Adequacy of Larch Wood Treated with Wood Tar and Wood Vinegar as Erosion Control Wooden-Dam Materials

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The durability of small-diameter larch wood was studied with respect to its treatments with wood tar and wood vinegar in three environments—underground, underwater, and outdoors—for 53 months. This study involved assessing wood cell wall deterioration using optical microscopy, X-ray computed tomography imaging, and X-ray diffraction, along with evaluating various physical and mechanical properties using Korean standards. Severe deterioration was observed in vinegar-treated sapwood after being buried underground. Collapsed cells were often found in untreated and wood vinegar-treated wood buried underground. Noticeable decreases in the physical and mechanical properties were observed in the sapwood of wood vinegar-treated wood buried underground. The wood tar-treated wood buried underground remained relatively intact with minimal changes in its physical properties. No significant degradation was observed in the wood discs submerged in water, and there was no difference in density, shrinkage, hardness, and shear strength between the untreated and preserved wood submerged in water. Under outdoor conditions, wood vinegar-treated wood showed less degradation of the wood discs than untreated and wood tar-treated wood. In conclusion, wood tar enhanced the durability of the wood when it was buried in soil, whereas the wood vinegar treatment provides an advantage when exposed to outdoor conditions.

DOI: 10.15376/biores.19.4.7946-7962

Keywords: Wood tar-treated wood; Wood vinegar-treated wood; Deterioration of wood

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INTRODUCTION

The Korea Forest Service has been continuously installing erosion-control dams to prevent disasters in mountainous areas because of frequent local floods, leading to an increase in damage from landslides and stream overflow, caused by recent climate change. Most erosion-control dams are concrete structures (Park *et al*. 2010).

Concrete erosion-control dams are incompatible with the surrounding environment and can cause destruction to river ecosystems due to their concrete components. Additionally, their size, which generally ranges from 10 to 20 m in length, 1 to 2 m in width, and 5 to 10 m in height, depends on the size of the valley (Jang *et al.* 2013). Replacing concrete structures with wood can significantly reduce carbon emissions, and there has recently been an increase in the social demand for environmentally friendly construction of erosion-control dams, which are being constructed using wood and natural stone (Korea Forest Service 2011). In addition, using wood as a civil engineering material, such as wooden retaining walls, vegetation mats, slope protection, wood grass, agricultural drainage, and landscape facility materials, has been actively promoted (Korea Forest Service 2013).

Wood is a biological material that is difficult to use in outdoor environments, where it is prone to decay. As a result, many scientists have conducted studies to improve the preservation and durability of wood. Various studies have been devoted to increasing the utilization value of domestic wood (Kwon *et al.* 2003; Cha 2008).

Natural wood preservatives are environment-friendly and sustainable options for improving the preservation and durability of wood. Organic preservative materials can be extracted from wood or biomass using a high-temperature carbonization process without oxygen. During the thermal decomposition of wood, the smoke generated is liquefied to obtain pre-wood vinegar, and approximately 4 to 11% of wood tar and 31 to 37% of wood vinegar are produced after the refining process (Elder and Soltes 1980).

Wood vinegar is a by-product of pyrolysis and consists of a complex mixture of various organic compounds, including acetic acid, methanol, acetone, and phenolic compounds. Wood vinegar is widely used as a wood preservative because of its antimicrobial and insecticidal properties. Adfa *et al*. (2020) reported that wood vinegar from the stem wood of *Cinnamomum parthenoxylon* is more toxic to white-rot fungi (*Schizophyllum commune*) than to brown-rot fungi (*Fomitopsis palustris*). Desvita *et al.* (2022) reported that wood vinegar produced from cocoa pod shells at 300 to 380 °C showed antimicrobial activity against *Candida albicans* and *Aspergillus niger*. Wood vinegar from sunflower seed hulls has been used to protect grains and products in storage against *Sitophilus oryzae*, *Lasioderma serricorne*, and *Tribolium castaneu*m (Urrutia *et al*. 2022). Teo (2022) reported that wood vinegar from *Rhizophora apiculata* exhibited antimicrobial activity against *Enterococcus faecalis*, *Escherichia coli*, *Proteus vulgaris*, and *C. albicans*. Imaningsih *et al*. (2022) reported that vinegar from ulin wood (*Eusideroxylon zwager* Teijsm. and Binn) exhibits antifungal activity against *Pyricularia oryzae*.

Wood tar is obtained by the pyrolysis of lignin, which can be regarded as a complex mixture of aromatic and oxygenated compounds mainly composed of aromatic hydrocarbons (Amen-Chen *et al.* 1997; Blanco *et al.* 2012). Many studies have explored efficient methods for utilizing wood tar. Wood tar, with creosote as the main component, can be used as a disinfectant and preservative (Kartal *et al.* 2004). Kartal *et al*. (2006) reported that *Cryptomeria japonica* treated with various natural compounds (wood tar oil, cassia oil, *etc.*), food additives (cinnamaldehyde, cinnamic acid, *etc.*), and cosmetic compounds showed resistance against the subterranean termite (*Coptotermes formosanus*). In addition, cinnamaldehyde, cassia oil, and wood tar oil were effective against the brown-rot fungus (*Tyromyces palustris*) and white-rot fungus (*Trametes versicolor*). Mazela (2007) reported that wood tar extracted by the pyrolysis of old creosote-treated wood and then used to treat wood may have the potential as a preservative for wood protection, or as a component of preservatives against *Coriolus versicolor* and *Postia placenta.* Ahmed *et al*. (2017) reported that thermally modifying aspen and birch wood followed by impregnation with tung oil and pine tar improved the water repellency and dimensional stability of treated wood. However, the treatment combination did not significantly improve mold resistance.

Larix kaempferi wood, commonly known as Japanese larch, is a major Korean wood species that is widely distributed in the mountains of South Korea. It is a significant resource for various wood products because of its rapid growth rate and excellent mechanical properties of its mature wood. This species is used for various purposes, including afforestation, building materials, flooring, furniture, decking, and railroad ties (Korea Forest Service 2011; Kim *et al.* 2021, 2022).

In a previous study, Kwon *et al*. (2011) performed a comparative study on the microscopic characteristics and relative crystallinity index of *Larix kaempferi* treated with wood tar and wood vinegar before and after weathering under various environmental conditions for 12 months, such as outdoor exposure, buried underground, and submerged in water. The larch wood treated with vinegar had better durability than the wood treated with tar.

However, to fully understand the durability of larch wood treated with wood vinegar and wood tar, further studies on vital indices are required to evaluate treated wood under various external conditions over an extended period. Therefore, this study investigated the changes in the morphological, physical, and mechanical durability of timber exposed to various external conditions over a long period. Domestic larch wood was processed with wood tar and wood vinegar, which enhance durability, for use in wooden erosion-control dams.

EXPERIMENTAL

Materials

The basic information of the wood samples is presented in Table 1. In this experiment, 54 logs of domestic larch wood (*Larix kaempferi*) with an average diameter of 25 cm and length of 90 cm were obtained from the National Forestry Cooperative Federation's Timber Distribution Center. Wood tar was produced in a traditional charcoal kiln at the Hongcheon Charcoal Factory. Wood vinegar, purchased from the National Forestry Cooperative Federation's Timber Distribution Center, has a pH of approximately 3 and is composed of 80 to 90% water, 3% acetic acid, and other components.

Table 1. Basic Information on the Larch Wood

Species	Logs	DBH (mm)	Length (mm)	Moisture Content (%)		Density (g/cm^3)	
				Sapwood	Heartwood	Sapwood	Heartwood
Larix kaempferi	54	250	900	22.6	24.6	0.57	0.61

Preservation Treatment and Durability Test

Figure 1 shows a graphic of the preservation treatments and durability tests performed in this study. The samples were coated with an average of 4.8 L/m² of wood tar and dried for 4 weeks (Fig. 2). The larch wood was soaked in 160 L of wood vinegar solution for 2 weeks and then air-dried for 4 weeks (Fig. 3).

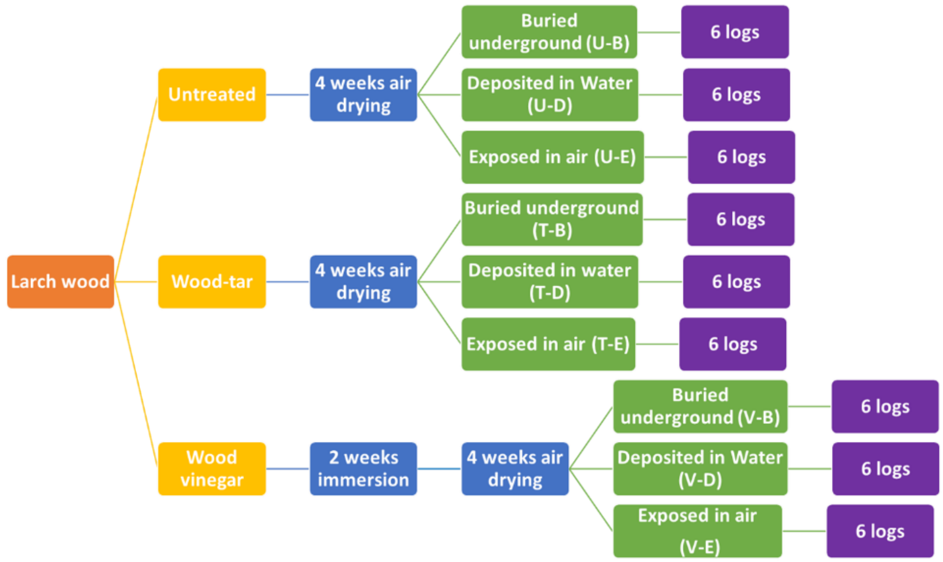

Fig. 1. The preservation treatments and durability test performed in the present study

Fig. 2. Wood tar-treatment process: applying the wood tar on the longitudinal surface and transverse of the log (A) and air-drying process (B)

Fig. 3. Wood vinegar-treatment process: applying the wood vinegar on the longitudinal surface and transverse of the log (A), immersion for two weeks (B), and air-drying process (C)

The treated wood was exposed to three different environments–buried in soil, submerged in water, and exposed to outdoor conditions, with six samples per environment (Fig. 4). The experiment was conducted from November 7, 2008, to April 6, 2013, for a total of 53 months. Wood disc samples with a thickness of 50 mm were extracted from a point 300 mm inward from the outermost part of the decayed logs to evaluate the properties (Fig. 5) (Kwon *et al*. 2011).

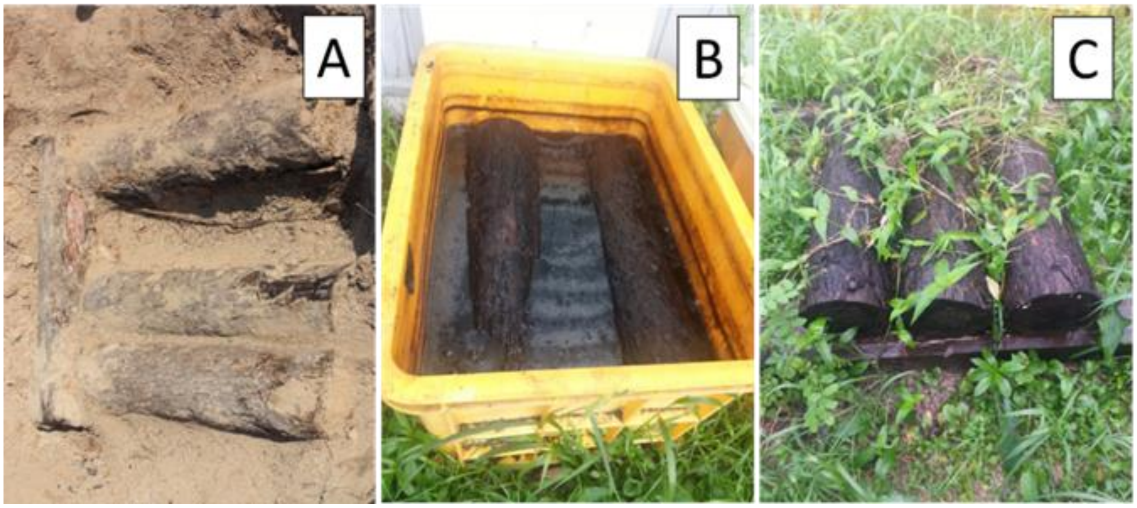

Fig. 4. The samples were buried in soil (A), submerged in water (B), and exposed to outdoor conditions, (C) for 53 months

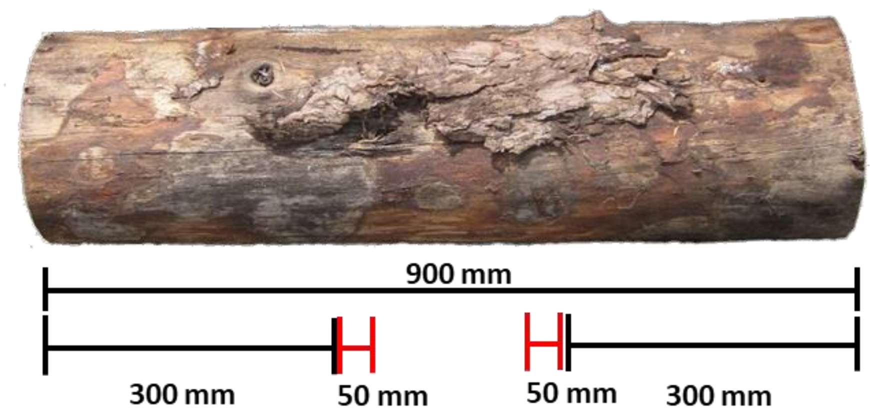

Fig. 5. The sampling position of the wood discs

Macroscopy and Optical Microscopy

The degree of weathering in the macroscopic observations was analyzed by visually inspecting the cross sections of the decayed wood discs. For the optical microscopy, cross sections of 15 to 25 μm thickness were collected using a sliding microtome (MSL-H model, Nippon Optical Works, Nagano, Japan) and stained with 1% safranin solution. Stained samples were dehydrated using a graded series of alcohol (50%, 70%, 90%, 95%, and 99%) and xylene, and permanent slides were prepared using Canada balsam. All permanent slides were observed under an optical microscope (Nikon ECLIPSE E600, Nikon, Tokyo, Japan) connected to the i-Solution-lite software (IMT i-Solution Inc., Burnaby, BC, Canada).

X-ray Computed Tomography Imaging

A computed tomography (CT) scanner (TSX-0001A, Toshiba, Tokyo, Japan), installed at the National Institute of Forest Science in Seoul, Korea, was used to observe the cross sections of the decayed wood discs at 120 kV and 110 mA for 10 s at 10 mm intervals.

Physical and Mechanical Properties Evaluation

The samples were divided into heartwood (HW) and sapwood (SW), with ten samples for each property, each with dimensions of 40 mm (L) × 20 mm (R) × 20 mm (T). The air-dried density (KS F 2198 2016) and shrinkage (KS F 2203 2004) of the larch wood samples were measured. The compressive strength parallel to the grains (KS F 2206 2004), shear strength (KS F 2209 2004), and hardness (KS F 2122 2004) of larch wood samples were measured using a universal testing machine (UTM 4482, Instron, USA).

Crystallinity Properties

The thickness and width of the specimens were 1 and 10 mm, respectively. The relative crystallinity index (RCI) was measured using an X-ray diffractometer (DMAX2100V; Rigaku, Tokyo, Japan) with CuKα radiation under the conditions of 40 kV and 40 mA. Relative crystallinity was calculated using the Segal method (Lee *et al.* 2023), as shown in Eq. 1:

$$RCI\ (\%) = \frac{I_{200} - I_{am}}{I_{am}} \tag{1}$$

where I_{200} and I_{am} represent the diffraction intensities of the crystalline region at $2\theta = 22.8°$ and the amorphous region at $2\theta = 18°$, respectively.

Statistical Analysis

Significant differences in the physical properties of the decayed samples were analyzed with one-way analysis of variance (ANOVA) and *post-hoc* Duncan's multiple range tests using SPSS software (SPSS ver. 26, IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Macroscopical and Microscopical Characteristics

Figure 6 shows samples preserved for 53 months under various weathering conditions. Severe degradation, cracking, and splitting were observed in V-B SW, whereas relatively less degradation was noted in U-B and T-B SWs. T-B exhibited less degradation than U-B, possibly due to the presence of creosote in the wood tar. The severe degradation in V-B could be due to the interaction between wood vinegar and animal excrement within the soil environment, which can accelerate decomposition processes and nutrient release. There was no clear evidence of significant degradation in the U-D, T-D, and V-D samples. However, the T-E and U-E samples showed more distinct evidence of insect damage to the SW than the V-E sample. Wood degradation is primarily driven by factors such as temperature, moisture, and oxygen availability. Wood submerged in water creates an unsuitable environment for mold, which may explain the lower levels of degradation. Shin and Ahn (2003) reported that wood submerged in water undergoes less degradation than wood exposed to other conditions because of the lack of conducive environmental factors for mold activity under these conditions. Figure 7 shows optical micrographs of SW in the larch wood after the weathering test. The adjacent tracheid cell walls in the cross section (indicated using red arrows) collapsed or were lost. It was determined that the hyphae moved transversely to the cell axis, mainly through the pit membrane, as collapse was observed on the radial surface where the pit membrane is mainly located. No significant degradation was observed under outdoor exposure conditions.

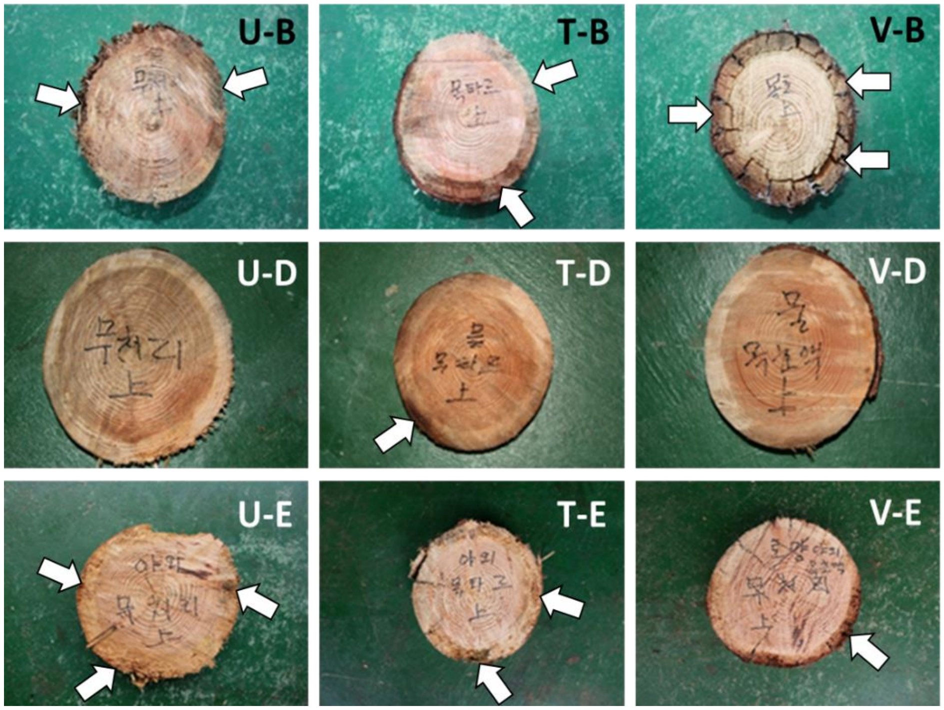

Fig. 6. The appearance of untreated (U-B, U-D, and U-E), wood tar-treated (T-B, T-D, and T-E), and wood vinegar-treated samples (V-B, V-D, and V-E) was examined after being buried in soil (U-B, T-B, and V-B), submerged in water (U-D, T-D, and V-D), and exposed to air (U-E, T-E, and V-E) for 53 months. White arrows indicate the degradation in the sapwood.

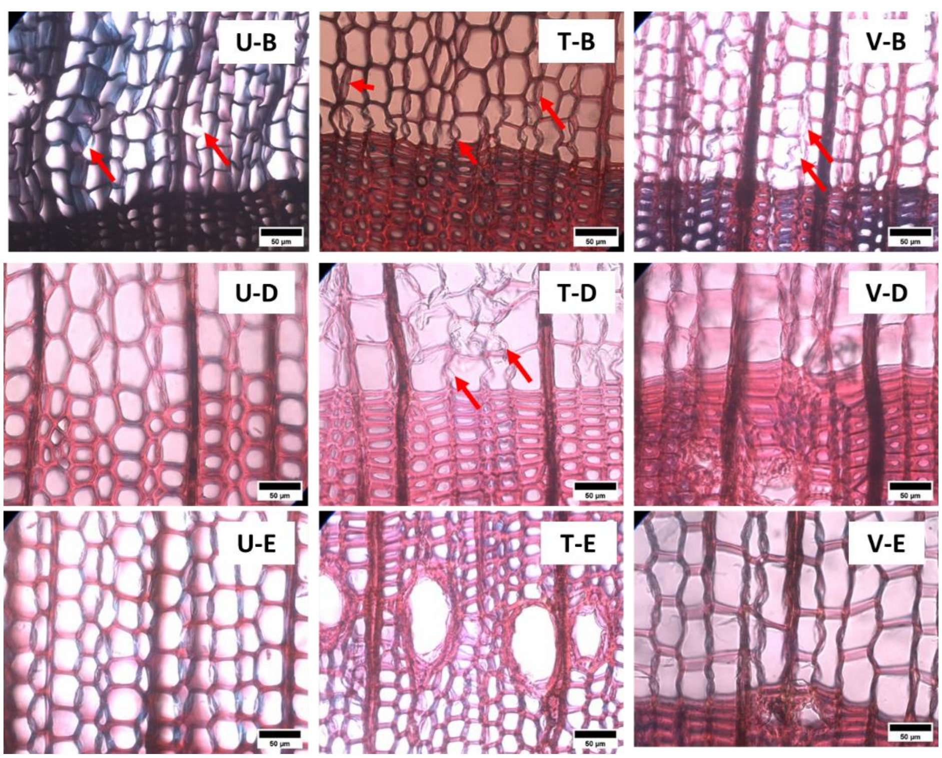

Fig. 7. Optical micrographs of untreated (U-B, U-D, and U-E), wood tar-treated (T-B, T-D, and T-E), and wood vinegar-treated samples (V-B, V-D, and V-E) of larch wood after being buried in the soil (U-B, T-B, and V-B), submerged in water (U-D, T-D, and V-D), and exposed to air (U-E, T-E, and V-E); Scale bars: 50 µm

According to an investigation of the movement path of the brown-rot fungus, hyphae penetrate deeply into the HW through the ray tissue and mainly move to the vessel through the field pit (Greaves and Levy 1965; Wilcox 1968). In previous studies, collapsed cells and transwall fractures in the transverse section of decayed wood were attributed to fungal exposure. Wilcox (1993) found that *Abies concolor* exposed to brown-rot fungi exhibited cell separation in the late- and earlywood. Anagnost (1998) observed that the earlywood of brown-rotted *Pinus taeda* and *Pseudotsuga menziesii* displayed collapsed cells and transwall fractures in transverse sections due to weakened cells. Additionally, Lee *et al*. (2004) reported that *Coniophora puteana* degraded *Pinus densiflora* tracheids and *Quercus acutissima* fibers while retaining their shape.

CT Scan Analysis

Figure 8 shows CT images of the untreated and preserved samples under each weathering condition. The CT image analysis can non-destructively predict the hardness, decay, and resin. Darker colors indicate low density and high MC, whereas lighter colors indicate high density (Watanabe *et al.* 2012; Seibold *et al.* 2022).

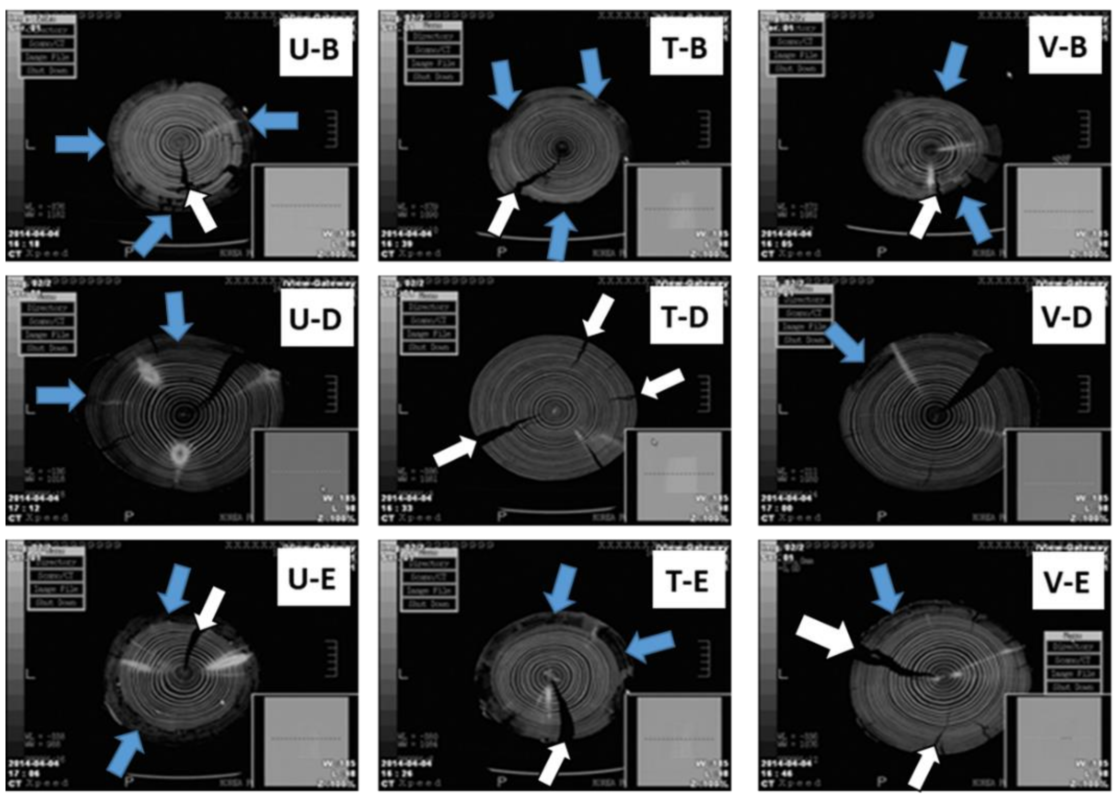

Fig. 8. CT images of untreated (U-B, U-D, and U-E), wood tar-treated (T-B, T-D, and T-E), and wood vinegar-treated samples (V-B, V-D, and V-E) that were examined after being buried in soil (U-B, T-B, and V-B), submerged in water (U-D, T-D, and V-D), and exposed to air (U-E, T-E, and V-E) for 53 months

Numerous splits were observed from the SW to the HW area in all samples (indicated using white arrows). In the U-B, T-B, and V-B samples, the surface of the SW was almost black (indicated using blue arrows). The HW of U-B and T-B had a larger apparent surface area than that of V-B. The current results indicated that V-B showed more severe degradation than U-B and T-B, which could be due to the nutrient-rich composition of wood vinegar and its potential benefits in enhancing soil health. Wood vinegar provides a favorable environment and necessary nutrients, indirectly supporting fungal growth (Zhu *et al.* 2021; Akley *et al.* 2023).

The U-D, T-D, and V-D samples showed clear surfaces, whereas the T-D sample showed brighter surfaces than the U-D and V-D samples, indicating a higher density or lower moisture content. Ahmed and Morén (2012) reported that tar-treated *Pinus sylvestris* and *Picea abies* showed improved anti-swelling and water-repellence efficiencies.

The SW of the U-E and T-E samples exhibited a large dark area, whereas the V-E sample showed only a small dark spot, indicating less wood degradation. Wood vinegar, obtained from many different wood species, such as *Pinus densiflora* and *Quercus serrata*, is recognized for its antifungal, termiticidal, and insect-repelling properties (Yatagai *et al.* 2002; Velmurugan *et al.* 2009).

Physical Properties

Air-dry density

Table 2 presents the densities of untreated and preserved larch wood. After being buried underground, wood vinegar-treated larch wood exhibited the lowest density, whereas untreated wood was intermediate between wood vinegar-treated and wood tar-treated larch wood. There were no significant differences between HW and SW in any of the treatments.

Table 2. Density of the Untreated and the Preserved Larch Wood (Unit: g/cm^3)

	Untreated wood		Wood Tar-treated		Wood Vinegar-treated	
	SW*	HW*	SW*	HW*	SW*	HW*
Buried Underground	0.45 ± 0.03^{b}	0.50 ± 0.07^{bc}	0.58 ± 0.04^{c}	0.62 ± 0.16^{c}	0.31 ± 0.03^{a}	0.31 ± 0.03^{a}
Deposited in Water	0.54 ± 0.03^{bc}	0.58 ± 0.02^{c}	0.48 ± 0.01^{a}	0.55 ± 0.06^{bc}	0.53 ± 0.03^{abc}	0.51 ± 0.02^{ab}
Exposure in Air	0.55 ± 0.18^{ab}	0.60 ± 0.22^{b}	0.49 ± 0.06^{a}	0.53 ± 0.03^{ab}	0.54 ± 0.06^{ab}	0.61 ± 0.06^{b}

* SW: sapwood; HW: heartwood; similar superscript letters in the same row indicate a non-significant difference between the samples in Duncan's multiple range tests at the 5% significance level

After being submerged in water, the wood tar-treated SW had the lowest density, which was noticeably lower than that of the wood tar-treated HW. Wood vinegar-treated SW and HW had comparable densities, whereas their densities were lower than those of untreated SW and HW and wood tar-treated HW.

After exposure to air, wood tar-treated SW showed the lowest density; wood tar-treated HW, untreated SW, and wood vinegar-treated SW showed comparable values, which were slightly higher than that of wood tar-treated SW.

Severe loss in density is a common characteristic of wood degradation. A severe decrease in density was observed in buried wood vinegar-treated larch wood in this study, which could be because wood vinegar provides a favorable environment and necessary nutrients, indirectly supporting fungal growth (Zhu *et al.* 2021; Akley *et al.* 2023). Cline *et al*. (2018) reported that a white-rot species from the genus *Trametes* was prevalent in living *Betula papyrifera* stems and continued to exist within the stems on the forest floor for at least 3.5 years. Stems experienced a density loss of up to 40%. The wood density of *Pinus densiflora* stems substantially decreased during the decomposition process, which was dominated by white rot basidiomycetes (Fukasawa *et al.* 2009; Fukasawa 2018).

The shrinkages of untreated and preserved larch wood are presented in Table 3. After being buried underground, the untreated wood had the greatest radial and tangential shrinkage, whereas the vinegar-treated wood had the smallest shrinkage. In addition, wood vinegar-treated wood exhibited the greatest longitudinal shrinkage.

Table 3. Shrinkages of the Untreated and Preserved Larch Wood (Unit: %)

		Untreated wood		Wood Tar-treated		Wood Vinegar-treated	
		SW*	HW*	SW*	HW*	SW*	HW*
Buried Underground	R*	6.00 ± 1.73^{b}	6.53 ± 1.25^{b}	5.06 ± 0.91^{ab}	4.72 ± 0.77^{ab}	6.67 ± 2.77^{b}	3.37 ± 0.89^{a}
	T*	9.44 ±1.66^{a}	10.17 ± 2.43^{a}	7.98 ± 0.54^{a}	7.29 ± 1.50^{a}	10.16 ± 2.83^{a}	7.85 ± 3.07^{a}
	L*	1.61 ±1.12^{b}	1.65 ± 1.36^{b}	0.28 ± 0.18^{a}	0.98 ± 0.78^{b}	3.85 ± 0.65^{c}	2.74 ± 2.02^{bc}
Deposited in Water	R*	4.83 ± 1.30^{b}	4.89 ± 1.73^{b}	2.95 ± 0.84^{a}	3.37 ± 0.89^{ab}	3.30 ± 0.45^{ab}	2.85 ± 0.37^{a}
	T*	7.94 ± 0.88^{b}	8.98 ± 0.38^{b}	6.30 ± 1.20^{a}	5.82 ± 0.65^{a}	6.49 ± 0.57^{a}	6.53 ± 0.17^{a}
	L*	0.04 ± 0.06^{ab}	0.06 ± 0.05^{ab}	0.05 ± 0.04^{ab}	0.16 ± 0.19^{b}	0.02 ± 0.02^{a}	0.07 ± 0.07^{ab}
Exposure to Air	R*	2.45 ± 0.61^{a}	2.87 ± 0.70^{a}	2.60 ± 0.67^{a}	2.61 ± 0.49^{a}	2.49 ± 0.68^{a}	2.56 ± 0.52^{a}
	T*	4.85 ± 0.77^{b}	4.49 ± 0.85^{b}	5.24 ± 0.81^{b}	3.99 ± 1.04^{a}	4.82 ± 0.95^{b}	4.62 ± 0.70^{ab}
	L*	0.11 ± 0.07^{a}	0.26 ± 0.14^{a}	0.12 ± 0.03^{a}	0.27 ± 0.16^{ab}	0.42 ± 0.29^{b}	0.25 ± 0.10^{ab}

* R: radial direction, T: tangential direction, L: longitudinal shrinkage, SW: sapwood, HW: heartwood; similar superscript letters in the same row indicate a non-significant difference between the samples according to Duncan's multiple range tests at the 5% significance level

After being submerged in water, the untreated wood exhibited higher shrinkage than the preserved wood. In the untreated wood, SW and HW showed comparable shrinkage values. In the tar-treated wood, the radial shrinkage of HW was slightly higher than that of SW, whereas the tangential shrinkage of SW was higher than that of HW. The longitudinal shrinkage of all the samples was minimal after being deposited in water.

After exposure to air, the radial shrinkages of all samples were comparable. The wood tar-treated SW had the highest tangential shrinkage compared to the untreated and wood vinegar-treated SWs. The tangential shrinkages of untreated wood vinegar-treated wood and wood vinegar-treated HW were comparable.

The longitudinal shrinkage of all samples was minimal after exposure to air. In addition, the longitudinal shrinkage of the samples submerged in water and exposed to air was noticeably lower than that of the buried sample, possibly because of severe decay on the transverse surface of the buried wood samples.

Mechanical properties

The mechanical properties of untreated and preserved larch wood are presented in Table 4. After being buried underground, the SW of untreated and preserved wood showed lower compression, shearing strength, and hardness than HW. Wood tar-treated woods showed the best mechanical properties among the SWs, whereas wood vinegar-treated woods had the smallest values. The HW of wood tar showed better mechanical properties than the untreated and wood vinegar woods, and the compression, shearing strength, and hardness of the untreated and wood vinegar HW were comparable.

Table 4. Mechanical Properties of Untreated and Preserved Larch Wood (Unit: MPa)

			Untreated wood		Wood Tar-treated		Wood Vinegar-treated	
			SW	HW	SW	HW	SW	HW
Buried Underground	Compression		42.8 ± 7.22	48.1 ± 5.17	52.8 ± 2.12	54.0 ± 4.32	32.4 ± 7.14	41.7 ± 2.44
	Shearing		4.5 ± 1.40	7.4 ± 2.47	6.2 ± 1.24	8.9 ± 4.62	1.9 ± 0.98	7.2 ± 2.41
	Hardness	C*	12.2 ± 4.37	32.2 ± 4.14	39.3 ± 3.58	42.1 ± 5.33	10.4 ± 1.86	35.3 ± 4.51
		R*	4.9 ± 1.11	11.5 ± 3.11	7.6 ± 1.84	12.9 ± 2.22	3.7 ± 0.88	11.9 ± 2.17
		T*	3.2 ± 1.64	9.7 ± 1.44	4.9 ± 1.05	10.3 ± 1.01	2.8 ± 1.47	8.4 ± 2.72
Deposited in Water	Compression		54.0 ± 4.14	55.1 ± 3.13	49.3 ± 4.32	52.1 ± 3.20	60.1 ± 2.24	62.7 ± 4.11
	Shearing		8.8 ± 1.53	7.8 ± 2.43	7.0 ± 3.21	7.5 ± 2.44	8.2 ± 1.42	9.4 ± 3.24
	Hardness	C*	35.4 ± 2.87	36.6 ± 5.14	30.7 ± 6.54	33.1 ± 3.78	38.2 ± 5.14	38.7 ± 3.94
		R*	7.4 ± 1.99	10.8 ± 4.10	7.1 ± 2.86	11.4 ± 3.71	7.5 ± 0.97	14.0 ± 2.39
		T*	6.8 ± 1.31	10.4 ± 2.55	6.3 ± 2.27	7.2 ± 1.44	7.4 ± 2.48	10.1 ± 2.21
Exposure in Air	Compression		55.0 ± 4.89	51.6 ± 5.17	57.4 ± 2.41	60.8 ± 1.41	57.1 ± 6.83	58.0 ± 7.74
	Shearing		8.2 ± 2.07	10.4 ± 3.27	7.2 ± 2.82	9.8 ± 1.48	11.2 ± 2.14	10.1 ± 2.77
	Hardness	C*	41.3 ± 6.59	44.1 ± 5.21	41.7 ± 7.02	36.0 ± 5.47	44.1 ± 3.16	43.3 ± 4.53
		R*	9.6 ± 3.41	14.3 ± 1.44	9.2 ± 1.04	12.6 ± 4.77	11.8 ± 2.88	10.3 ± 3.95
		T*	8.5 ± 2.08	9.2 ± 1.25	6.5 ± 1.78	5.9 ± 2.45	6.9 ± 2.29	7.4 ± 2.78

*C, cross section; R, radial section; T: Tangential section; SW, sapwood; HW, heartwood

After being submerged in water, the untreated and wood tar-treated woods showed comparable compressive strengths, and the wood vinegar-treated woods had higher compressive strength than the untreated and wood tar-treated woods. There was no noticeable difference in the shear strength between the untreated, wood tar-treated, and wood vinegar-treated woods. The wood tar-treated woods had the smallest hardness in the cross section, whereas the untreated and wood vinegar-treated woods showed comparable hardness.

After exposure to air, untreated wood had the lowest compression strength, whereas wood tar-treated and wood-vinegar-treated wood had higher compression strengths. The shear strengths of untreated and preserved HW were comparable. Wood vinegar-treated SW showed a higher shear strength than untreated and wood tar-treated SW, which had comparable values. The hardness values of the untreated and treated samples were comparable.

Kim *et al*. (2021) reported that the compression and shear strengths of Japanese larch SW were 68.2 ± 3.4 MPa and 8.8 ± 1.5 MPa, respectively, whereas those of HW were 72.2 ± 3.7 MPa and 9.8 ± 1.8 MPa, respectively. Additionally, the hardness of SW was 42.9 ± 2.2 MPa on the transverse surface, 16.8 ± 0.9 MPa on the radial surface, and 17.5 ± 4.2 MPa on the tangential surface. For HW, the hardness was 53.0 ± 3.4 MPa on the transverse surface, 18.6 ± 2.2 MPa on the radial surface, and 17.8 ± 1.6 MPa on the tangential surface. The mechanical properties of the decayed samples in this study were noticeably lower than those of sound wood, as reported by Kim *et al*. (2021). Among the samples, the SW in wood vinegar-treated underground wood showed the lowest mechanical strength. The nutrient-rich composition of wood vinegar enhances soil health and indirectly supports fungal growth (Zhu *et al.* 2021; Akley *et al.* 2023). Maeda *et al*. (2015) reported that the compressive strength of *Picea sitchensis* showed a noticeable decrease after 3 weeks of exposure to brown-rot fungus and 5 years of exposure to white-rot fungus. In general, a more significant decrease in strength was observed in the SW than in the HW. Lee (1992) analyzed the decline in strength by injecting different types of mycelia into pine and oak trees and found different rates of change depending on the type of mycelium. However, the average decrease in SW was more than five times greater than that in the HW.

Crystalline Properties

The RCI values of untreated and preserved larch wood are summarized in Table 5. The RCI of all samples decreased noticeably after 53 months of exposure, and the buried samples had the lowest RCI. After being buried underground, wood vinegar-treated wood had the smallest RCI, whereas the untreated and wood tar-treated wood had comparable values. Samples submerged in water and exposed to air exhibited comparable RCI values.

The RCI measures the crystalline structure of cellulose in wood, which provides insight into the degree of degradation by decay fungi. The relative crystallinity of the decayed wood in the present study tended to decrease with increasing exposure period, which is consistent with the findings of several other studies. In a study by Suri *et al*. (2023), the RCI of *Pinus koraiensis* decreased significantly after exposure to brown rot. Similarly, Howell *et al*. (2009) found that the percentage of crystallinity in pine wood, when exposed to *Gloeophyllum trabeum*, decreased below control levels by weeks 8 to 12. Hastrup *et al*. (2012) observed that the RCI of red maple decreased significantly after exposure to *Meruliporia incrassata* (brown-rot fungus). Conversely, wood exposed to *G. trabeum* (brown-rot fungus) maintained a constant RCI for nine weeks before sharply decreasing at twelve weeks. Additionally, the RCI of wood decayed by white-rot fungi, such as *Irpex lacteus* and *Pycnoporus sanguineus*, increased after nine weeks of exposure.

Table 5. Relative Crystallinity Index of the Untreated and Preserved Larch Wood (unit: %)

		0 days*	12 months	24 months	53 months
Buried underground	Untreated	73	63	53	37
	Wood tar-treated	73	46	55	41
	Wood vinegar-treated	73	59	37	30
Deposited in water	Untreated	73	60	47	44
	Wood tar-treated	73	55	48	43
	Wood vinegar-treated	73	55	53	45
Exposure in air	Untreated	73	60	53	44
	Wood tar-treated	73	63	50	42
	Wood vinegar-treated	73	60	54	48

*Kim *et al*. (2022)

CONCLUSIONS

Each material treated with wood vinegar and wood tar was buried in soil, submerged in water, and exposed outdoors to investigate methods to enhance the durability of domestic larch wood as a material for eco-friendly erosion-control dams. The results were as follows:

1. In the macroscopic and CT (computed tomography) image analyses, some degradation, cracking, and splitting were observed in the SW (sapwood) of all the samples; however, the V-B samples (vinegar-treated wood buried in soil) showed the most severe deterioration. Microscopically, no significant degradation was observed in the larch wood exposed to outdoor conditions, whereas the buried samples commonly exhibited collapsed tracheid walls. Collapsed tracheid walls were also observed in T-D (wood tar-treated woods deposited in water), but rarely in U-D (untreated woods deposited in water) and V-D (wood vinegar-treated woods deposited in water).
2. V-B showed the lowest air-dried density value among the buried samples, whereas T-B (wood tar-treated wood buried in soil) showed the highest value. The SW of tar-treated wood exhibited the lowest density after exposure to underwater and outdoor conditions. In contrast, untreated and wood vinegar-treated wood had comparable densities under underwater and outdoor conditions.
3. The buried larch wood showed the highest shrinkage, whereas the samples exposed outdoors showed the smallest shrinkage. Untreated woods showed the highest

shrinkage under underground and underwater conditions, whereas the wood tar- and wood vinegar-treated woods showed comparable properties. There was no noticeable difference in the shrinkage between the samples after exposure to air.

4. Buried larch wood exhibited the lowest mechanical properties among all weathering conditions. Among the buried samples, wood vinegar-treated wood showed the lowest mechanical properties, whereas wood tar-treated wood showed the highest mechanical properties. There were no noticeable differences in the mechanical properties between any of the treatments under either underwater or outdoor conditions.
5. The RCI (relative crystallinity index) decreased over time in the samples under all conditions, and the buried larch wood exhibited a lower RCI than the underwater and outdoor samples. V-B showed the lowest relative crystallinity among all the samples.
6. Hence, it was concluded that the application of wood tar enhanced the durability of the material when buried in soil. In the case of water immersion, neither wood tar- nor wood vinegar-treatment had any impact on the strength. However, wood vinegar-treatment, which offers resistance against pests, provided an advantage when exposed to outdoor conditions.

ACKNOWLEDGMENTS

This study was supported by the Academic Research Composition Fund of Kangwon National University in 2013; the Science and Technology Support Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MSIT) under Grant No. 2022R1A2C1006470; the Basic Science Research Program through the NRF funded by the Ministry of Education under Grant No. 2018R1A6A1A03025582; and the R and D Program for Forest Science Technology under Project No. 2021350C10-2323-AC03, provided by the Korea Forest Service (Korea Forestry Promotion Institute).

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Article submitted: June 25, 2024; Peer review completed: July 19, 2024; Revised version received: July 31, 2024; Accepted: August 4, 2024; Published: September 3, 2024.
DOI: 10.15376/biores.19.4.7946-7962