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Wood Modification Using Fast Pyrolysis Bio-Oil (FPBO): Formulation Development, Characterization, and Evaluation of Wood Performance

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Abstract

This study presents a wood modification process using Fast Pyrolysis Bio-Oil (FPBO) as a fully biobased alternative to conventional, fossil-based and potentially toxic preservatives such as copper salts, organic biocides, and creosote. Standard FPBO was used in the development of 10 formulations, which were systematically characterized in terms of pot life, viscosity evolution, density, and pH. Radiata pine samples were subsequently impregnated using a bench-scale reactor, with specimens prepared in multiple geometries to assess treatment performance across different dimensions. The modified wood was comprehensively characterized with respect to moisture uptake, dimensional stability, density, mechanical strength, fixation efficiency, biological durability, and VOC emissions. Additional screening focused on properties relevant to outdoor applications, including aesthetic appearance and colour uniformity after UV exposure. The results enabled the identification of three top-performing formulations, treatments H, A, and E, which exhibited the most favourable balance between durability, environmental performance, and structural integrity. Overall, the findings demonstrate the strong potential of FPBO-based impregnation as a sustainable, multifunctional, and high-performance alternative for advanced wood protection systems.

Keywords: wood modification; fast pyrolysis bio-oil (FPBO); durability; bio-based impregnation treatment

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1. Introduction

Wood is a versatile, renewable construction material widely used in both structural and decorative applications. However, its susceptibility to moisture, fungal decay, insect attack, and ultraviolet (UV) degradation limits its durability and service life. To overcome these shortcomings, wood is commonly modified using a variety of approaches, including thermal, thermo-hygro-mechanical, chemical, and physical treatments [1]. Among these, preservation of wood bulk with selected chemicals is broadly accepted as an effective solution for improving wood products' performance as well as extending the service life of wood components.

Traditionally, wood impregnation processes have relied on chemical preservatives such as copper-based salts, organic biocides, and creosote. Although these treatments are generally highly effective, they raise significant environmental and health concerns due to their toxicity, persistence, and dependence on fossil-derived compounds [2]. Increasing regulatory restrictions, coupled with growing awareness of sustainability issues, have consequently driven the search for safer and more environmentally friendly alternatives [3].

In this context, biobased wood modification solutions represent a promising approach to replacing conventional preservatives while maintaining, or even enhancing, wood performance. Fast pyrolysis is an established thermochemical conversion process in which biomass is rapidly heated (within seconds) to temperatures of approximately 450 to 600 °C under inert conditions [4]. This process involves depolymerization, cracking, and gasification reactions generating vapours, which are subsequently condensed into a liquid product known as fast pyrolysis bio-oil (FPBO).

FPBO retains much of the chemical functionality of the original biomass and consists of a complex mixture of compounds derived from cellulose, hemicellulose, and lignin thermolysis [5,6]. Cellulose and hemicellulose predominantly yield pyrolytic sugars, organic acids, and water, whereas lignin is transformed into phenolic-rich fractions often referred to as pyrolytic lignin. As a result, FPBO contains a diverse array of reactive and potentially bioactive components, making it a promising candidate for wood modification applications [7].

Several studies have explored the use of FPBO and related pyrolysis-derived fractions for wood protection and modification. Previous research has demonstrated that impregnation with pyrolysis liquids can reduce wood hygroscopicity, improve dimensional stability, and increase resistance against biological degradation through the presence of phenolic and other bioactive compounds [8–10]. Additional investigations have reported enhanced hydrophobicity and reduced weathering susceptibility when pyrolysis-derived products were incorporated into wood treatment systems [8,11]. These studies have established the technical feasibility of utilizing pyrolysis liquids as biobased alternatives to conventional preservatives and have highlighted their potential contribution to more sustainable wood protection strategies.

Despite these advances, several important challenges remain unresolved. The chemical composition of FPBO strongly depends on biomass feedstock, pyrolysis conditions, and post-processing procedures, resulting in significant variability in physicochemical properties and treatment performance [12]. Consequently, direct comparisons between studies are often difficult, and a clear understanding of the relationships between FPBO formulation characteristics, impregnation behavior, fixation efficiency, and resulting wood properties is still lacking. Furthermore, most previous investigations have focused on a limited number of performance indicators, while comprehensive evaluations encompassing physical, chemical, mechanical, and aesthetic effects remain scarce. The long-term suitability of FPBO formulations for industrial wood impregnation processes therefore remains insufficiently understood. Such uncertainty, as well as limited understanding of

the wood properties alteration after FPBO impregnation, limits the implementation of this technology in the state-of-the-art wood industry.

To address these knowledge gaps, the present study systematically investigates a series of tailored FPBO-based formulations using conventional wood impregnation procedures. The novelty of this work lies in the comparative assessment of multiple formulations combined with a comprehensive evaluation of treated wood performance, including physical, chemical, mechanical, and aesthetic characteristics. Through this approach, the study aims to identify formulations that provide an optimal balance between treatment effectiveness, processability, environmental behavior, and preservation of wood properties, thereby supporting the future industrial implementation of FPBO-based wood modification technologies.

2. Materials and Methods

2.1. Experimental Samples

All experimental samples were prepared from a single batch of radiata pine (Pinus radiata) originating from New Zealand. This wood species is recognized for its high permeability and porosity, making it particularly suitable for impregnation and chemical modification. However, it is generally classified as non-durable to slightly durable. Therefore, its performance and market value can be significantly enhanced through modification. The material was processed into block specimens in accordance with relevant testing standards. Consequently, three sample sizes (thickness × width × length) were prepared for each FPBO formulation, including small ($5 \times 10 \times 220$ mm^3), medium ($20 \times 20 \times 220$ mm^3), and large ($20 \times 150 \times 220$ mm^3) sample sets.

2.2. Fast Pyrolysis Bio-Oil Production

The FPBO used in this study was produced by Pyrocell fast pyrolysis plant (Gävle, Sweden), which is based on BTG-BTL's patented technology operated at 500 °C under inert conditions [13]. The process exhibited high efficiency, reaching approximately 90%. Due to the short vapor residence time, up to 70% weight of the initial biomass is converted into FPBO. The remaining products, including char and non-condensable gases (approximately 15% each), are combusted in situ to supply a.o. the reactor's internal energy demand. As a result, the overall energy balance of the process is positive, and the surplus energy is used to generate heat and electricity for for the whole pocess.

2.3. Development of Impregnation Solutions

The impregnation formulations were based on FPBO, polyols, and selected green additives, stabilizers, and catalysts. Due to their relatively low viscosity, these formulations can be applied at ambient temperature using conventional vacuum-pressure processes (full-cell or empty-cell methods). This allows for an extended pot life and enables reuse of excess formulation, reducing both waste and operational costs. Ten different formulations were prepared using standard FPBO process developed by Pyrocell (Gävle, Sweden), varying in catalyst systems, additives, and component ratios (Table 1). Polyols, such as propylene glycol (PG), were used to obtain homogeneous mixtures, while stabilizers improved formulation stability, pot life, and water tolerance. Catalysts were added to ensure proper curing at 130 °C. In some formulations, water was used as a solvent to adjust viscosity. Catalyst 2 was included to evaluate whether a lower-cost catalytic system could provide comparable curing performance while maintaining acceptable formulation stability. This specific formulation was selected because preliminary laboratory testing showed the best balance of homogeneity and pot life among the Catalyst 2-containing candidates, making it the most suitable representative for comparison.

Table 1. Chemical composition of formulated impregnation solutions (treatment). Note: numbers correspond to the percent weight ratio. FPBO—fast pyrolysis bio-oil, (M)PG—(Mono-) Propylene Glycol, Residue—mass rate of the solid residues after formulation curing.

Treatment	FPBO	(M)PG	Stabilizer 1	Water	Catalyst 1	Stabilizer 2	Catalyst 2	Residue
A	75	8	8	8	1	0	0	45.1
B	88	8	0	2	0	2	0	45.0
C	88	8	0	2	0	0	2	43.8
D	87	8	0	2	1	2	0	54.8
E	81	8	6	2	1	2	0	47.7
F	89	8	0	0	1	2	0	56.6
G	93	0	3	0	1	3	0	57.8
H	79	8	6	2	1	4	0	53.8
I	78	8	6	4	1	4	0	52.0
J	78	8	6	4	0	4	0	45.5

For each formulation, approximately 26 kg of liquid product was synthesized. Of this, ~1 kg was used for formulation characterization, while the remaining ~25 kg was used in impregnation experiments.

2.4. Impregnation Process

Wood modification was carried out using a vacuum-pressure method, which is a standard industrial-scale preservation technique. This method maximizes the uptake of the treatment solution and ensures deep and uniform penetration into the wood structure. Samples were treated in a bench-scale reactor using all developed formulations. Initially, specimens were subjected to a pre-vacuum of 20 kPa for 30 min to remove air from the wood pores. Subsequently, the impregnation solution was introduced to fully submerge the samples. The pressure phase was then applied by increasing the autoclave pressure to 1000 kPa for 120 min, ensuring thorough penetration of the formulation. Finally, a post-vacuum stage (20 kPa for 10 min) was applied to remove excess solution from the surface and improve retention efficiency.

After impregnation, the samples underwent controlled thermal curing in a laboratory oven. The temperature was gradually increased to 130 °C over 8 h to minimize thermal stress and was maintained for 24 h to ensure complete curing of the FPBO formulations and stabilization of the wood structure. This process promoted crosslinking between the impregnated compounds and wood polymers while preserving the core mechanical properties due to the relatively mild treatment temperature.

2.5. Characterization Methods for the FPBO Formulation

2.5.1. Stability of Formulations

Formulation stability was evaluated immediately after preparation (0 months), after 6 months, and after 12 months of storage. Each formulation was monitored for pH, density, and viscosity according to a standardized protocol. The pH values of the formulations were determined using a Thermo Scientific Orion Versa-Star Pro Meter (Thermo Fisher Scientific, Waltham, MA, USA) equipped with an IS-68X591206-B-VSTAR pH/LogR module with automatic temperature compensation (ATC). Measurements were conducted at room temperature (approximately 23 ± 2 °C), with a pH resolution of up to 0.001 and a temperature resolution of 0.1 °C. Before measurements, the pH meter was calibrated using standard buffer solutions.

2.5.2. Viscosity

The viscosity of the formulations was measured using a rotational viscometer Anton Paar ViscoQC 300-L (Graz, Austria) equipped with a temperature probe and integrated heating system (PTD 80). Measurements were performed at 20 and 50 °C under controlled laboratory conditions. The analysis was conducted using spindle CC-18 in TruMode™, which automatically determines the right spindle/speed configuration. Each sample was measured in triplicate, and the results were expressed as mean values. The density of formulations was determined using an analytical balance and the corresponding density measurement procedure at room temperature (approximately 23 ± 2 °C). Each sample was analyzed in triplicate, and the obtained values were expressed as mean values. Stability was evaluated over one year, with 3 measurement points.

2.6. Characterization of Wood

2.6.1. Wood Density and Weight Percent Gain (*WPG*) After Impregnation

Wood density was determined according to ISO standard [14]. Samples were conditioned at 20 °C and 50% relative humidity until constant mass was achieved. Mass was measured using a precision balance, and volume was calculated from dimensions measured with a caliper. Density was expressed in kg/m^3 at air-dry conditions.

Wet (WPG_w) and dry (WPG_d) weight percent gains were calculated using Equations (1) and (2), respectively.

$$WPG_w\ (\%) = \frac{m_{wa} - m_d}{m_d} \times 100\% \quad (1)$$

$$WPG_d\ (\%) = \frac{m_{da} - m_d}{m_d} \times 100\% \quad (2)$$

where m_{wa}—mass immediately after impregnation, m_d—oven-dry mass before impregnation, m_{da}—oven-dry mass after impregnation.

Based on WPG_d values, samples within each tested formula were categorized into three classes: low (L), medium (M), and high (H) uptake.

2.6.2. Moisture Uptake

Moisture uptake was determined according to the CEN standard [15]. Both floating and full immersion methods were applied. For each formulation, nine samples ($10 \times 5 \times 50$ mm^3) representing L, M, and H *WPG* levels were selected whenever samples within each treatment batch differed sufficiently.

Samples were sealed on two or four sides using epoxy resin. Specimens were exposed to demineralized water at controlled conditions. Mass changes were recorded during absorption (1–144 h) and desorption (1–168 h). Water uptake (W) was calculated using Equation (3).

$$W = \frac{m_x - m_i}{A} \quad (3)$$

where m_x—the final mass of impregnated wood, m_i—the initial mass of impregnated wood, and A—the surface area of the specimen.

2.6.3. Leaching of Impregnation Components

The fixation of FPBO components within wood bulk w was assessed with an accelerated leaching procedure according to EN standard [16]. Samples were vacuum-treated with demineralized water (4 kPa, 20 min), soaked for 2 h, and immersed for 14 days with

periodic water replacement (nine times). After leaching, samples were air-dried for two weeks. Leaching was calculated using Equation (4).

$$Leaching\ Loss(\%) = \frac{m_b - m_a}{m_b} \times 100 \quad (4)$$

where m_b—oven dry mass of the treated wood before leaching, m_a—oven dry mass after completing EN 84 leaching.

2.6.4. Dimensional Stability

Dimensional stability was assessed according to the ISO standard [17]. Radial and tangential shrinkage and swelling, as well as volumetric changes, were measured between oven-dry and water-saturated states. Volumetric changes were expressed as percentage differences relative to the initial volume (Equation (5)).

$$Volumetric\ Shrinkage(\%) = \frac{V_g - V_d}{V_g} \times 100 \quad (5)$$

where V_g—volume at full saturation (above fibre saturation point), V_d—oven dry volume.

2.6.5. Impact Bending Strength

Deterioration of the mechanical performance of experimental samples was evaluated by dynamic impact bending strength on Pendulum Impact Tester ZwickRoell HIT25P (Zwick, Ulm, Germany), using 5J hammer [18]. This test assesses resistance to sudden loads that may be affected by its exposure to elevated temperatures during post-treatment conditioning. Energy absorption A_w during impact loading was recorded for ten replica samples.

2.6.6. UV Stability

UV resistance and stability were evaluated according to ISO standard [19]. Samples were exposed to UVA, UVB, UVC, and daylight (D65) conditions using an Opsytec BS-03 UV/VIS chamber (Opsytec Dr. Gröbel GmbH, Ettlingen, Germany) for 480 h, corresponding to approximately eight years of natural exposure. The chamber provided UVA (5.1–5.8 mW/cm^2) and UVB (1.0–1.20 mW/cm^2) continuous radiation. At the same time, the temperature was maintained at approximately 20 °C through an air-cooling system to prevent excessive heating and degradation due to high temperature. Color and gloss changes were measured before and after exposure to assess photodegradation. *CIE Lab** coordinates were calculated assuming D65 illumination and a 10° observer angle. The instrument used for color/gloss evaluation was portable Color and Gloss Unit SPEKTRO-MASTER 565-45 (ERICHSEN GmbH & Co. KG, Hemer, Germany).

2.6.7. VOC Emission

Volatile organic compound (VOC) emissions from the impregnated wood samples were determined following the ISO standard [20]. Samples were conditioned in a climatic chamber at 20 °C and 50% relative humidity before measurements. Emissions were collected using active sampling on Tenax TA® (Buchem B.V., Apeldoorn, the Netherlands) sorbent in both chamber and indoor conditions. Analysis was performed using thermal desorption coupled with GC-MS Agilent 5977B GC/MSD (Wilmington, DE, USA).

2.6.8. Biological Durability

Resistance to wood-decaying fungi was evaluated according to the EN standard [21]. Two replica samples were exposed to *Rhodonia placenta* and *Trametes versicolor* cultures

for 16 weeks under controlled conditions (22 ± 2 °C, 70 ± 5% RH). Durability class was assessed based on the percentage of dry mass loss.

3. Results

3.1. Monitoring of the Stability of Formulations

Across the 10 formulations, pH, density, and viscosity were monitored over one year to assess storage stability. The pH remained consistently acidic for all formulations, with only minor fluctuations over time. Density values were likewise stable. In contrast, viscosity showed more pronounced variation between formulations and some changes over time. Despite this, all formulations remained homogeneous and processable during storage and showed no phase separation or leaching. The summary results are presented in Figure 1.

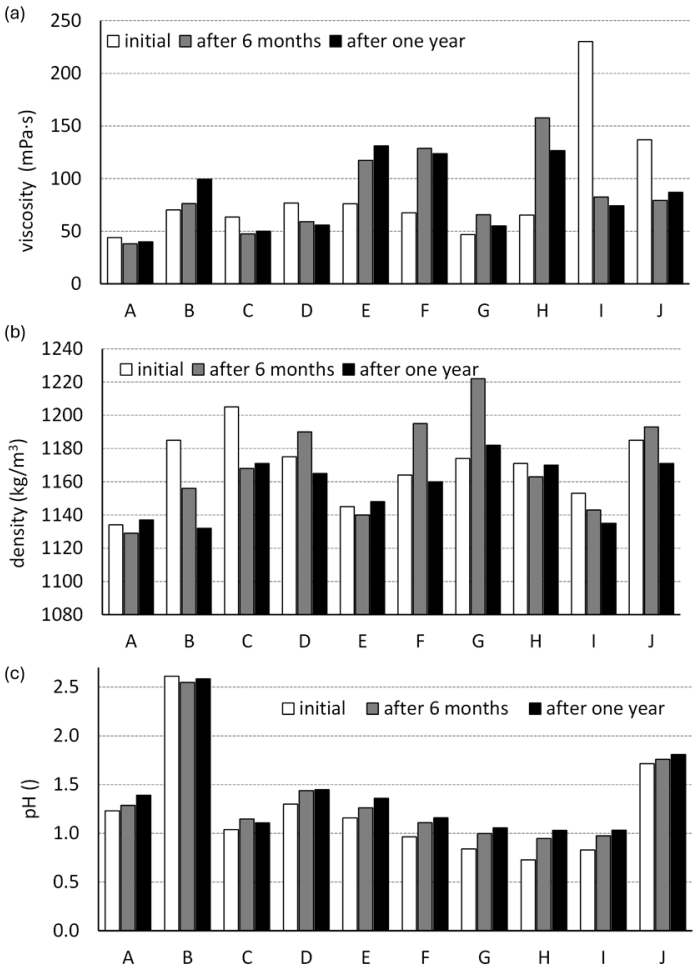

Figure 1. Basic characteristics of the fast pyrolysis bio-oil formulations used for impregnation of experimental samples: viscosity (**a**), density (**b**) and pH (**c**).

3.2. Wood Impregnation Results

The section below discusses the most relevant results, focusing on a comparison of the performance of wood treated with all tested formulations. At the end of the section, there is a table containing numerical values from all performed tests, which serves as an objective basis for comparing performance.

3.2.1. Wood Density and Weight Percent Gain

Density and weight percent gains (WPG_d and WPG_w) were determined for Radiata pine samples treated with all formulations (Figure 2), with untreated wood included as a

baseline. The reference samples showed the lowest density and no *WPG*, as expected. All impregnated samples exhibited an increase in density compared to the reference, although the extent of this increase varied between formulations. Similarly, *WPG* values differed across formulations, indicating differences in uptake and retention of the impregnation solutions. The results indicate that Catalyst 2 was less effective than Catalyst 1 in promoting the curing reactions required for optimal fixation of FPBO components within the wood. Although the exact catalyst identities cannot be disclosed, the observed behavior suggests differences in catalytic activity and/or selectivity toward the condensation and cross-linking reactions of the reactive carbohydrate- and lignin-derived fractions. While Catalyst 2 provided satisfactory formulation stability, it likely promoted network formation less efficiently, resulting in a lower degree of curing and fixation within the wood structure. Overall, the data confirms successful impregnation of radiata pine for all tested formulations, with apparently varying degrees of uptake.

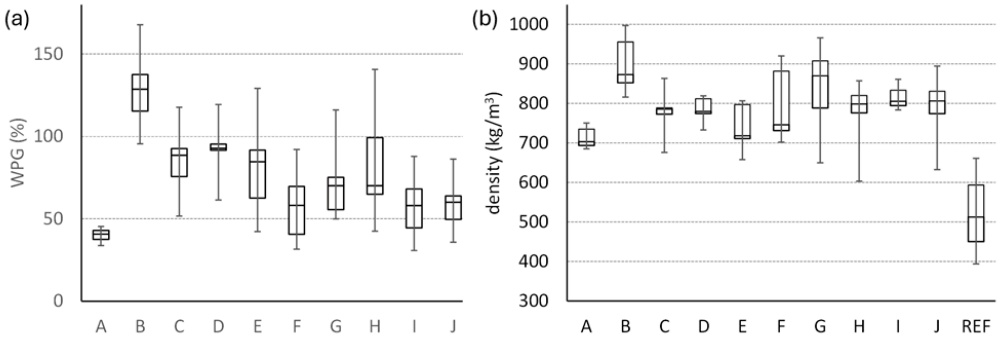

Figure 2. Weight percent gain (dry) of tested formulations (**a**) and resulting treated wood density (**b**) after wood impregnation with fast pyrolysis bio-oil. Note: The box represents the first (Q1) and third (Q3) quartiles, while the whiskers indicate the minimum and maximum observed values.

3.2.2. Leaching Test (Fixation of Components)

The leaching test revealed significant differences in the fixation behavior of the treated samples (Figure 3). Sample B exhibited the highest amount of leached material, with leaching values more than double compared to other samples. This indicates a substantially lower fixation efficiency of impregnated components in Sample B compared to the rest.

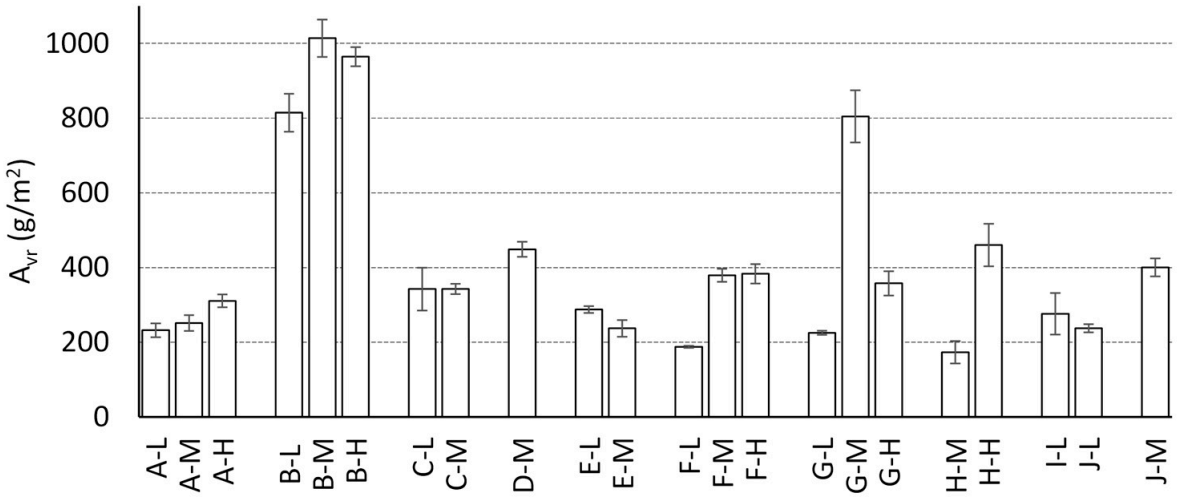

Figure 3. Results of leaching wood impregnated with FPBO in relation to the weight percent gain. Note: Error bars (whiskers) represent the standard deviation of the measurements.

3.3. Impregnated Wood Characteristics

3.3.1. Appearance of Impregnated Wood

The appearance of the FPBO-impregnated samples was generally uniform, exhibiting a consistent brown coloration across most specimens, as presented in Figure 4. However, in several samples, localized areas of darker tone and slight surface irregularities suggest an excess of impregnation solution, likely due to uneven uptake or incomplete removal of surplus liquid.

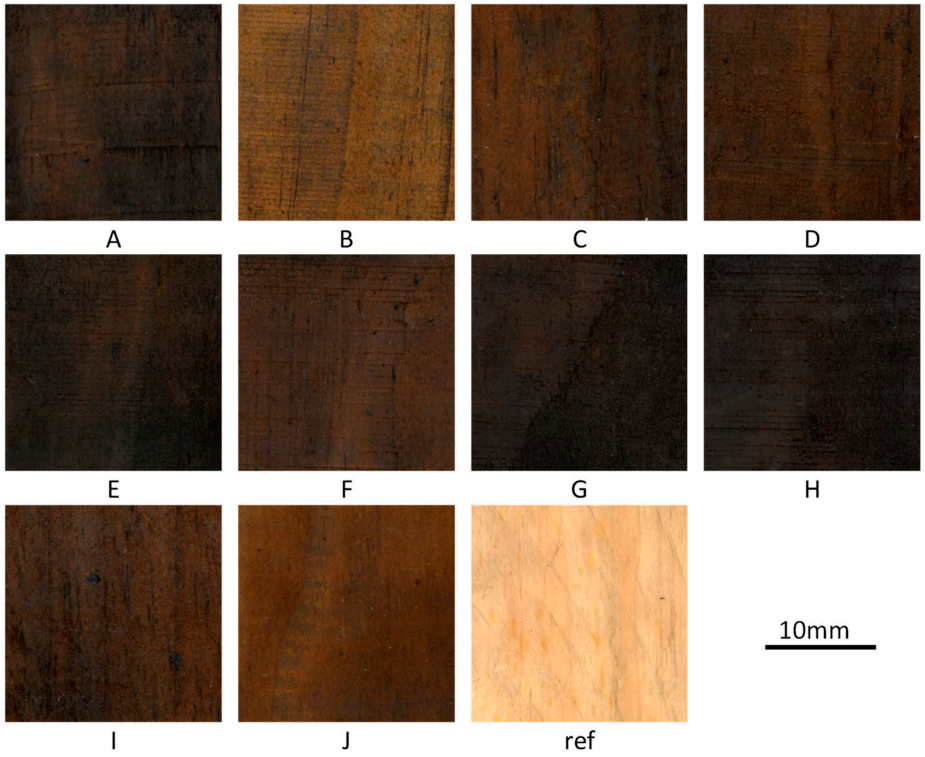

Figure 4. Images of wood samples treated with formulation A to J and not treated reference (ref). Note: Samples after conditioning were scanned with an office scanner Bizhub C258 (Konica Minolta), with a resolution of 600 dpi.

Compared to the untreated (ref) samples, the color change is clearly noticeable, indicating successful impregnation. A decrease in lightness (*CIE L**) and a shift in chromatic parameters (*CIE a** and *CIE b**) toward higher redness and yellowness values would correspond to the observed darker brown tone. Such changes are consistent with the presence and distribution of the impregnating solution within the wood structure.

3.3.2. Dimensional Stability

The summary of results from the shrinkage/swelling analysis is included as part of Table 4. All FPBO-modified samples showed substantially lower values compared to the reference, ranging from 4% to 7%. This corresponds to an approximate reduction of 40%–67% in shrinkage compared to the reference. The lowest values were obtained for samples B, C, and D, signifying their highest dimensional stability. Overall, the results indicate that FPBO impregnation significantly improves the dimensional stability of wood by reducing its susceptibility to shrinkage.

3.3.3. Mechanical Performance—Impact Bending Strength

All modified samples have lower mechanical properties compared with the reference radiata pine, as evidenced in Figure 5. The drop in mechanical properties is lower for

samples E and J, and those might be recommended for applications where (dynamic) mechanical strength is relevant.

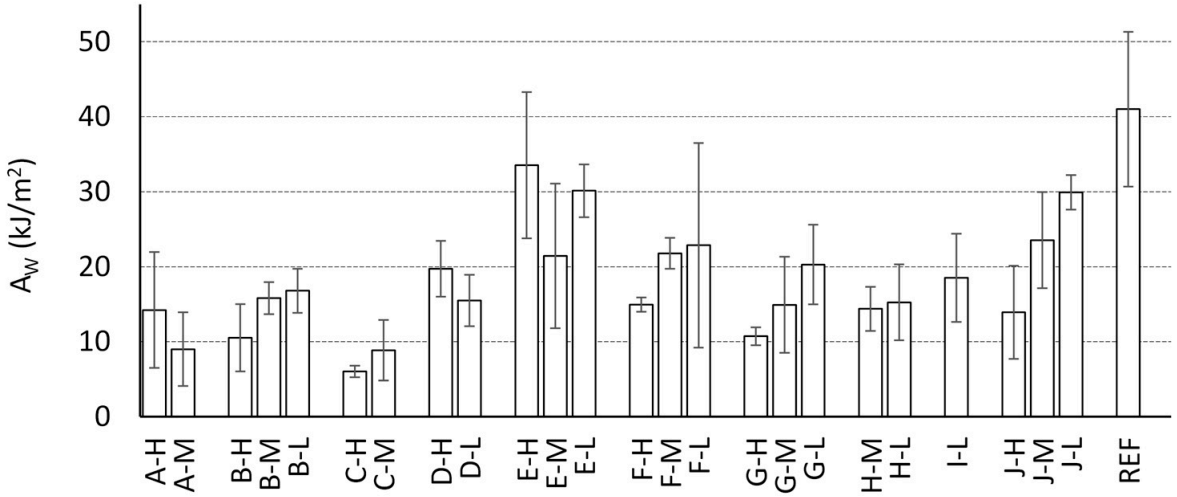

Figure 5. Impact bending strength of wood impregnated with fast pyrolysis bio-oil in relation to the weight percent gain. Note: Error bars (whiskers) represent the standard deviation of the measurements.

3.3.4. UV Stability

The color change (ΔE) after UV exposure was noticeably higher in the reference (untreated) sample, reaching a value close to 20, indicating substantial photodegradation. In contrast, all FPBO-impregnated samples exhibited significantly lower ΔE values, generally ranging between approximately 1 and 6 (Figure 6).

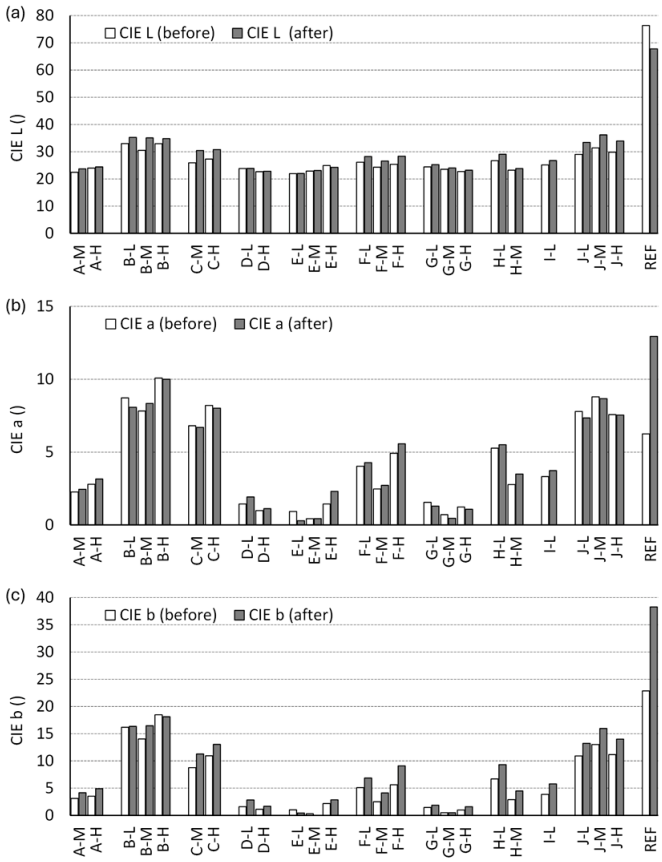

Figure 6. *Cont.*

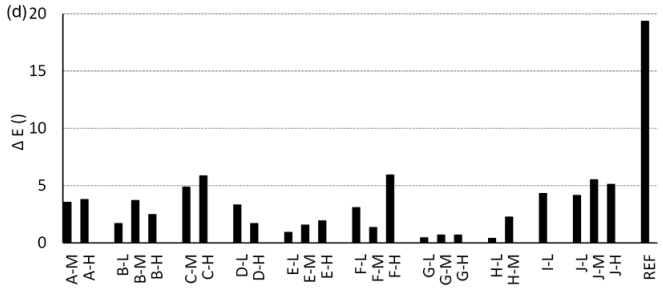

Figure 6. CIE L (**a**), CIE a (**b**), CIE b (**c**) and ΔE (**d**) colour alterations of wood impregnated with FRBO after exposure to UV radiation for 480 h.

Although some variability is observed among the modified groups, the overall reduction in color change suggests that FPBO impregnation effectively enhances resistance to UV-induced discoloration. Samples with lower Δ*E* values (<3) demonstrated particularly high color stability (G, E, and H), while a few treatments, reaching values 4 < Δ*E* < 6, indicate moderate changes. Overall, the treatment appears to mitigate photochemical degradation, contributing to improved color stability under UV exposure.

The gloss change (Δ*g*) after UV exposure was relatively small for most FPBO-impregnated samples, generally remaining within ±1% (Figure 7). This indicates that the treatment largely preserved the overall surface appearance despite irradiation. In contrast, the reference (untreated) sample showed the highest gloss increase (>2%), indicating more pronounced surface alteration under UV exposure. Overall, the FPBO-impregnated wood demonstrates more stable gloss behavior, suggesting improved resistance to UV-induced surface alterations.

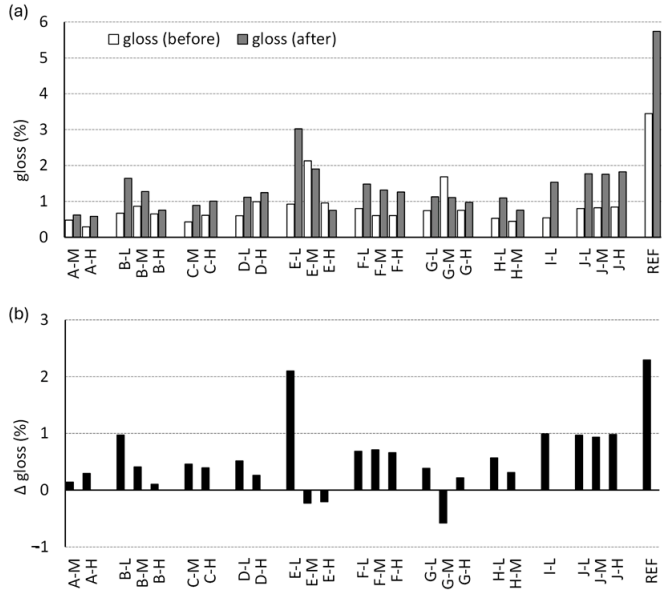

Figure 7. Surface gloss alterations of wood impregnated with FPBO after exposure to UV for 480 h; values measured before and after exposure (**a**), as well as change of gloss (**b**).

3.3.5. Volatile Organic Components Emission

To evaluate the evolution of VOC emissions over time, measurements were conducted at two distinct stages: immediately after impregnation and curing (representing the "brand new" condition), and after two months of storage in a conditioning chamber. This approach enables assessment of the temporal changes in both the magnitude and composition of VOC emissions. After 2 months of storage, the VOC emissions seem to drop by approximately a factor of 5 to 10. One exception is sample J, which revealed similar emission rates. The

sample F releases the least number of VOCs. There seems to be no correlation between the total VOC emission and the treatment effectiveness (low or intermediate). Beyond the total emission levels, it is essential to analyze the chemical composition of the emitted VOCs. Therefore, for each sample, the compounds detected at the highest concentrations were identified. These results are presented in Table 2, which provides an overview of the dominant VOCs in each sample. This information is relevant for correlating pyrolysis oil preparation conditions with VOC emission composition, enabling predictions of how specific processing routes may influence emission profiles.

Table 2. Chemical compounds of VOC emission detected in analysis of the FPBO-impregnated wood samples. Note: An "x" denotes the presence of a specific compound.

Compounds	A	B	C	D	E	F	G	H	I	J
Acetic acid	x		x	x	x	x	x	x	x	
(S)-(+)-1,2-propanediol	x	x	x	x	x	x		x	x	x
1,2-propanediol, 1-acetate	x		x	x	x	x	x	x	x	x
1,2-propanediol, 2-acetate	x		x	x	x	x	x	x	x	x
2-cyclopenten-1-one, hydroxyl-3-methyl-	x		x	x	x	x				x
1,2-propanediol, diacetate	x									x
Phenol, 2-methoxy	x	x	x	x	x	x	x	x	x	x
creosol	x	x	x	x	x	x	x	x	x	x
Phenol, 4-ethyl-2-methoxy-	x	x	x	x	x	x	x		x	x
Oxazolidin-2-one		x								
1,3-dioxolane, 2-butyl-4-methyl		x	x	x	x					
2,4-dimethylfuran			x							
Urea, (2-hydroxyethyl)			x	x	x					x
Butanoic acid, 4-hydroxy			x	x						
2(5H)-Furanone			x		x					
Furfural				x	x			x		
Eugenol				x	x					
Phenol, 2-methoxy-4-propyl				x						
Acetic anhydride					x	x	x	x		
Ethanone, 1-(2-furanyl)					x					
3-Furaldehyde						x	x		x	

3.3.6. Biological Durability

Results of the mycological tests of all samples impregnated with the FPBO are presented in Table 3. Among the tested formulations, only treatment H met the requirements for durability class 2 against brown-rot decay caused by *Rhodonia placenta*. Therefore, treatment H can be classified as durable under these conditions.

Table 3. Results of biological durability test of wood samples impregnated with FPBO solutions, including mean/median mass loss (%) and corresponding durability class.

Treatment	Brown Rot (*Rhodonia placenta*)			White Rot (*Trametes versicolor*)		
	Mean (%)	Median (%)	Durability Class	Mean (%)	Median (%)	Durability Class
A	15.5	14.9	DC3	9.6	9.7	DC2
B	27.5	25.7	DC4	19.7	19.5	DC4
C	19.5	19.7	DC4	10.4	10.7	DC3
D	17.5	18.1	DC4	13.3	14.6	DC3
E	18.7	18.5	DC4	8.7	8.6	DC2
F	17.8	18.1	DC4	11.1	12.3	DC3
G	19.8	18.8	DC4	11.6	11.4	DC3
H	13.3	11.9	DC2	9.5	9.4	DC2
I	19.5	19.1	DC4	11.0	10.9	DC3
J	18.3	18.5	DC4	9.2	8.5	DC2

In the case of white-rot decay (*Trametes versicolor*), a broader range of treatments performed well: H, A, F, and J all achieved durability class 2, indicating good resistance.

In contrast, treatment B exhibited relatively high mass loss despite limited visible mycelial coverage on the wood surface. This is the treatment exhibiting the highest leaching among all samples tested. This suggests insufficient fixation of the bio-oil compounds within the wood structure, and thus optimization of the curing protocol is recommended to reduce leaching and further improve durability performance.

3.4. Summary of Key Technical Characteristics

The overall performance of all investigated FPBO-based formulations is summarized in Table 4, which compiles the key results obtained across the full set of characterization methods applied in this study. The table integrates data on impregnation efficiency (weight percent gain and density increase), and the resulting wood performance, including moisture uptake, dimensional stability, mechanical properties, UV resistance, fixation behavior, VOC emissions, and biological durability. By presenting these parameters in a consolidated manner, the table enables direct comparison between formulations and highlights the relationships and trade-offs between different performance aspects. This comprehensive overview served as the basis for the multi-criteria assessment, allowing the identification of the three best-performing treatments (H, A, and E), which demonstrated the most balanced combination of durability, stability, environmental performance, and structural integrity.

Table 4. Summary of the key characteristics for FPBO-impregnated wood samples compared to not treated Radiata pine wood (REF). Note: WPG—weight percent gain, EMC—equilibrium moisture content, FSP—fiber saturation point. An "x" denotes the presence of a specific compound.

Property	REF	A	B	C	D	E	F	G	H	I	J
WPG_d (%)	–	41	129	89	93	85	58	70	70	58	60
Density (kg/m^3)	520 (88)	713 (24)	902 (63)	778 (50)	785 (29)	743 (56)	789 (84)	851 (99)	776 (89)	813 (40)	812 (76)
Leaching resistance (g/m^2)	-	265 (18)	930 (42)	342 (35)	449 (20)	262 (15)	316 (15)	462 (36)	316 (43)	276 (55)	318 (17)
Fixation rate (%)	-	62	46	72	67	81	70	65	75	74	72
Moisture absorption (A_w) (-)	0.21	0.38	0.19	0.32	0.31	0.32	0.29	0.29	0.29	0.29	0.30
volumetric shrinkage (%)	12	6	4	5	4	6	7	7	5	6	6
EMC at FSP (%)	18.0	14.1	15.5	12.5	12.3	10.7	10.4	10.3	10.0	12.3	15.0
Impact bending strength (kJ/m^2)	41 (10)	11 (6)	14 (3)	7 (2)	17 (3)	28 (7)	19 (5)	15 (4)	14 (4)	18 (6)	22 (5)
UV stability color (ΔE)	19.4	3.7	2.6	5.4	2.5	1.5	3.5	1.3	0.6	4.3	4.9
UV stability gloss ($\Delta gloss$)	2.3	0.2	0.5	0.4	0.4	0.6	0.7	0.4	0	1	1
Durability class (*Rhodonia*)	5	3	4	4	4	4	4	4	2	4	4
Durability class (*Trametes*)	5	2	4	3	3	2	3	3	2	3	2
Mold index (*Cladosporium*)	5	3	0	2	2	3	2	1	2	2	1
Mold index (*Aureobasidium*)	5	2	0	1	1	2	1	2	1	2	1
VOCs emission (% reduction)	-	92.6	82.1	78.8	87.2	88.8	99.4	82.8	72.4	78.8	35.9
Adlehydes						x	x	x		x	
Ketones		x		x	x	x	x				x
Alcohols		x	x	x	x	x	x		x	x	x
Esters		x		x	x	x	x	x	x	x	x
Acids		x		x	x	x	x	x	x	x	
Heterocycles			x	x	x	x			x		x
Aromatics		x	x	x	x	x	x	x	x	x	x

4. Discussion

The one-year assessment of the FPBO-based formulations demonstrates good physicochemical stability, supporting their suitability for storage and subsequent application in wood impregnation. Across all ten formulations, pH and density remained largely unchanged throughout the monitoring period. The consistently acidic pH indicates that no significant chemical degradation or neutralization reactions occurred [22], while the stable density suggests the absence of phase separation or major compositional changes, confirming that the formulations maintained their integrity during storage. In contrast, viscosity exhibited more pronounced variation, both between formulations and over time. This behavior is likely associated with slow ongoing reactions within the formulations, such as mild polymerization or structural rearrangements, which are typical for FPBO-derived systems [23]. The observed differences in viscosity trends highlight the influence of formulation composition, including the type and ratio of polyols, stabilizers, and catalysts, on these processes. Despite these variations, viscosity changes remained within an acceptable range, and all formulations stayed homogeneous and processable, confirming their practical usability after storage. The inclusion of Catalyst 2 was intended to assess whether a lower-cost catalytic system could achieve comparable performance while maintaining adequate formulation stability. Although Catalyst 2 provided acceptable homogeneity and pot life, the resulting performance was inferior to that obtained with Catalyst 1. This suggests that catalyst effectiveness is governed not only by formulation stability but also by the ability to promote the condensation and cross-linking reactions of reactive FPBO fractions. The results indicate that Catalyst 1 provided a more favorable balance between impregnation and curing, leading to improved network formation and fixation of FPBO-derived species within the wood structure.

The absence of phase separation during storage and the lack of visible leaching after curing further underline the physical stability and compatibility of the formulations. These are critical factors for wood impregnation applications, where uniform penetration and retention within the wood structure are essential.

In addition to storage stability, the performance of the formulations during wood impregnation was evaluated through density changes and *WPG*. The increase in density relative to untreated reference samples reflects the successful incorporation of formulation components into the wood structure. Variations in density and *WPG* among formulations indicate that formulation composition significantly influences impregnation efficiency and retention [24]. Properties such as viscosity, polarity, and chemical reactivity likely govern the ability of the formulations to penetrate and fix within the wood matrix [25]. Higher *WPG* values generally correspond to greater uptake, which may enhance the functional performance of the treated wood, although this also depends on curing behavior and the uniformity of distribution within the material [26]. The observed variability between samples may additionally be influenced by the natural heterogeneity of radiata pine, which can affect permeability and uptake.

Overall, the results show that all formulations are suitable for wood impregnation, while also demonstrating that their performance can be tuned through careful formulation design. By adjusting composition, it is possible to control both storage stability, particularly viscosity evolution, and impregnation characteristics, enabling optimization for specific application requirements.

The observed high leaching in sample B suggests inadequate fixation of the impregnated components within the wood structure. Since the leaching of impregnation solution is undesirable, as it reduces durability and long-term performance, these results highlight the importance of optimizing treatment conditions [27]. It was initially assumed that increasing curing temperature or extending curing duration could improve fixation by enhancing the

bonding or polymerization of impregnates within the substrate [28]. However, the elevated leaching in Sample B indicates that its processing conditions were insufficient to achieve stable incorporation of the treatment chemicals. The *WPG*-based classification further supports the relationship between impregnation level and leaching behavior. Samples with higher *WPG* generally showed better retention, suggesting that greater uptake may contribute to improved fixation [28], although it does not guarantee it alone. This implies that both impregnation efficiency and curing parameters must be carefully controlled to minimize leaching and ensure long-term stability of the treated wood. Overall, the results emphasize that optimizing curing conditions is critical but must be considered alongside impregnation level to effectively reduce leaching of active components.

The observed differences in dimensional stability have direct implications for the performance of wood used in exterior cladding applications. Materials employed as cladding are routinely exposed to fluctuating moisture conditions, leading to repeated cycles of swelling and shrinkage that can induce internal stresses, surface checking, and deformation [29]. In this context, the lower radial, tangential, and volumetric changes recorded for samples B, C, and D indicate a reduced susceptibility to such moisture-driven movements. This enhanced stability is particularly advantageous for maintaining dimensional integrity and preserving the visual appearance of façade elements over time. In case impregnated wood is further protected by surface treatment, improved dimensional stability contributes to longer service life by reducing coating degradation and limiting pathways for moisture ingress [30]. Therefore, samples B, C, and D appear to be more suitable candidates for wooden cladding applications, especially in environments characterized by pronounced humidity variations.

Impact bending was selected as a relevant mechanical test because wooden cladding and utility poles (considered as secondary applications) are both subjected to sudden and dynamic loading events in service, such as windborne debris, handling damage during installation, and impact from falling objects or environmental hazards, making resistance to shock loading a critical performance criterion [31]. The results indicate a clear compromise between mechanical performance and enhanced surface durability of the modified wood. All treated samples exhibited reduced mechanical properties compared to untreated radiata pine, suggesting that the impregnation and curing processes, as well as the incorporation of FPBO-based formulations, may alter the structural integrity of the wood matrix. Such reductions are commonly reported in the literature for chemically or thermally modified wood, where changes in cell wall composition, partial degradation of structural polymers, or increased brittleness can occur [32]. However, the extent of mechanical property loss varied between formulations. Samples E and J showed comparatively smaller reductions, indicating that formulation composition and processing conditions play a crucial role in preserving structural performance. These samples may therefore represent a more balanced compromise between modification and mechanical integrity, making them more suitable for applications where load-bearing capacity remains important. Similar findings have been reported in studies on bio-based wood treatments, where optimized formulations can mitigate strength losses while still providing functional benefits [33,34].

In contrast to the mechanical behavior, all modified samples demonstrated improved resistance to UV-induced degradation, as evidenced by enhanced color and gloss stability compared to untreated radiata pine. The initial color of all treatments was found to be quite similar, indicating a relatively uniform visual appearance before any treatment effects. This improvement is consistent with previous studies showing that bio-oil-derived treatments and other lignin-rich or aromatic systems can act as UV stabilizers by absorbing radiation and reducing photodegradation of wood components [35–37]. Notably, samples G, E, and H exhibited minimal changes in appearance after UV exposure, highlighting their superior

resistance. The combination of improved aesthetic stability and reduced photodegradation suggests potential for enhanced weathering performance in exterior applications where visual durability is important. Literature on exterior wood performance emphasizes that color stability is a key factor influencing service life and maintenance requirements [38–41]. In this context, the enhanced UV resistance of the modified samples represents a clear advantage over untreated wood. However, accelerated laboratory aging cannot fully replicate natural weathering conditions, and therefore, long-term outdoor exposure studies are required to confirm the durability benefits observed in this work.

Overall, the findings align with existing research indicating that wood modification often involves balancing mechanical performance with durability enhancements [42]. The results suggest that, through careful formulation design, it is possible to tailor FPBO-based treatments to achieve improved weathering resistance while minimizing the loss of mechanical properties, thereby expanding the range of potential applications.

The VOC emission measurements provide important insight into the environmental and long-term performance of the modified wood. It is noteworthy that FPBO-treated wood exhibits a strong barbecue-like odor, which may not be well received by end users or customers. The observed decrease in emissions by a factor of 5 to 10 after two months of conditioning indicates that a significant portion of volatile compounds is released shortly after impregnation and curing. This behavior is consistent with findings in the literature on bio-based wood treatments, where readily volatile fractions evaporate during early stages, followed by a stabilization phase with substantially lower emissions [43]. From a practical perspective, this suggests that a conditioning or aging period prior to end-use could effectively reduce VOC-related concerns and reduce undesirable smell.

VOC emissions from the treated wood decreased noticeably within two months after production, indicating a progressive reduction in volatile release over time, likely associated with post-curing processes and depletion of residual low-molecular-weight compounds [44,45]. The absence of a clear correlation between total VOC emissions and treatment intensity (low vs. intermediate) indicates that emission behavior is more strongly governed by formulation chemistry. This is further supported by the differences observed between samples, such as consistently low emissions from sample F and the relatively unchanged emissions in sample J over time. Such variability highlights the importance of formulation design, particularly the composition of the pyrolysis oil and additives, in controlling both the type and quantity of emitted compounds [46]. The identification of the dominant VOC species (Table 2) provides an additional layer of understanding, as it enables linking emission profiles to specific pyrolysis oil production conditions. The dominant VOCs detected were primarily organic acids, glycol derivatives, furans, and methoxyphenols originating from FPBO. The methoxyphenolic compounds, particularly guaiacol and related alkyl-substituted derivatives, are likely responsible for the characteristic smoky odor observed in freshly treated specimens [47]. Across all formulations, a range of organic compounds was detected, including organic acids (acetic acid, butanoic acid), glycols (1,2-propanediol and its acetate derivatives), furan-based compounds (furfural, 3-furaldehyde, 2,4-dimethylfuran, 2(5H)-furanone), phenolic compounds (2-methoxyphenol, 4-ethyl-2-methoxyphenol, 2-methoxy-4-propylphenol, creosol, eugenol), as well as other oxygenated species such as acetic anhydride, oxazolidin-2-one, and various esterified intermediates. From a health and environmental perspective, the most relevant emissions are the phenolic compounds and furan derivatives, particularly furfural and substituted phenols, due to their known irritant properties and potential toxicity at elevated exposure levels [48]. Acetic anhydride and low-molecular-weight organic acids such as acetic acid may also contribute to short-term sensory irritation [49], although they are generally less persistent in the environment. Overall, the observed decline in VOC emissions over time

suggests improved emission stability, while the remaining compound profile indicates that phenolic and furan-based species are the primary contributors to potential health and environmental concern in the treated materials. Literature suggests that the presence of certain compounds, such as phenolics or low-molecular-weight oxygenates, can influence not only emissions but also reactivity and fixation within the wood structure [50]. Therefore, tailoring the chemical composition of the formulations could be a key strategy to simultaneously optimize emission characteristics and material performance.

When considered alongside durability results, an interesting relationship emerges between VOC emissions, impregnation solution fixation, and biological resistance. Treatment H, which fulfils the requirements of durability class 2 against brown rot (*Rhodonia placenta*), demonstrates that effective fixation and resistance to degradation can be achieved with appropriately designed formulations. Similarly, treatments H, A, F, and J showed good resistance to white rot (*Trametes versicolor*), indicating that sufficient incorporation and stabilization of active components within the wood matrix can enhance biological durability [29]. However, the case of treatment B highlights the complexity of this relationship. Despite relatively high mass loss, the low mycelial coverage suggests that biological activity may have been limited, potentially due to leaching of active components rather than their absence. This supports the earlier observation that insufficient curing and fixation can lead to loss of protective substances, negatively affecting durability [51]. In this context, VOC emissions, leaching behavior, and durability are interconnected: inadequate fixation may result in both higher emissions (especially at early stages) and reduced long-term resistance due to the depletion of active compounds. Overall, the results emphasize that optimizing FPBO-based wood treatments requires a holistic approach. Reducing VOC emissions over time, ensuring adequate fixation to minimize leaching, and achieving high biological durability are closely linked objectives. By controlling formulation chemistry and curing conditions, it is possible to design systems that not only exhibit low emissions after conditioning but also provide durable protection against biological degradation, thereby enhancing their suitability for practical applications.

The comprehensive evaluation of FPBO-based formulations demonstrates that their performance in wood modification is governed by a complex interplay between formulation chemistry, impregnation efficiency, curing conditions, and long-term stability. While all investigated systems showed satisfactory storage stability and suitability for impregnation, clear differences emerged when considering key performance indicators such as moisture uptake, dimensional stability, WPG, mechanical strength retention, UV resistance, fixation efficiency, and VOC emission behavior. Among the tested variants, treatments H, A, and E consistently exhibited the most balanced and favorable performance across these criteria. These formulations combined effective impregnation and fixation, reflected in adequate density increase and low leaching, with improved dimensional stability and reduced moisture sensitivity, while maintaining comparatively better mechanical integrity. In addition, they demonstrated superior resistance to UV-induced degradation, ensuring enhanced visual durability, and showed acceptable VOC emission profiles after conditioning, indicating their environmental suitability. Importantly, the strong fixation of active components in these treatments is further supported by their enhanced biological durability, as confirmed by laboratory tests against fungi and molds. The superior performance of formulations H, A, and E is attributed not only to their favorable physical properties but also to their curing behavior. Stabilizers help maintain formulation homogeneity during impregnation, preventing phase separation and enabling uniform penetration of reactive FPBO fractions into the wood structure. The catalyst promotes curing through condensation and cross-linking reactions among carbohydrate- and lignin-derived components, while still allowing sufficient time for deep impregnation before extensive network formation occurs. As

curing progresses, a cross-linked polymer network is formed and immobilized within the wood cell walls and lumina. Consequently, the optimized stabilizer-catalyst combination is believed to enhance FPBO fixation, improve retention, and contribute to the overall performance observed for formulations H, A, and E. Altogether, these results highlight that treatments H, A, and E represent the most promising candidates for advanced wood protection systems. More broadly, the study confirms that optimizing FPBO-based formulations requires an integrated approach, where durability, environmental performance, and structural functionality are addressed simultaneously to achieve high-performance, application-ready modified wood materials.

5. Conclusions

FPBO-based wood modification presents several important advantages over conventional preservative systems, particularly in terms of sustainability, functionality, and potential for further performance optimization. Unlike traditional preservatives, which often rely on metal-based or synthetic biocides, FPBO formulations are derived from renewable resources and enable a more environmentally aligned approach while still providing effective protection. In addition to their biobased origin, these systems offer multifunctionality: beyond biological resistance, they contribute to improved dimensional stability, reduced moisture uptake, and enhanced UV resistance, which are not always simultaneously achieved with conventional treatments. The ability to tailor formulation composition further allows precise control over impregnation process, fixation, and emission profiles, representing a significant advancement in wood protection technology. Based on comprehensive analysis, treatments H, A, and E are recommended as the most promising candidates for future upscaling and testing, as they demonstrated the best overall balance between durability, mechanical performance, fixation efficiency, and environmental behavior. These formulations should be prioritized for extended field trials and long-term exposure studies to validate their performance under real service conditions. However, several limitations and challenges remain. The observed reduction in mechanical properties across treated samples highlights the need for further optimization to minimize strength losses. Additionally, variability in viscosity evolution and its impact on processing consistency, as well as the sensitivity of fixation to curing conditions, indicate that process control remains critical. VOC emissions, although significantly reduced after conditioning, still require careful consideration due to the presence of phenolic and furan-based compounds. In addition, although the accelerated UV aging results indicate improved resistance to photodegradation, long-term outdoor exposure studies are required to confirm the durability benefits under natural weathering conditions. Finally, the inherent heterogeneity of wood and its influence on impregnation uniformity introduce an additional level of variability that must be addressed when scaling up. Overall, while FPBO-based systems show strong potential as next-generation wood modification solutions, further refinement of formulation design and processing parameters is necessary to fully overcome these challenges and ensure reliable industrial application.

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