designated as VOD uptake, calculated from the difference between treated and original dry weights.

### Leaching procedure

Treated specimens were submerged in saline water prepared by dissolving 35 g solar salt per 1 liter of deionized water and maintained for 2 weeks to evaluate the resistance of the VOD treatments to leaching. After the leaching period, specimens were rinsed at least five times with tap water to remove surface salts, then air-dried at room temperature for 1 week. Air-dried specimens were oven-dried at 70°C for 48 h and weighed to determine post-leaching dry weight. Leachability of the VOD treatment was expressed as the percentage of retained treatment lost during leaching and calculated as follows (Kwon et al. 2023):

$$\text{Leachability (\%)} = [(W1 - W2)/W1] \times 100 \quad (1)$$

where: W1 is the treated dry weight before leaching and W2 is the dry weight after leaching and oven drying.

**Determination of fatty acid in leachate**

One liter of saline water from each leaching test was collected for quantitative analysis of fatty-acids included in the leachates. Samples were filtered through an HLB 6 cc Vac cartridge (Waters Inc., Milford, MA, USA) to remove salts and particulates. The filtrate was concentrated to dryness using a vacuum concentrator (SpeedVacTM DNA 130, Thermo Fisher Scientific, Waltham, MA, USA). Visible oil residues adhering to the concentrator vessel were rinsed into a 50 mL Falcon® conical tube with 1 mL n-heptane. Two mL of methylation reagent (MeOH:benzene:2,2-dimethoxy-propane:72% $H_2SO_4$ = 39:20:5:2, v/v/v/v) was added to the n-heptane solution for trans-esterifying fatty acids to fatty acid methyl esters (FAMEs) following Seppänen-Laakso et al. (2002). The mixture was transferred to a 4 mL glass vial and heated at 80°C for 2 h. After cooling to room temperature, the n-heptane layer (supernatant) containing FAMEs was collected for gas chromatographic (GC) analysis.

FAMEs were analyzed using a Thermo Fisher Scientific TRACETM 1610 GC equipped with an injector and flame ionization detector (FID). Separation was performed on a Supelco J&W DB-23 column (120 m × 0.25 mm i.d. × 0.25 µm film). Hydrogen was used as the carrier gas in constant-flow mode at 2 mL/min. FID gas flows were set to $H_2$: 35 mL/min, air: 350 mL/min, and helium: 35 mL/min (Fisk et al. 2014; Goldschmidt and Byrdwell 2021). Samples were injected in split mode (10:1) with an injection volume of 1 µL. Inlet and detector temperatures were 250°C and 280°C, respectively.

The GC oven program was: initial 80°C; ramp 30°C/min to 110°C, hold 2 min; ramp 15°C/min to 200°C, hold 8 min; ramp 1°C/min to 215°C, hold 8 min; ramp 2°C/min to 250°C, hold 3 min. Chromatograms were integrated using Chromperfect software and exported to Excel for quantification. Fatty acids were identified by comparison of retention times with the standard of a Supelco 37 Component FAME Mix. Quantification was performed on the basis of integrated peak areas.

**Dimensional stability of leached wood blocks**

Total volumetric swelling (TVS) was used to evaluate dimensional stability of treated and control wood blocks after saline-water submersion. For each block (JAC, DOF, HEM, YEP), linear dimensions in the longitudinal (L), radial (R) and tangential (T) directions were measured on air- and oven-dried specimens before and after the 2-week submersion procedure. Volumes were calculated as the product of the three orthogonal dimensions. TVS was expressed as the percentage change in volume between the pre- and post-leach dry states and calculated as:

$$TVS\ (\%) = [(D2 - D1)/D1] \times 100 \quad (2)$$

where: D1 is the volume of the air- and oven-dried specimen after VOD treatment (pre-submersion) and D2 is the volume of the air- and oven-dried specimen after 2-week saline-water submersion (post-submersion).

### Microscopic observation

Retention and spatial distribution of VOD in JAC strips after the 2-week saline-water submersion were examined by X-ray microscopy following the procedure of Kwon et al. (2023). Leached, air- and oven-dried strips were mounted on the X-ray stage and scanned using a Xradia 620 X-ray microscope (Zeiss, Oberkochen, Germany). Raw projection data were reconstructed and rendered to produce structural and contrast-enhanced images using Dragonfly Pro software (Object Research Systems, QC, Canada).

### Experimental design and statistical analysis

A full factorial design (4 × 4 × 4) was used to evaluate the effects of wood species (JAC, DOF, HEM, YEP), VOD type (CAO, HCO, SBO, WCO), and impregnation method (SPR, IMM, VAC, VAC-PRES) on VOD uptake, leaching resistance, and dimensional stability. For each species × suspension × method combination, twelve wood blocks were tested.

Statistical analyses were performed using the General Linear Model (GLM) procedure in Minitab. All tests were conducted at a 95% confidence level. Factors and interactions that were significant at $p < 0.05$ were subjected to pairwise comparisons using the least significant difference (LSD) test. Results are reported as means ± standard deviation unless otherwise noted.

*Tab. 1: Effects of VOD type and impregnation method on VOD uptake (%) by wood blocks.*

| | Japanese cedar | Douglas fir | Western hemlock | Yellow poplar |
|---|---|---|---|---|
| **Type of vegetable oils and its derivatives** | | | | |
| Castor oil | 98.87±60.39 (A) | 91.56±46.93 (A) | 36.26±19.13 (B) | 101.65±72.89 (B) |
| Hydrogenated castor oil | 104.19±58.38 (A) | 85.36±44.73 (A) | 41.35±25.24 (A) | 116.01±64.75 (A) |
| Soybean oil | 92.81±56.02 (A) | 87.14±47.58 (A) | 41.43±27.39 (A) | 117.77±78.57 (A) |
| Waste cooking oil | 95.08±60.51 (A) | 89.42±52.60 (A) | 31.58±21.42 (C) | 114.49±67.32 (AB) |
| **Impregnation method** | | | | |
| Spreading | 31.22±8.61 (D) | 26.22±5.78 (C) | 12.83±2.17 (D) | 25.50±7.38 (D) |
| Immersion | 69.68±16.87 (C) | 76.02±28.80 (B) | 21.99±6.89 (C) | 79.72±31.98 (C) |
| Vacuum | 121.58±26.90 (B) | 120.73±19.29 (A) | 49.39±7.27 (B) | 158.06±29.77 (B) |
| Vacuum-pressure | 168.47±42.87 (A) | 130.51±32.22 (A) | 66.40±17.62 (A) | 186.63±39.31 (A) |

Different capital letters within a column indicate significant differences ($p < 0.05$; LSD test).

## RESULTS AND DISCUSSION

### Uptake of vegetable oils and its derivatives (VOD)

VOD uptake differed significantly among wood species, regardless of its type ($p < 0.01$). YEP exhibited the highest uptake (112.5%), followed by JAC (97.7%), DOF (88.4%) and HEM (37.7%). These results indicate that VOD uptake is strongly influenced by species-specific anatomical characteristics, particularly porosity and cell-wall structure (Spies and Franklin 1991; DeBell et al. 2004; Feng et al. 2021; Ogawa et al. 2022).

VOD type did not significantly affect its uptake in JAC and DOF (Tab. 1). In contrast, HEM and YEP showed lower uptake of CAO than that of HCO and SBO. This reduced uptake may be attributed to the restricted flow of CAO within these species. Unlike most vegetable oils, ricinoleic acid, the major fatty acid component of CAO, contains a hydroxyl group capable

of forming hydrogen bonds with wood cell-wall constituents. Such interactions can increase frictional resistance during liquid transport and thereby reduce oil penetration (Chauke et al. 2019). Nicholas and Siau (1973) similarly reported that nonpolar liquids flow more readily through wood than polar liquids with comparable viscosity. The lower CAO uptake in HEM may be further associated with its relatively small cell-wall micropores compared with JAC and DOF (Spies and Franklin 1991; DeBell et al. 2004; Ogawa et al. 2022). The narrower pore structure likely amplifies frictional resistance during CAO transport, thereby limiting penetration. In YEP, the abundance of cell-wall micropores may increase the total contact area between CAO and cell-wall polymers, further enhancing frictional drag and suppressing uptake (Jang et al. 2019). In addition, WCO showed significantly lower uptake than HCO, SBO, and even CAO in HEM ($p < 0.01$). This result may be attributed to pore blockage caused by residual impurities in WCO, despite filtration, particularly in the narrower pore network of HEM.

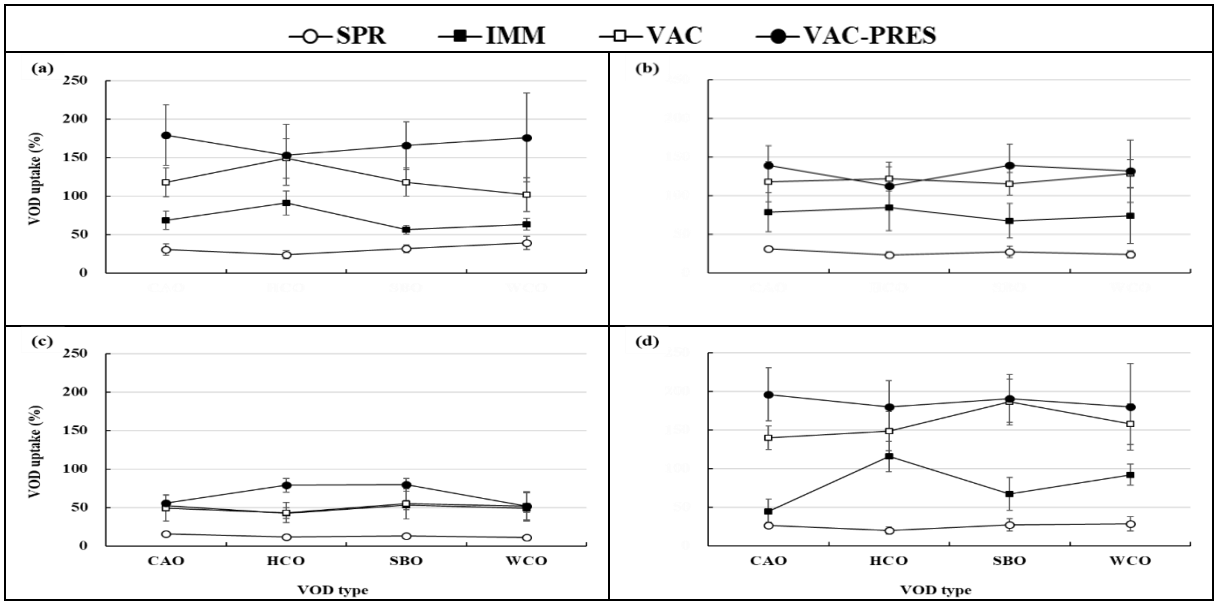


*Fig. 1: Interactive effects of VOD type (CAO, castor oil; HCO, hydrogenated castor oil; SBO, soybean oil; and WCO, waste cooking oil) and impregnation method (SPR, spreading; IMM, immersion; VAC, vacuum; and VAC-PRES, vacuum followed by pressure treatment) on VOD uptake in (a) Japanese cedar, (b) Douglas-fir, (c) western hemlock, and (d) yellow-poplar wood blocks.*

As expected, VOD uptake increased with treatment intensity, following the order: SPR < IMM < VAC < VAC-PRES for all wood species (Tab. 1). However, the influence of VOD type varied according to impregnation method and wood species (Fig. 1). Under SPR treatment, WCO and SBO exhibited higher uptake than HCO in JAC and YEP. This observation is likely related to the physical properties of HCO, which solidifies below approximately 85 °C, thereby restricting its ability to penetrate the wood structure during surface application (Chauke et al., 2019). Conversely, in the denser species DOF and HEM, CAO showed greater uptake than SBO and WCO. This may be due to the higher molecular weight of CAO (928 g $mol^{-1}$) compared with SBO (882 g $mol^{-1}$) and WCO (873 g $mol^{-1}$) (da Silva et al. 2011; Refvik & Larock 1999; Toralles et al. 2015). The short dipping period used in the SPR treatment (10 s) may have been

insufficient for SBO and WCO to penetrate the micro- and macro-pore networks of these higher-density species. In contrast, the higher viscosity of CAO likely promoted the formation of a thicker surface film, resulting in greater apparent uptake (Choi et al. 2025).

**Leaching resistance of VOD**

After 48 h of submersion in saline water, untreated control specimens exhibited slight weight gains of 2.25%, 2.06%, 0.04%, and 1.13% for JAC, DOF, HEM, and YEP, respectively. The weight increase is likely attributable to residual sea salt retained on or within the surface layers of the wood despite rinsing after the submersion. In contrast, VOD-treated specimens showed negligible mass loss, indicating high resistance to saline water submersion. The average leachabilities were -0.11%, -0.18%, -0.49%, and 0.12% for JAC, DOF, HEM, and YEP, respectively, regardless of VOD type. These results suggest that most of the impregnated VOD remained within the wood structure following exposure to saline water. No significant differences in leachability were observed among JAC and DOF (p=0.37), JAC and YEP (p=0.16) as well as DOF and YEP (p=0.06). However, HEM exhibited the lowest leachability despite showing the lowest VOD uptake overall. This result suggests that although the total amount of retained VOD was limited in HEM, the absorbed fraction may have penetrated more deeply into the cell wall and been retained more effectively, thereby increasing leaching resistance.

*Tab. 2. Effects of VOD type and impregnation method on the leachability (%) of VOD-treated wood blocks after 2 weeks of submersion in saline water.*

| | Japanese cedar | Douglas fir | Western hemlock | Yellow poplar |
|---|---|---|---|---|
| **Type of vegetable oils and its derivatives** | | | | |
| Castor oil | 1.55±3.99 (C) | 1.24±3.85 (C) | 0.18±1.27 (C) | 0.40±1.67 (B) |
| Hydrogenated castor oil | -1.58±0.41 (A) | -1.95±0.60 (A) | -1.98±0.46 (A) | -1.38±0.41 (A) |
| Soybean oil | -1.13±0.92 (B) | -0.73±1.55 (B) | -1.39±1.26 (B) | -1.03±2.54 (A) |
| Waste cooking oil | 0.72±0.94 (C) | 0.70±1.23 (C) | 1.24±1.35 (D) | 2.48±2.06 (C) |
| **Impregnation method** | | | | |
| Spreading | -0.82±1.78 (A) | -1.09±2.17 (A) | -1.01±2.06 (A) | -1.42±2.10 (A) |
| Immersion | -0.65±0.95 (A) | -1.04±1.11 (A) | -0.41±1.85 (B) | 0.07±2.49 (B) |
| Vacuum | -0.43±0.67 (A) | -0.03±0.89 (B) | -0.48±1.28 (B) | 0.03±0.88 (B) |
| Vacuum-pressure | 1.46±4.08 (B) | 1.42±3.80 (C) | -0.06±1.43 (B) | 1.80±2.52 (C) |

The negative leachability value indicates that the weight of the VOD-treated specimen increased following the leaching test. Different capital letters within a column indicate significant differences ($p < 0.05$; LSD test).

The effects of VOD type on leaching resistance are presented in Tab. 2. Among the tested VODs, HCO exhibited the lowest leachability across all wood species, followed by SBO, CAO, and WCO. The superior leaching resistance of HCO is likely attributable to its semi-solid, wax-like characteristics at ambient temperature and its low solubility in both water and organic solvents (Kodjo et al. 2011; Chauke et al. 2019). In contrast, CAO showed greater leachability than SBO, which may be related to the presence of hydrophilic ricinoleic acid that reduces resistance to water-assisted removal. The relatively high leachability of WCO may result from the presence of lower-molecular-weight degradation products and fatty acids generated during repeated heating of SBO (Lopresto et al. 2024).

Impregnation method also influenced leaching resistance (Tab. 2). Leachability was highest

following VAC-PRES treatment and lowest following SPR treatment. The greater leachability observed after VAC-PRES treatment is likely due to the larger amounts of VOD retained within lumina and other macroporous structures, where they are more susceptible to removal during submersion. Conversely, SPR-treated specimens exhibited the highest leaching resistance, consistent with their lower VOD uptake and the limited amount of oil available for extraction.

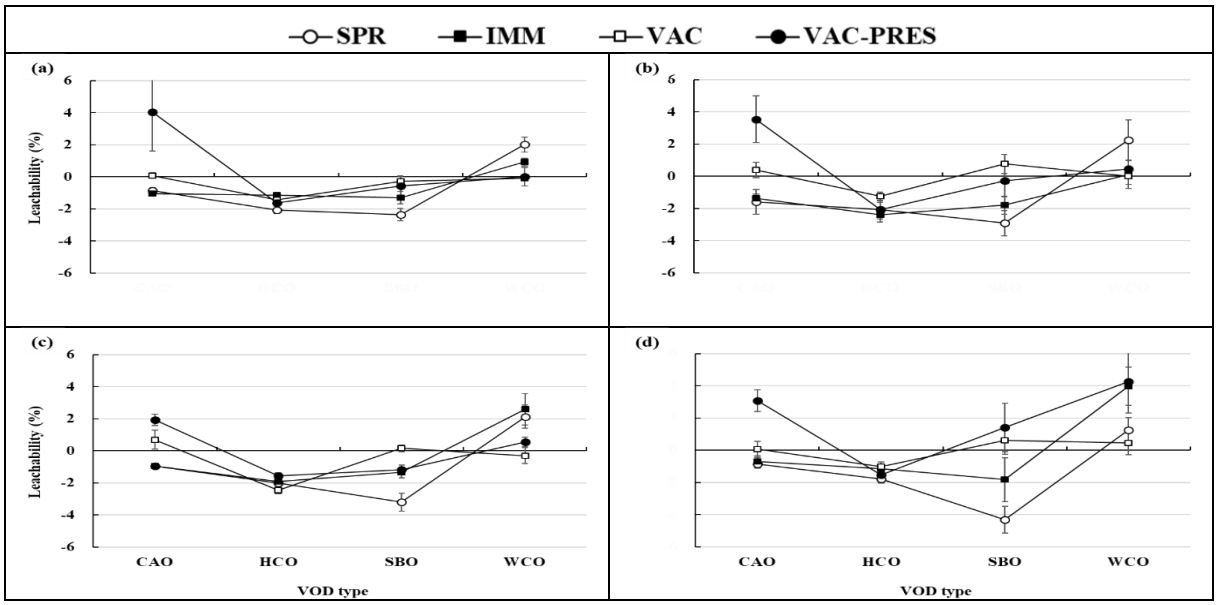


*Fig. 2. Interactive effects of VOD type (CAO, castor oil; HCO, hydrogenated castor oil; SBO, soybean oil; and WCO, waste cooking oil) and impregnation method (SPR, spreading; IMM, immersion; VAC, vacuum; and VAC-PRES, vacuum followed by pressure treatment) on the leachability of VOD-treated (a) Japanese cedar, (b) Douglas-fir, (c) western hemlock, and (d) yellow-poplar wood blocks after 2 weeks of submersion in saline water.*

Fig. 2 illustrates the interactive effects of VOD type and impregnation method on leachability in each wood species. Among SPR-treated specimens, SBO consistently exhibited the greatest resistance to leaching, followed by HCO, CAO, and WCO. In contrast, for IMM-, VAC-, and VAC-PRES-treated specimens, HCO consistently showed the lowest leachability regardless of wood species, whereas the leaching behavior of CAO, SBO, and WCO varied among species. These findings indicate that HCO provides the most stable retention within wood under saline-water exposure, particularly when applied using IMM or VAC treatments.

**Fatty acid content in leachates**

The concentrations of fatty acids in leachates collected from VOD-treated JAC strips after two weeks submersion in saline water were determined to further evaluate the leaching behavior of CAO, HCO, SBO, and WCO under different impregnation methods (Tab. 3). Among the tested VODs, WCO-treated specimens produced leachates with the highest fatty acid concentrations, whereas HCO-treated specimens yielded the lowest concentrations. The fatty acid content detected in leachates from CAO-treated strips was lower than that from SBO-treated strips. This trend contrasts with the leachability results based from percentage weight loss (Fig. 2). This discrepancy is likely attributable to differences in the fatty acids quantified

during the leachate analysis. Specifically, ricinoleic acid was analyzed in the CAO-treated leachates, whereas linoleic, oleic, palmitic, and stearic acids were analyzed in the SBO-treated leachates. These fatty acids account for approximately 85–90% and 95–99% of the total fatty acid content in CAO and SBO, respectively, and therefore likely influenced the observed results (Chauke et al. 2019).

*Tab. 3. Concentrations of VOD-derived fatty acids in leachates collected from VOD-treated Japanese cedar strips after 2 weeks of submersion in saline water (unit: μg/mL).*

| Type | Spreading | Immersion | Vacuum | Vacuum-pressure | Total |
|---|---|---|---|---|---|
| Castor oil[1] | 0.083 | 0.124 | 0.075 | 0.087 | 0.369 |
| Hydrogenated castor oil[1] | 0.084 | 0.114 | 0.067 | 0.066 | 0.331 |
| Soybean oil[1] | 0.126 | 0.186 | 0.067 | 0.091 | 0.470 |
| Waste cooking oil[1] | 0.122 | 0.100 | 0.172 | 0.244 | 0.638 |
| Total | 0.415 | 0.524 | 0.381 | 0.488 | - |

[1] The concentrations of ricinoleic acid in CAO, the triglyceride of 12-hydroxystearic acid in HCO, and linoleic, oleic, palmitic, stearic, and linolenic acids in SBO and WCO were determined.

Impregnation method significantly affected the amount of fatty acids contained in the leachate. The highest fatty acid concentrations were measured in leachates from IMM-treated specimens, followed by VAC-PRES, SPR, and VAC treatments. This ranking differs from that observed for percentage weight loss, where VAC-PRES treatment exhibited the greatest leachability. The discrepancy may be related to the chemical characteristics of ricinoleic acid, the principal fatty acid in CAO. Because ricinoleic acid contains a hydroxyl group, its behavior during extraction and analysis may differ from that of the major fatty acids present in HCO, SBO, and WCO, potentially affecting the measured fatty acid concentrations in the leachates (Kodjo et al. 2011; Chauke et al. 2019).

*Tab. 4: Main effects of VOD type and impregnation method on the total volumetric swelling (TVS, %) of VOD-treated wood blocks after 2 weeks of submersion in saline water.*

| | Japanese cedar | Douglas fir | Western hemlock | Yellow poplar |
|---|---|---|---|---|
| Untreated control | 3.86±0.54 | 3.30±0.44 | 2.56±0.33 | 3.48±0.70 |
| **Type of vegetable oils and its derivatives** | | | | |
| Castor oil | 0.49±0.83 (B) | 0.86±1.22 (B) | 0.12±1.44 (C) | 0.40±1.26 (C) |
| Hydrogenated castor oil | 0.64±1.54 (B) | 0.87±1.92 (B) | 0.78±2.02 (B) | 0.44±1.47 (C) |
| Soybean oil | 0.71±1.06 (B) | 1.00±1.50 (B) | 0.79±1.79 (B) | 1.33±1.64 (B) |
| Waste cooking oil | 1.73±1.42 (A) | 1.57±1.53 (A) | 1.47±1.87 (A) | 2.03±1.49 (A) |
| **Impregnation method** | | | | |
| Spreading | 1.69±0.94 (A) | 1.97±0.78 (A) | 1.97±0.97 (A) | 2.15±0.96 (A) |
| Immersion | 1.52±0.75 (A) | 2.06±0.41 (A) | 1.88±0.90 (A) | 1.85±1.00 (B) |
| Vacuum | -0.69±1.14 (C) | -1.09±1.28 (C) | -1.96±0.79 (C) | -1.06±0.87 (D) |
| Vacuum-pressure | 1.06±0.88 (B) | 1.35±0.99 (B) | 1.25±0.92 (B) | 1.27±1.17 (C) |

Different capital letters within a column indicate significant differences ($p < 0.05$; LSD test).

The effects of impregnation method varied among VOD types. For CAO-, HCO-, and SBO-treated JAC strips, VAC treatment consistently resulted in lower fatty acid concentrations in the leachates than SPR and IMM treatments, indicating improved retention of these VODs within the wood structure. In the case of WCO, fatty acid concentrations were highest after

VAC-PRES treatment, followed by VAC, SPR, and IMM treatments. The elevated values observed for VAC-PRES-treated specimens likely reflect the larger quantity of WCO retained within cell lumina, pores, and cell-wall voids, increasing the amount available for leaching.

**Dimensional stability of VOD-treated wood**

A comparison of TVS values between untreated controls and VOD-treated specimens is presented in Tab. 4. Most treated specimens exhibited significantly lower TVS than the corresponding controls, demonstrating the effectiveness of VOD treatments in improving dimensional stability. Average TVS values were 0.89% for JAC, 1.40% for DOF, 0.79% for HEM, and 1.05% for YEP regardless of VOD type or impregnation method. Among the tested species, DOF exhibited significantly greater TVS than the others ($p < 0.01$). This behavior may be associated with its relatively high density, as denser woods contain a greater proportion of cell-wall material per unit volume, providing more sorption sites for moisture and consequently greater swelling during immersion.

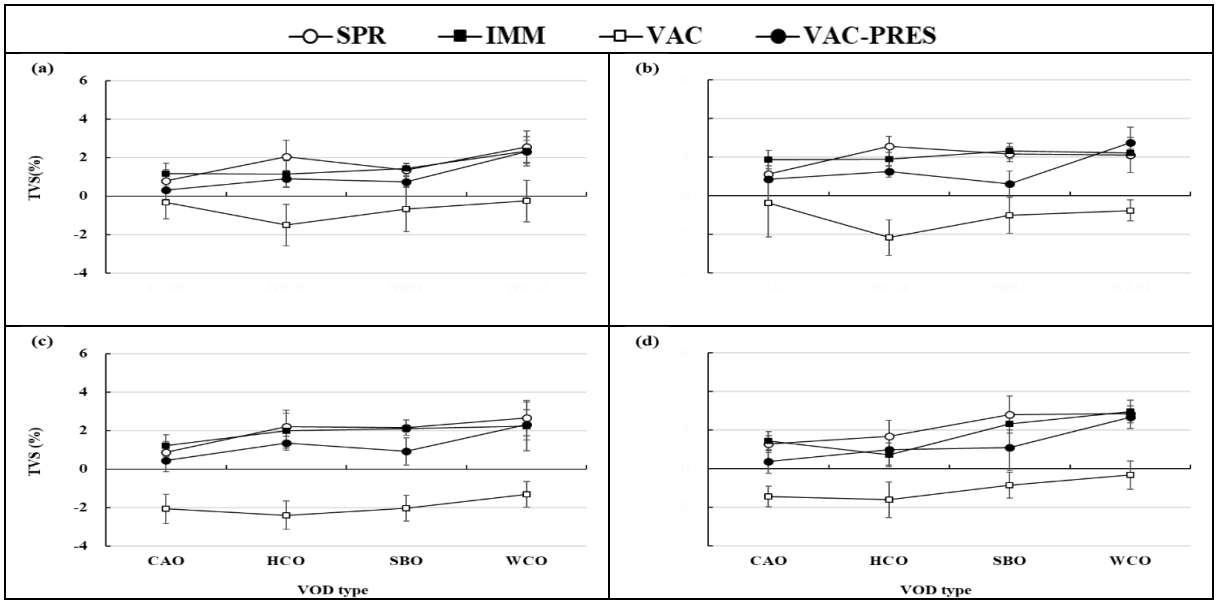


*Fig. 3. Interactive effects of VOD type (CAO, castor oil; HCO, hydrogenated castor oil; SBO, soybean oil; and WCO, waste cooking oil) and impregnation method (SPR, spreading; IMM, immersion; VAC, vacuum; and VAC-PRES, vacuum followed by pressure treatment) on the total volumetric swelling (TVS) of VOD-treated (a) Japanese cedar, (b) Douglas-fir, (c) western hemlock, and (d) yellow-poplar wood blocks after 2 weeks of submersion in saline water.*

The effects of VOD type and impregnation method on TVS are presented in Fig. 3. In all wood species, WCO-treated specimens exhibited significantly higher TVS than specimens treated with CAO, HCO, or SBO ($p < 0.01$). The inferior dimensional stability of WCO-treated wood is likely related to its lower resistance to leaching. As WCO components are removed during saline-water submersion, void spaces become available for water ingress, leading to increased moisture absorption and subsequent cell-wall swelling. These findings highlight the importance of VOD retention in maintaining dimensional stability under wet conditions. In contrast, no significant differences in TVS were observed between CAO and HCO, CAO and

SBO, or HCO and SBO in JAC and DOF. Similarly, no significant difference was detected between HCO and SBO in HEM or between CAO and HCO in YEP. These results suggest that, despite differences in chemical composition and leaching behavior, CAO, HCO, and SBO provide comparable swelling resistance in certain wood species. The markedly higher TVS observed in WCO-treated specimens indicates that dimensional stability is more strongly influenced by retention performance than by VOD type.

Impregnation method also significantly influenced dimensional stability. All VAC-treated specimens exhibited slight shrinkage after leaching, which may be attributable to partial collapse of wood cells caused by the removal of air, moisture and oil from the cellular structure. In contrast, VAC-PRES-treated specimens exhibited swelling, suggesting that pressure-assisted impregnation increased VOD loading within lumina and pore spaces, thereby partially restoring the specimen volume. Nevertheless, the TVS values of VAC-PRES-treated specimens remained lower than those of SPR- and IMM-treated specimens, indicating that pressure treatment enhanced VOD penetration and retention within the wood structure (Wang et al. 2021). Among the evaluated VODs, CAO- and HCO-treated specimens generally exhibited lower TVS values than WCO-treated specimens, regardless of whether IMM, VAC, or VAC-PRES treatment was applied. This observation suggests that both the VOD type and the impregnation method influence the extent of VOD penetration and retention within the wood structure. Greater penetration into the cell wall is expected to reduce the availability of hydroxyl groups for water sorption and to physically restrict moisture ingress, thereby improving dimensional stability.

**Microscopic observation**

X-ray microscopy was used to visualize the distribution of VOD within JAC strips and to assess their retention after saline-water submersion. Comparison of untreated control specimens before and after submersion revealed the presence of residual sea salts within the wood structure, indicating that components of the saline solution penetrated the strips and remained within the cell walls despite thorough rinsing (Fig. 4). This observation is consistent with the slight weight gains observed in untreated controls following the leaching test.

The distribution of VOD within the wood was strongly influenced by impregnation method. In SPR-treated specimens, VODs were rarely detected beyond the immediate surface region, indicating limited penetration into the wood structure. In contrast, IMM treatment promoted penetration into the interior of the strips, particularly for CAO and HCO. The extent of VOD distribution increased further following VAC and VAC-PRES treatments, demonstrating the effectiveness of these processes in enhancing penetration of VOD into the wood.

Among the tested VODs, SBO exhibited the most extensive distribution throughout the wood structure. Similarly, CAO and HCO were detected within both surface and internal regions of the treated strips. The broad distribution of these VODs suggests effective penetration into accessible cell-wall and pore structures, which may contribute to reduced moisture uptake and improved dimensional stability. These observations are consistent with the lower TVS values and enhanced leaching resistance observed for CAO-, HCO-, and SBO-treated specimens. In contrast, WCO showed a more limited distribution within IMM-, VAC-, and VAC-PRES-treated specimens compared with the other VODs. This reduced presence is likely associated with the greater leaching susceptibility of WCO during saline-water submersion.

The lower retention of WCO observed by X-ray microscopy agrees with its higher leachability and poorer dimensional stabilization performance relative to CAO, HCO, and SBO.

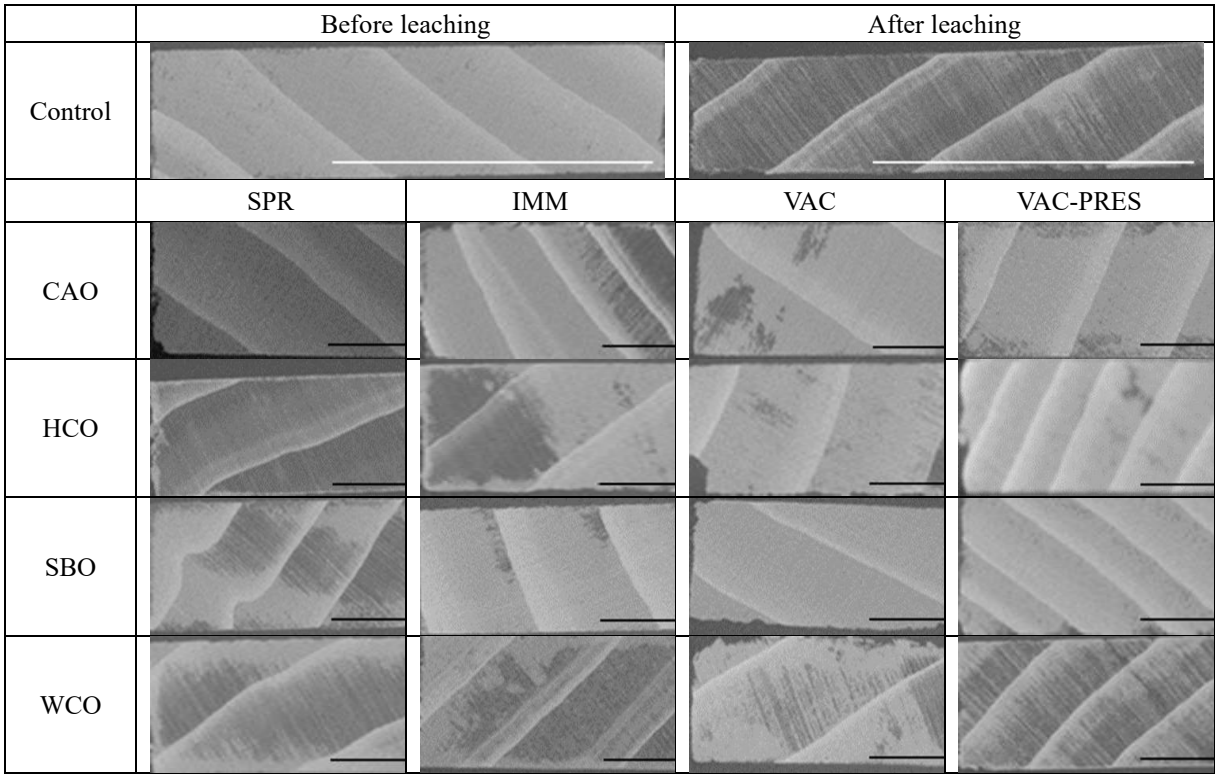


*Fig. 4: Microscopic images of Japanese cedar strips treated with castor oil (CAO), hydrogenated castor oil (HCO), soybean oil (SBO), and waste cooking oil (WCO) using spreading (SPR), immersion (IMM), vacuum (VAC; 15 min), and vacuum-pressure (VAC-PRES; 15 min vacuum followed by 15 min pressure), followed by 2 weeks submersion in saline water. The long white and short black scale bars represent 0.5 mm and 1.0 mm, respectively.*

## CONCLUSIONS

*(1)* VOD uptake was highest in YEP, followed by JAC, DOF, and HEM. For all species, VAC-PRES and VAC treatments resulted in substantially greater uptake than IMM and SPR treatments. The effect of VOD type on uptake varied among species, with HCO and SBO generally showing high uptake in JAC and YEP, whereas CAO and HCO/SBO showed relatively high uptake in DOF and HEM. *(2)* Among the VODs tested, leaching resistance followed the order HCO > SBO > CAO > WCO. By impregnation method, resistance generally followed the order VAC > IMM > SPR > VAC-PRES, indicating that VAC treatment promoted more stable retention of VOD within the wood. *(3)* HCO-treated JAC specimens subjected to VAC treatment released the lowest concentrations of fatty acids into the saline solution, confirming the superior retention and leaching resistance of this treatment combination. *(4)* Most specimens treated with CAO, HCO, or SBO exhibited lower TVS than untreated wood. Vacuum-treated specimens generally showed the greatest improvement in dimensional stability, with HCO-treated specimens exhibiting the lowest TVS values. In contrast, WCO-treated specimens showed relatively poor performance owing to their higher susceptibility to leaching.

*(5)* CAO, HCO, and SBO exhibited deeper and more uniform penetration, particularly when applied using IMM, VAC, and VAC-PRES treatments. X-ray microscopic observations were consistent with the enhanced leaching resistance and dimensional stability observed for these treatments.

Overall, VOD impregnation effectively enhanced the water resistance and dimensional stability of wood under saline-water exposure. Among the treatment combinations evaluated, VAC impregnation with HCO provided the most favorable balance of uptake, retention, leaching resistance, and dimensional stability. When applied to JAC, a widely available and economically important species in South Korea, this treatment shows considerable potential for marine application. Nevertheless, additional research is required to evaluate its effects on long-term durability, and mechanical properties before commercial implementation. Investigations addressing these aspects are currently underway.

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## REFERENCES

1. AUGUSTINA, S., DWIANTO, W., LUBIS, M.A.R., DAMAYANTI, R., ADI, D.S., MALIK, J., WAHYUDI, I., DARMAWAN, W., GERARDIN, P., MARBUN, S.D.V. & ISODA, H. (2023): Effect of anatomic structure on dimensional stability of low molecular weight phenol-formaldehyde impregnated wood. In: Wood Research 68(3), 425-443 pp.
2. CHAUKE, N.P., MUKAYA, H.E. & NKAZI, D.B. (2019): Chemical modification of castor oil: A review. In: Science Progress 10, 199-217 pp.
3. CHOI, S., LEE, K.U., KWON, O., CHOI, W., LEE, Y., CHO, S., CHOI, J.W. & YANG, I. (2025): Evaluating the applicability of wood treated with fatty acid as a raw material for exterior uses. In: Korean Chemical Engineering Research 63(10), 108-122 pp.
4. DA SILVA, N.D., BATISTELLA, C., FILLHO, R.M. & MACIEL, M.R.W. (2011): Determination of castor oil molecular weight by vapor pressure osmometry technique. In: Chemical Engineering Transactions 24, 601-606 pp.
5. DEBELL, D.S., SINGLETON, R., GARTNER, B.L. & MARSHALL, D.D. (2004): Wood density of young-growth western hemlock: Relation to ring age, radial growth, stand density, and site quality. In: Canadian Journal of Forest Research 34, 2433-2442 pp.
6. FENG, X., SHENG, Y., GE, X., WU, Z. & HUANG, G. (2021): Evaluation of the properties of hybrid yellow poplar (*Liriodendron sino-americanum*): A comparison study with yellow poplar (*Liriodendron tulipifera*). In: Maderas: Ciencia y Tecnología 23, 23.
7. FISK, H.L., WEST, A.L., CHILDS, C.E., BURDGE, G.C. & CALDER, P.C. (2014): The use of gas chromatography to analyze compositional changes of fatty acids in rat liver tissue during pregnancy. In: Journal of Visualized Experiments 85, 51445.
8. GABRIELLI, C.P. & KAMKE, F.A. (2010): Phenol-formaldehyde impregnation of densified wood for improved dimensional stability. In: Wood Science and Technology 44(1),

95-104 pp.
9. GOLDSCHMIDT, R. & BYRDWELL, W. (2021): GC analysis of seven seed oils containing conjugated fatty acids. In: Separations 8(4), 51.
10. HAZARIKA, A. & MAJI, T.K. (2014): Properties of softwood polymer composites impregnated with nanoparticles and melamine formaldehyde furfuryl alcohol copolymer. In: Polymer Engineering & Science 54(5), 1019-1029 pp.
11. HUMAR, M. & LESAR, B. (2013): Efficacy of linseed- and Tung-oil treated wood against wood-decay fungi and water uptake. In: International Biodeterioration & Biodegradation 85, 223-227 pp.
12. JANG, E., KANG, C. & JANG, S. (2019): Pore characterization in cross section of yellow poplar (*Liriodendron tulipifera*) wood. In: Journal of Korean Wood Science and Technology 47(1), 8-20 pp.
13. KARTAL, S.N. (2006): Combined effect of boron compounds and heat treatments on wood properties: Boron release and decay and termite resistance. In: Holzforschung 60(4), 455-458 pp.
14. KODJO, T.A., GBÉNONCHI, M., SADATE, A., KOMI, A., YAOVI, G., DIEUDONNÉ, M. & KOMLA, S. (2011): Bio-insecticidal effects of plant extracts and oil emulsions of *Ricinus communis* L. (*Malpighiales*: *Euphorbiaceae*) on the diamondback, *Plutella xylostella* L. (*Lepidoptera*: *Plutellidae*) under laboratory and semi-field conditions. In: Journal of Applied Biosciences 43, 2899-2914 pp.
15. KWON, O., CHOI, Y.S., CHOI, W., LEE, Y., CHOI, J., CHOI. J.W. & YANG, I. (2023): Decay resistance and dimensional stability of wood impregnated with castor oil using a pressure treatment. In: Holzforschung 77(11-12), 879-888 pp.
16. LESAR, B., STRAŽE, A. & HUMAR, M. (2011): Sorption properties of wood impregnated with aqueous solution of boric acid and montan wax emulsion. In: Journal of Applied Polymer Science 120(3), 337-345 pp.
17. LIU, C., WANG, S., SHI, J. & WANG, C. (2011): Fabrication of superhydrophobic wood surfaces via a solution-immersion process. In: Applied Surface Science 258(2), 761-765 pp.
18. LOPRESTO, C.G., DE PAOLA, M.G. & CALABRŎ, V. (2024): Importance of the properties, collection, and storage of waste cooking oils to produce high-quality biodiesel – An overview. In: Biomass and Bioenergy 189, 107363.
19. MOHEBBY, B. & MILITZ, H. (2010): Microbial attack of acetylated wood in field soil trials. In: International Biodeterioration & Biodegradation 64(1), 41-50 pp.
20. NICHOLAS, D.D. & SIAU, J.F. 1973: Factors influencing the treatability of wood. In: Wood deterioration and its prevention by preservative treatments, Vol II (ed. Nicholas DD). Syracuse University Press. Syracuse. 299-343 pp.
21. OGAWA, K., FUKUTA, S. & KOBAYASHI, K. (2022): Embedment properties of Japanese cedar (*Cryptomeria japonica*) treated with resin impregnation. In: Journal of Wood Science 68, 9.
22. PAPADOPOULOS, A.N. & HILL, C.A.S. (2003): The sorption of water vapour by anhydride modified softwood. In: Wood Science and Technology 37(3-4), 221-231 pp.
23. PASSIALIS, C.N. & VOULGARIDIS, E.V. (2009): Water repellent efficiency of organic solvent extractives from Aleppo pine leaves and bark applied to wood. In: Holzforschung

53(2), 151-155 pp.
24. REFVIK, M.D. & LAROCK, R.C. (1999): The chemistry of metathesized soybean oil. Journal of the American Oil Chemists' Society 76(1), 99-102 pp.
25. ROWELL, R.M., IBACH, R.E., JAMES, M. & THOMAS, N. (2009): Understanding decay resistance, dimensional stability and strength changes in heat-treated and acetylated wood. In: Wood Material Science & Engineering 4(1-2), 14-22 pp.
26. SCHOLZ, G., KRAUSE, A. & MILITZ, H. (2012): Full impregnation of modified wood with wax. In: European Journal of Wood and Wood Products 70(1-3), 91-98 pp.
27. SEPPÁNEN-LAAKSO, T., LAAKSO, I. & HILUNEN, R. (2002): Analysis of fatty acids by gas chromatography, and its relevance to research on health and nutrition. In: Analytica Chimica Acta 465(1–2), 39-62 pp.
28. SINGH, T. & SINGH, A.P. (2012): A review on natural products as wood protectant. In: Wood Science and Technology 46(5), 851-870 pp.
29. SPIES, T.A. & FRANKLIN, J.F. (1991): The structure of natural young, mature, and old-growth Douglas-fir forests in Oregon and Washington. In: USDA General Technical Report PNW-GTR-285. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland. 91-110 pp.
30. TORALLES, L.P., ALVES, C.T., TORRES, E.A., ANDRADE, H.M.C., PESSOA, F.L.P. & VIEIRA DE MELO, S.A.B. (2015): Hydrolysis of waste frying oils in subcritical water for biodiesel production by esterification using a heterogeneous catalyst. In: Chemical Engineering Transactions 43, 565-570 pp.
31. WANG, J., BI, Z., CHEN, Z., YAN, L. & LEI, Y. (2021): Decay resistance, dimensional stability and mechanical strength of poplar wood modified with plant-derived compounds. In: Wood Research 66(4), 556-568 pp.
32. WEI, X., SUN, F. & LIN, J. (2022): Impregnation on poplar wood with vegetable oils: Effects on physical mechanical and dimensional stability properties. In: Wood Research 67(5), 760-772 pp.
33. WESTIN, M., STERLEY, M., ROSSI, F. & HERVÉ, J.J. (2009): Compreg-type products by furfurylation during hot-pressing. In: Wood Material Science & Engineering 4(1-2), 67-75 pp.

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