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Effects of Different Orientations and Treatments in an Outdoor Natural Aging of Japanese Cryptomeria and Scots Pine Wood

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Abstract

Wood is an excellent material in terms of sustainability; however, for durability reasons, it is critical to understand its aging over time, especially in outdoor spaces. Maximizing the lifespan of outdoor timber requires identifying the primary drivers of early-stage deterioration. This understanding ensures the selection of the most effective treatment and maintenance strategies. For this purpose, a natural aging exposure test was conducted on 32 samples of Cryptomeria wood and Scots pine, with 4 different solar orientations and 4 treatments, in a coastal area. To assess material behavior during the early stages of exposure without maintenance intervention, degradation was recorded over the initial 2 years of exposure. Those records were made based on visual analyses and classification tables for abiotic and biotic degradation, complemented by colorimetry to determine the specific effects of UV-induced photodegradation. The results obtained underline the importance of anti-tannin impregnation in the treatment process and demonstrate that treated pine wood shows greater color variations than treated Cryptomeria wood. This study reaffirms the indispensability of wood protection systems and suggests that reapplication must occur early in the service life to mitigate initial deterioration.

Keywords: wood aging; natural degradation; solar exposure; coastal environment; protective treatments

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1. Introduction

Wood is a natural and sustainable material, especially due to the low energy consumed in its production, but also because it is renewable [1]. The viability of wood as a construction material is fundamentally contingent upon its aging characteristics and inherent durability. While suitable for both interior and exterior applications, its performance under external exposure requires a comprehensive understanding of long-term material behavior [2]. Establishing effective maintenance protocols during a building's operational phase necessitates a precise analysis of degradation rates and the primary environmental drivers influencing the decay process [3].

During outdoor weathering, changes occur in molecular and anatomical structure, according to Reinprecht et al. [4] and Almeida et al. [5,6], accompanied by geometric structural changes that result in surface erosion, the creation of cracks (whether micro or macro) and darkening, for example. According to the same authors, in a study they conducted on seven tropical woods, the creation of visible cracks on the upper surfaces of tropical woods was influenced by their density and specific anatomical structure. The study of Kataoka et al. [7] states that the density of wood is strictly linked to its predisposition to degradation, since it has been concluded that the denser the wood, the shallower the depth of photo degradation. Thus, the density of the wood under study will directly influence its reaction to photo degradation and the creation of cracks [8,9].

Accelerated aging tests of wood, being simulated in the laboratory, allow for better control of ultraviolet radiation, temperature, and humidity. However, although accelerated aging allows for a quicker acquisition of results, several differences are recorded concerning natural degradation, and its results tend to be less severe, so they may not be as reliable, especially in the long term [10–13]. Furthermore, numerous extraneous variables influence degradation in natural environments—including seasonal fluctuations, atmospheric pollutants, and specific chemical constituents such as airborne acids and salts —which are frequently omitted from artificial weathering protocols. Consequently, the longitudinal study of wood subjected to natural environmental exposure remains imperative for a comprehensive understanding of material longevity.

The deterioration of wood is accelerated by a complex interplay of abiotic and biotic agents. Among the abiotic factors, solar radiation induces distinct modes of degradation; while lower energy wavelengths may affect polymeric components at the molecular level, ultraviolet (UV) radiation specifically initiates the depolymerization of lignin [14]. This structural alteration significantly compromises the material's surface integrity and mechanical resistance. Under the influence of ultraviolet (UV) radiation, the interfibrillar bonds within the cellulose matrix weaken, leading to the detachment of fibers and a concomitant loss of mechanical properties [6,15,16]. Macroscopically, this photodegradation results in gray discoloration and surface cracking [17]. By increasing the substrate's surface area and moisture absorption, these structural defects create a hospitable microenvironment for subsequent microbial or insect colonization [16].

Biotic agents tend to be more harmful to wood than abiotic ones because they directly impact on its cellular structure, leading to a decrease in mass and section size [4,13,18,19]. The primary biotic agents include organisms from the plant kingdom, such as bacteria and wood-decaying fungi, as well as agents from the animal kingdom, like wood-boring insects [20–22]. The damage caused by these agents can be detected in various forms, depending on the type of agent, and may manifest as small circular holes or a whitish, fibrous texture [23–26]. According to Martin et al. [27] the larval development period within wood ranges from 3 to 5 years, highlighting the necessity of preventive treatments early in the wood's life and regular maintenance at shorter intervals. Several treatments, including varnishes, lacquers, protectors, and paints, can be applied to the wood's surface, serving both protective and decorative purposes [28–30].

The wood exposed to the air changes color very quickly; usually, dark woods tend to lighten and light woods tend to darken [15,16,31]. This color change occurs after a few months, varying greatly depending on the species of wood, as demonstrated by the study conducted by Feist W. [15], but all the exposed species changed color to brown and gray after 6 months of exposure, highlighting that the great color variation occurred between 3 and 4 months of exposure. This color variation can be analyzed with the help of a measuring instrument, the colorimeter, which can help characterize these color changes and even help record impacts resulting from the action of abiotic agents on the wood [4,32].

The degree of natural wood degradation varies significantly by geographic location. Research conducted by Jérôme Vuillemin [33] in the Southern Hemisphere indicates that tropical environments are highly conducive to degradation mediated by biotic agents. Conversely, in Central Europe, abiotic factors typically initiate the decomposition process, with perceptible chromatic alterations occurring as early as the first month of exposure.

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To investigate the performance of timber cladding on coastal building envelopes, an in situ experimental study was conducted to evaluate the degradation of two wood species, allowing the performance of a comparative analysis between both, thereby enriching and broadening the scope of the results obtained. The experiments were performed under realistic field conditions to generate empirical data. The results could be an important tool to validate the accelerated weathering tests and protocols, relevant for more durability studies. Moreover, the multifactorial analysis, incorporating two wood species, different sample orientations, and several treatment methods, allows for a detailed evaluation of the individual and interacting effects of the variables considered.

The study utilized specimens of Japanese Cryptomeria and Scots pine (Pinus sylvestris), with mean densities of 0.360 g/cm^3 and 0.549 g/cm^3, respectively [13,20,34,35]. These density values are consistent with values previously reported in the literature. These specimens were subjected to natural weathering processes in Viana do Castelo, a location characterized by its proximity to the Atlantic Ocean and distinct maritime atmospheric conditions.

To evaluate the progression of material decay, periodic inspections were conducted, necessitating a systematic examination of the timber components to identify and document all manifestations of deterioration. Such regular monitoring facilitates early-stage intervention, thereby mitigating structural risks and extending the service life of the elements [36].

Regarding assessment methodologies, there is currently no unified European standard for visual inspection that harmonizes the measurement of degradation parameters. Existing visual grading scales, such as those delineated in the Portuguese standard NP EN 338, primarily prioritize mechanical strength and structural integrity rather than esthetic or surface degradation (EN 338:2009—Structural timber; Strength classes, Brussels: CEN, 2009) [37].

2. Description of Tested Specimens and Weather Conditions

2.1. Characterization of the Specimens and Exposure Orientation

The wooden specimens were exposed to an outdoor environment typical of the Portuguese Atlantic coast. For this purpose, the specimens were placed on the accessible flat roof of the sustainable building of the School of Technology and Management of the Polytechnic Institute of Viana do Castelo (IPVC) at an altitude of around 10 m. The structure maintains a direct proximity to the coastline, located roughly 150 m from the sea (Figure 1a).

To measure the experimental environmental conditions, a combined temperature and humidity sensor was placed in the middle of the roof terrace area (Figure 1b). A total of 32 specimens were installed, comprising 16 units of Japanese Cryptomeria and 16 units of Scots pine (Pinus sylvestris). The Cryptomeria specimens measured 375 × 145 × 20 mm, while the Scots pine specimens measured 160 × 40 × 40 mm.

To understand how solar orientation affects the degradation of wood over time, the various types of test specimens were placed with the largest face vertically, according to the 4 orientations corresponding to the four façades of the building. As the specimens were fixed to the roof terrace accessible from the inside, the specimens placed on the north terrace are those considered to be exposed to the south (Figure 1c).

The test specimens were then named according to their exposure orientation: north, south, east, and west. However, since the building has a northerly deviation of around 20° to the west, it is important to clarify that the specimens are in fact exposed to the north-northwest, east-northeast, south-southeast, and west-southwest, respectively. However, to simplify the description, the orientations of the specimens will now be referred to as N, S, E, and W, respectively.

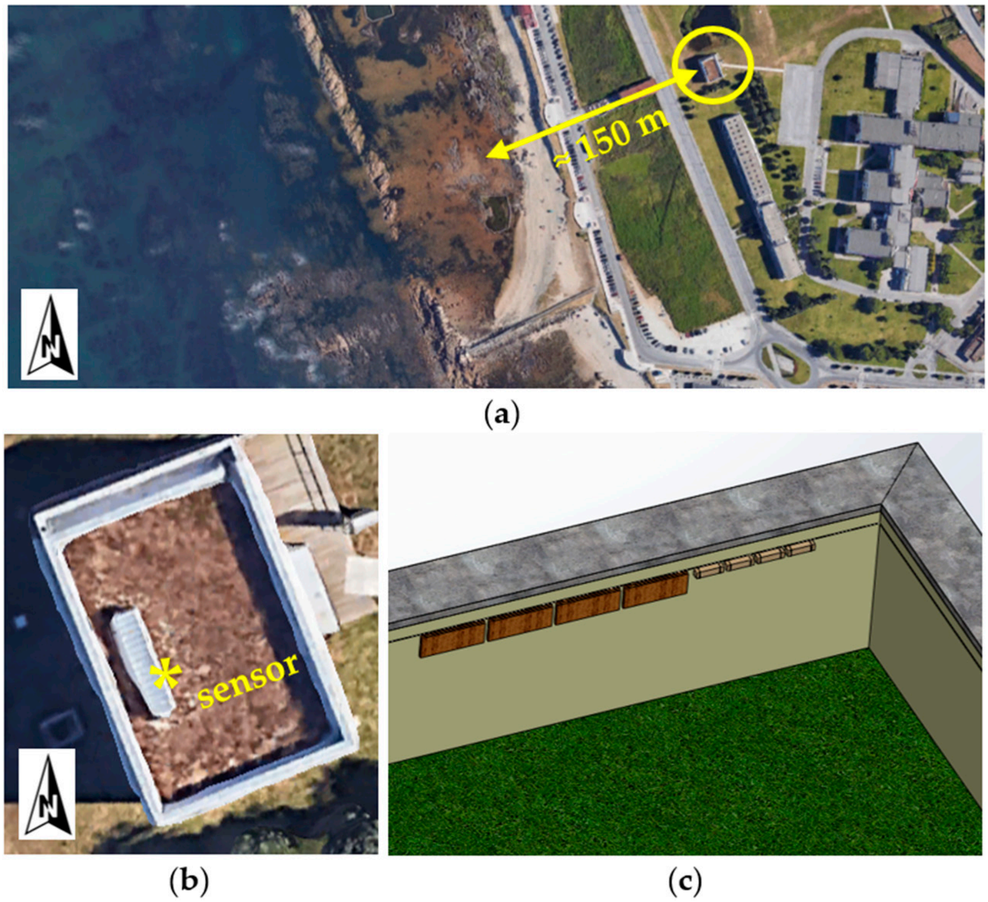

Figure 1. Test conditions in the sustainable building at IPVC: (**a**) Plant location; (**b**) zoom of the roof terrace with temperature and humidity sensor location (*); (**c**) 3D scheme of specimens orientation with south exposure.

The test specimens were coated with 4 different "treatments":

- Treatment O: The original wood was placed without any treatment;
- Treatment B: Wood with biocide;
- Treatment 3: 1st coat of biocide; 2nd coat of anti-tannin impregnant; 3rd and 4th coats of colored varnish, and then, an application of a top sealer;
- Treatment 4: 1st coat of biocide; 2nd, 3rd, and 4th coats of colored varnish. A top sealer was also applied.

The 32 specimens were then named according to the following scheme, corresponding to a sample for each kind of wood/treatment/orientation:

- 1st place: initial of the wood under study (C—Cryptomeria; P—Pine);
- 2nd place: treatment letter or number (O, B, 3, 4);
- 3rd place: solar exposure concerning the building (N, S, E, W).

For example, the specimen coding system is exemplified by the label POS, representing an untreated Pine sample with a southern orientation.

The applied treatments were identical for both wood species. To facilitate comparative visual analysis throughout the study, a systematic photographic record was maintained from the inception of the experiment. The baseline appearances of the 16 Japanese Cryptomeria specimens and the 16 Scots pine specimens are documented in Figure 2 and Figure 3, respectively.

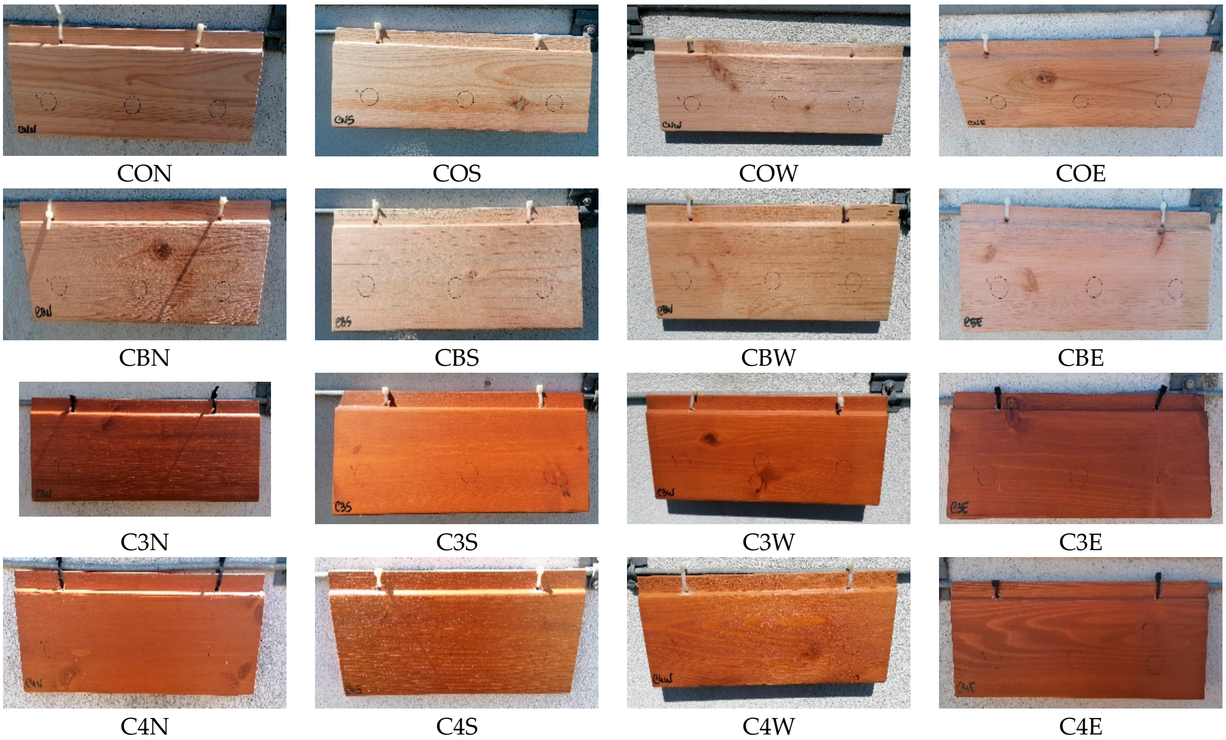

Figure 2. Initial photographs of the Cryptomeria specimens.

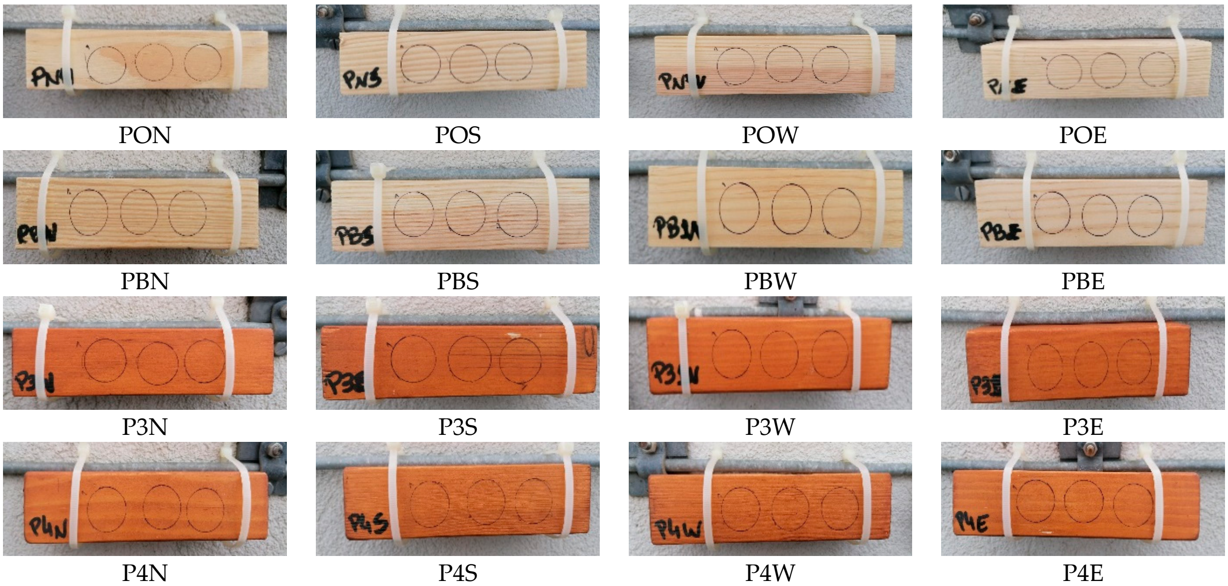

Figure 3. Initial photographs of Scots pine specimens.

2.2. Weather Conditions in the Test Area

In Viana do Castelo, a city located on the Atlantic coast of northern mainland Portugal, the climate is mild. According to the climate chart for the region provided by IPMA [38] the mean annual daily temperature is 14.8 °C, with a diurnal range of approximately 10 °C; these thermal conditions are considered moderate, posing limited demands on the dimensional stability of exterior timber and the performance of surface treatments. Conversely, the region records 2369.2 annual sunshine hours and a substantial mean annual precipitation of 1470.2 mm. Coupled with a high average relative humidity of 82%, these environmental factors significantly elevate the risk of biological degradation for exposed wood elements [39–41].

2.3. Temperature and Humidity Recording at the Test Site

To ensure a precise record of the environmental conditions during the experimental period, a combined temperature and humidity sensor was deployed at the test site with an east orientation, in the middle of the roof area (see Figure 1b). The resulting longitudinal data for temperature and relative humidity are presented in Figures 4 and 5, respectively. Monitoring was conducted across three distinct intervals: July 2022–March 2023, May 2023–October 2023, and March 2024–July 2024. The environmental data, covering all months of the year across two different years, allows the natural seasonal variability of the site to be adequately captured. In any case, the samples remained exposed on the test site for the entire two years.

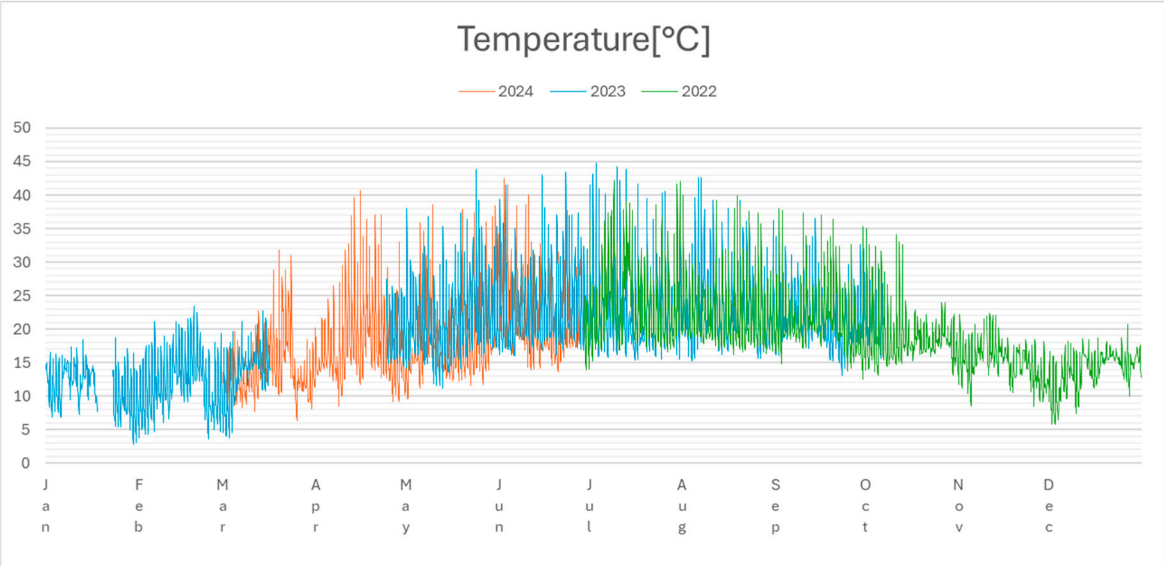

Figure 4. Temperature variation at the sensor between late June 2022 and early July 2024.

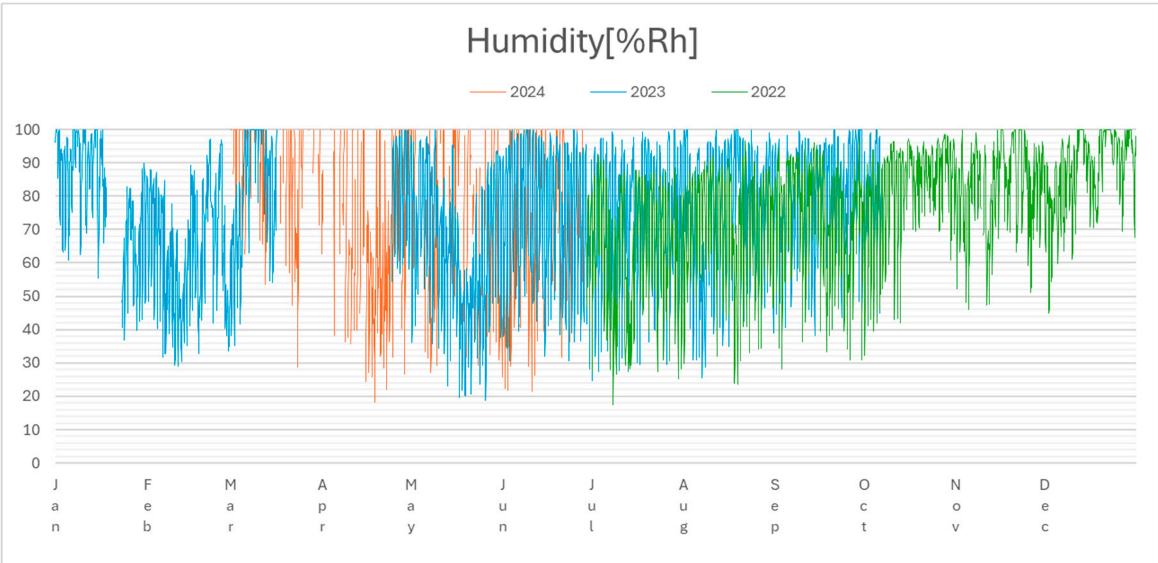

Figure 5. Relative humidity variation at the sensor between the end of June 2022 and the beginning of July 2024.

Environmental monitoring throughout the test period revealed a mean temperature of 17.9 °C, with a total thermal amplitude of approximately 42 °C. Notably, no sub-zero temperatures were recorded. The mean relative humidity was 76.3%, exhibiting a broad range of 82.6%, varying from saturation (100%) to a minimum of 17.4%. These climatic parameters are summarized in Table 1.

Table 1. Measured temperature and relative humidity profiles at the building site over the registered period.

	Temperature (°C)	Relative Humidity (%)
Average	17.9	76.3
Min.	2.8	17.4
Max.	44.8	99.9
Range	42.0	82.5

3. Evaluation and Testing Methods

The test consisted of exposing the various wooden specimens to the conditions described above and recording the respective changes over different exposure times.

3.1. Wetting Condition for Aging Assessment

To facilitate a comprehensive analysis of degradation mechanisms under natural weathering, precipitation frequency was recorded during the initial five-month exposure period. Table 2 summarizes the distribution of dry (D) and wet (W) days during this phase. Within this interval, dry conditions prevailed for 97 days (63%), while precipitation occurred on 56 days (37%) [38]. It is anticipated that these proportions will invert during the winter season due to regional climatic patterns.

Table 2. Weather and rainfall records during the test phase—June to November 2022.

Month\Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	**Total**
June	D	D	D	D	D	D	W	W	D	D	D	D	D	W	D	W	D	W	W	D	W	W	W	W	W	D	D	W	W	D	---	17 D; 13 W
July	D	D	W	D	D	W	D	D	D	D	D	W	D	W	D	D	D	D	W	W	D	D	D	W	D	D	D	W	W	D	D	22 D; 09 W
August	D	D	D	W	D	D	D	D	D	D	D	W	D	D	W	W	D	D	D	D	D	D	D	D	W	D	D	D	D	D	D	26 D; 05 W
September	D	D	D	D	W	W	W	W	D	D	D	W	W	W	W	D	D	D	D	D	W	D	D	D	D	D	D	W	W	D	---	19 D; 11 W
October	D	D	D	D	D	D	D	D	W	W	D	D	D	D	D	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	13 D; 18 W

3.2. Color Measurement

Ultraviolet radiation changes wood over time. The change in color of the wood under analysis was studied using measurements made with a Konica/Minolta colorimeter with the reference "Chroma Meter CR-400". The colorimeter used specifies color based on the CIELab system [42–44]. To evaluate colorimetric variations across different zones, the 1976 CIELAB, formulationwas utilized. While subsequent iterations offer enhanced accuracy, the standard was selected to streamline the computational process without compromising the fundamental analysis. Consequently, color shifts recorded by the colorimeter are quantified in terms of Just Noticeable Difference (JND) units, calculated according to the following equation [43]:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}, \text{ (JND)} \quad (1)$$

where:

ΔL^* represents the difference between the brightness of the parts;

Δa^* represents the difference between the magenta and green values;

Δb^* represents the difference between the yellow and blue values.

Long-term environmental exposure results in the graying of wood elements. This colorimetric shift is quantified by a decrease in L^*, representing surface darkening, and a reduction in *a** and *b** values toward the achromatic point (zero) [11]. These changes indicate a decline in red and yellow chromaticity as the surface layer degrades.

To be able to catalog the color variation ΔE^* between different specimens and between different time instants, it was used the Cui et al. [45], which establishes five levels of color change perceived by the human eye:

$0 < \Delta E^* < 0.5$—These colorimetric shifts are imperceivable to the human eye;

$0.5 < \Delta E^* < 1.5$—the color change is slightly perceptible;

$1.5 < \Delta E^* < 3.0$—the color change is barely perceptible;

$3.0 < \Delta E^* < 6.0$—the color change is noticeable;

$6.0 < \Delta E^* < 12.0$—the color change is very noticeable;

$\Delta E^* > 12.0$—the color change was total.

To establish a baseline for comparison, the unaged CIELAB coordinates were recorded for both wood species. Tables 3 and 4 present these baseline values for the Japanese Cryptomeria and Scots pine specimens, respectively. To ensure representative color values, each data point represents the arithmetic mean of three independent measurements taken across different surface zones (physically marked with three circles) on each specimen. All color measurements were performed with the samples under dry conditions.

Table 3. Initial CIELAB data for Cryptomeria specimens.

Speciments		*Zone 1*			*Zone 2*			*Zone 3*			*Average Values*		
		L	*a*	*b*	*L*	*a*	*b*	*L*	*a*	*b*	*L*	*a*	*b*
Treatment O	**CON**	72.96	7.67	24.20	71.31	7.86	23.40	72.56	7.84	24.94	**72.28**	**7.79**	**24.18**
	COS	72.66	7.63	23.71	70.34	7.95	24.56	68.90	8.86	25.01	**70.63**	**8.15**	**24.43**
	COW	69.68	8.71	19.10	69.12	8.09	18.75	70.99	7.66	19.26	**69.93**	**8.15**	**19.04**
	COE	64.78	10.14	21.16	65.93	9.89	21.60	64.64	10.53	22.78	**65.12**	**10.19**	**21.85**
Treatment B	**CBN**	69.73	11.42	24.23	71.06	11.11	23.78	68.67	11.12	23.17	**69.82**	**11.22**	**23.73**
	CBS	68.61	8.57	20.63	68.03	7.44	20.10	68.20	8.16	18.86	**68.28**	**8.06**	**19.86**
	CBW	66.12	11.93	26.06	67.46	11.12	26.80	65.86	10.89	26.47	**66.48**	**11.31**	**26.44**
	CBE	71.94	9.96	23.42	71.31	9.50	22.60	70.79	9.12	21.49	**71.35**	**9.53**	**22.50**
Treatment 3	**C3N**	46.07	19.83	28.11	46.29	19.99	28.58	46.12	20.14	28.41	**46.16**	**19.99**	**28.37**
	C3S	50.98	20.83	33.94	47.98	21.03	31.13	43.86	19.89	25.84	**47.61**	**20.58**	**30.30**
	C3W	48.03	20.40	28.57	47.67	20.78	20.88	46.76	20.38	29.32	**47.49**	**20.52**	**26.26**
	C3E	48.01	20.31	30.75	46.24	19.91	28.37	46.84	19.22	28.53	**47.03**	**19.81**	**29.22**
Treatment 4	**C4N**	46.20	18.38	29.06	47.02	18.65	29.54	49.68	18.39	31.83	**47.63**	**18.47**	**30.14**
	C4S	46.47	17.20	27.51	46.92	18.58	28.94	48.24	17.95	29.91	**47.21**	**17.91**	**28.79**
	C4W	43.92	17.63	25.19	45.78	17.26	27.08	46.98	17.70	28.35	**45.56**	**17.53**	**26.87**
	C4E	44.07	16.57	24.35	45.78	17.62	27.02	45.12	16.68	25.79	**44.99**	**16.96**	**25.72**

Table 4. Initial CIELAB data for Scots pine specimens.

Speciments		*Zone 1*			*Zone 2*			*Zone 3*			*Average Values*		
		L	*a*	*b*	*L*	*a*	*b*	*L*	*a*	*b*	*L*	*a*	*b*
Treatment O	**PON**	81.00	3.49	25.96	73.55	7.80	31.17	73.54	7.59	30.36	**76.03**	**6.29**	**29.16**
	POS	78.48	4.83	24.67	77.11	5.45	25.37	78.65	4.81	24.58	**78.08**	**5.03**	**24.87**
	POW	76.64	6.95	23.02	80.42	4.64	23.14	79.77	4.73	23.68	**78.94**	**5.44**	**23.28**
	POE	82.36	3.03	23.16	82.13	3.16	23.04	82.69	2.86	23.91	**82.39**	**3.02**	**23.37**
Treatment B	**PBN**	72.47	5.43	29.04	72.32	5.50	29.34	72.66	5.53	29.33	**72.48**	**5.49**	**29.24**
	PBS	76.06	6.94	26.06	77.40	6.72	26.27	76.75	6.99	24.46	**76.74**	**6.88**	**25.60**
	PBW	78.97	4.99	29.81	78.22	5.39	31.78	76.40	6.17	30.30	**77.86**	**5.52**	**30.63**
	PBE	81.40	3.53	23.81	83.72	3.01	23.68	83.91	2.62	23.42	**83.01**	**3.05**	**23.64**
Treatment 3	**P3N**	50.25	21.28	35.32	52.20	21.94	38.17	53.29	21.29	38.96	**51.91**	**21.50**	**37.48**
	P3S	52.64	21.03	36.36	52.22	20.71	36.00	51.56	19.72	34.47	**52.14**	**20.49**	**35.61**
	P3W	53.91	20.98	39.23	53.94	20.77	38.72	52.53	20.86	37.69	**53.46**	**20.87**	**38.55**
	P3E	53.77	20.55	38.49	53.76	21.18	39.27	53.93	20.67	39.20	**53.82**	**20.80**	**38.99**
Treatment 4	**P4N**	56.38	18.72	39.48	53.74	19.34	37.64	55.51	18.49	38.60	**55.21**	**18.85**	**38.57**
	P4S	55.10	18.22	37.61	55.33	17.93	37.56	55.86	17.30	37.44	**55.43**	**17.82**	**37.54**
	P4W	54.34	18.87	36.50	54.91	18.50	36.79	54.70	18.65	36.54	**54.65**	**18.67**	**36.61**
	P4E	56.26	17.09	37.49	56.21	17.70	38.04	54.33	18.34	36.57	**55.60**	**17.71**	**76.03**

3.3. Grading Degradation

To evaluate the service condition of the wood elements via visual inspection, the AB classification scale was implemented [5,6]. The application of these tables allows a categorization of the observation without any further tests, for a simple, easy and widespread application. This dual-parameter system distinguishes between degradation induced by abiotic agents (Parameter A) and biotic agents (Parameter B). As delineated in Tables 5 and 6, each parameter comprises four discrete levels, ranging from 0 to 3. Within this framework, a value of 0 signifies an optimal state with no detectable degradation, whereas a value of 3 represents the most advanced stage of deterioration.

Table 5. Visual classification: Parameter A—wood degradation by abiotic agents.

A0	A1	A2	A3
>After wetting, drops of water are visible on the surface. >Surface cracks with a maximum length of 600 mm >Cracks passed only at the ends and with a maximum length of 600 mm (no more than 1 per m)	>After wetting, no drops of water are visible on the surface >Surface with some wear (e.g., abrasion from windblown sand or loss of cross-section at edges) >Surface cracks with a maximum length of 900 mm >Cracks passed only at the ends and with a maximum length of 900 mm (no more than 1 per m) >Openings in connecting zones	>Peeling of the surface layer (separation of the outer membrane of the wood from its walls caused by UV rays) >Cracking longer than 900 mm >Cracks passed beyond the tops >Stains only in the vicinity of old iron connections and dark in color	>Cracks with an opening greater than 1 mm

Table 6. Visual classification: Parameter B—wood degradation by biotic agents.

B0	B1	B2	B3
>No stains	>Stains removable by surface cleaning	>Bluish to black stains (sometimes pinkish or greyish) on sapwood, with varying intensity and depth >Small and circular holes, smaller than 4 mm, with mounds of sawdust nearby >Holes with 1 mm deep by "sea fleas" (sea zones only)	>Whitish appearance with a fibrous texture. >Splitting in the transverse and longitudinal direction (forming cubes) >Oval holes, over 5 mm, for insect exit and wrinkled wood easy to lift with a blade >Veneer appearance >Wood destroyed with a honeycomb appearance >Musty odor >Dry crumbled areas or soft damp areas >Sounds hollow >Areas with burrows or nests

Given that biotic degradation typically represents a more severe threat to structural integrity than abiotic weathering, the overall assessment is weighted more heavily toward Parameter B. Consequently, a higher numerical value in Parameter B indicates a more critical condition.

4. Test Results

The physical condition of the specimens was monitored and classified at specific intervals throughout the experimental period, with representative results presented in the following sections. Notably, the specimens remain in situ to facilitate longitudinal analysis in future studies. At the commencement of the study in May 2022, all specimens exhibited no signs of deterioration, thereby conforming to the A0B0 classification level as defined in the aforementioned grading system.

4.1. Visual Observation After About 2 Months

Initial assessments were conducted at approximately two months post-exposure, encompassing the transition from late spring to early summer. The resulting classifications for Japanese Cryptomeria and Scots pine are illustrated in Figures 6 and 7, respectively. In these figures, each specimen's reference code—denoting species, treatment, and orientation—is paired with its corresponding degradation grade according to the previously defined AB scale.

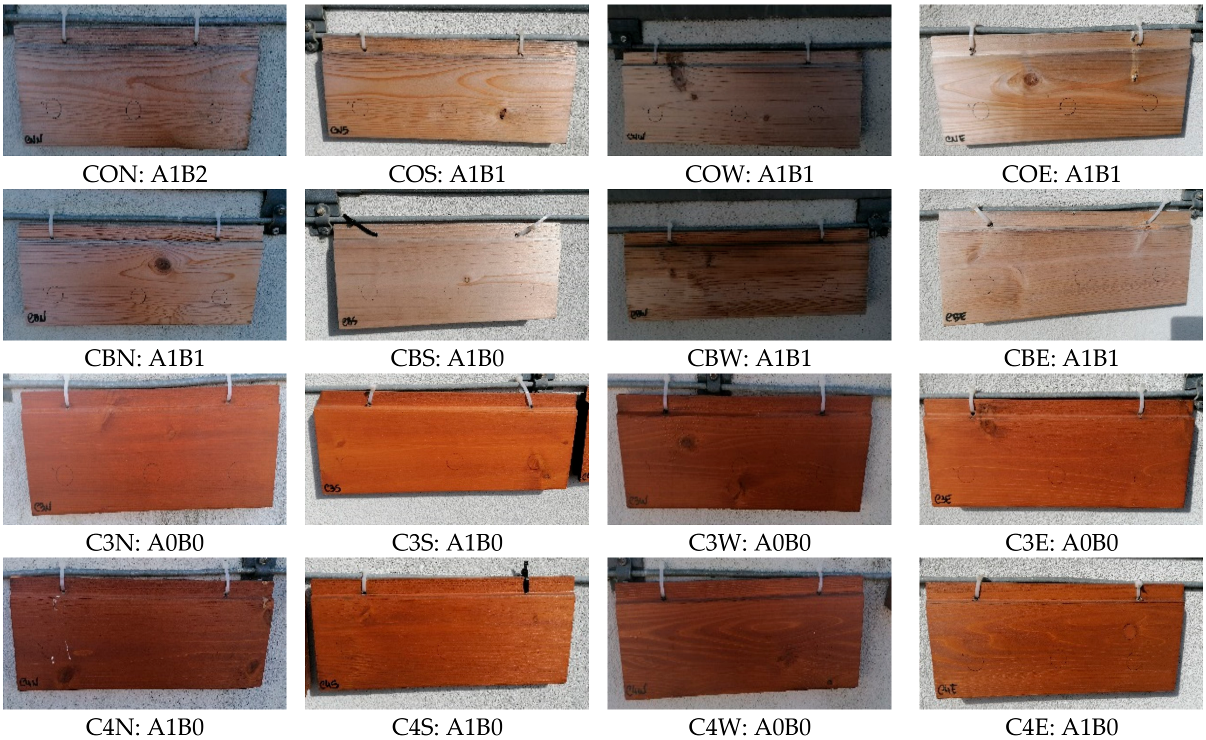

Figure 6. Images and condition of the Cryptomeria specimens after 2 months of study.

4.2. Visual Observation After About 2 Years

Following two years of natural weathering, a subsequent photographic record and visual classification were performed. The resulting data, shown in Figures 8 and 9, pair specimen metadata with their corresponding AB degradation scores to highlight the progression of the aging process. The rating tables used in this study were developed with detailed descriptions to support the categorization of visual observations. Nevertheless, it is not possible to completely eliminate some subjectivity. Therefore, supplementary "−" and "+" signs were introduced in Figures 8 and 9 when the results of the classification were a bit closer to the immediately lower or higher rating level, respectively.

4.3. Analysis of Visual Degradation Evolution Results

The temporal progression of degradation—accounting for wood species, treatment types, and solar exposure—is illustrated in Figures 10 and 11. These figures detail the evolution of abiotic deterioration (Parameter A) and biotic degradation (Parameter B), respectively, across the various test groups.

As anticipated, specimens that were either untreated or treated solely with a biocide exhibited significantly accelerated degradation, underscoring the necessity of robust surface protection for outdoor applications. A comparison between the original (O) and biocide-treated (B) specimens reveals that while the biocide provided performance parity or slight improvements, its efficacy was limited strictly to biotic degradation. Furthermore, based on visual degradation classification, an evaluation of treatments 3 and 4 indicates that treatment 3 seems to perform slightly better than treatment 4 across both species. This trend highlights the critical role of the anti-tannin impregnant in enhancing the overall durability of both Pine and Cryptomeria wood.

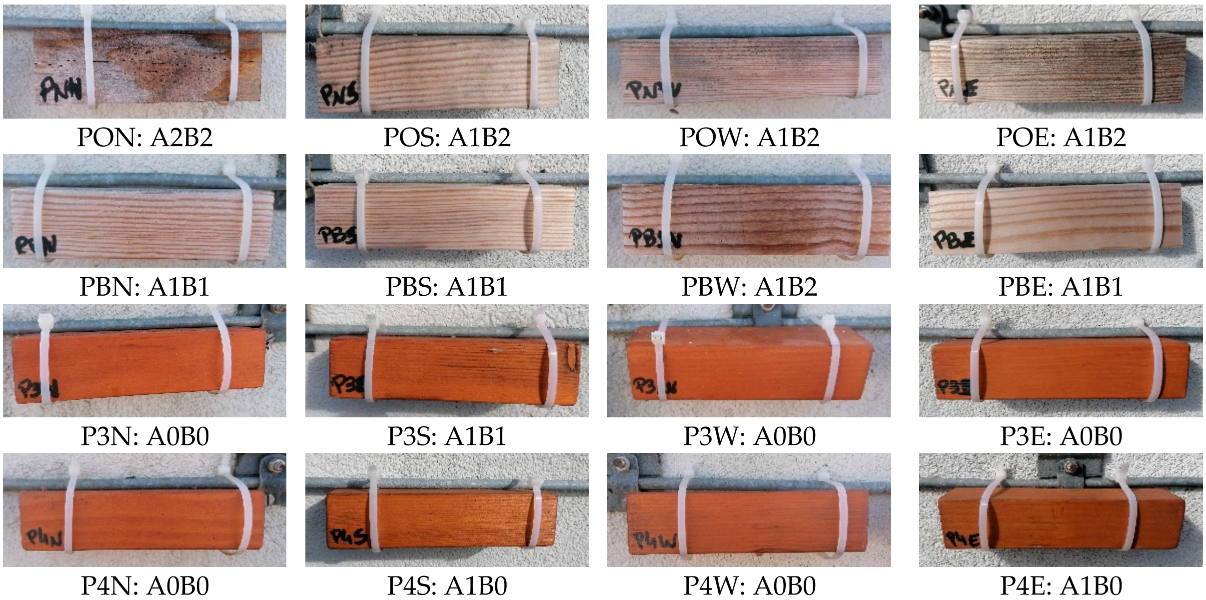

Figure 7. Images and condition of Scots pine specimens after 2 months of study.

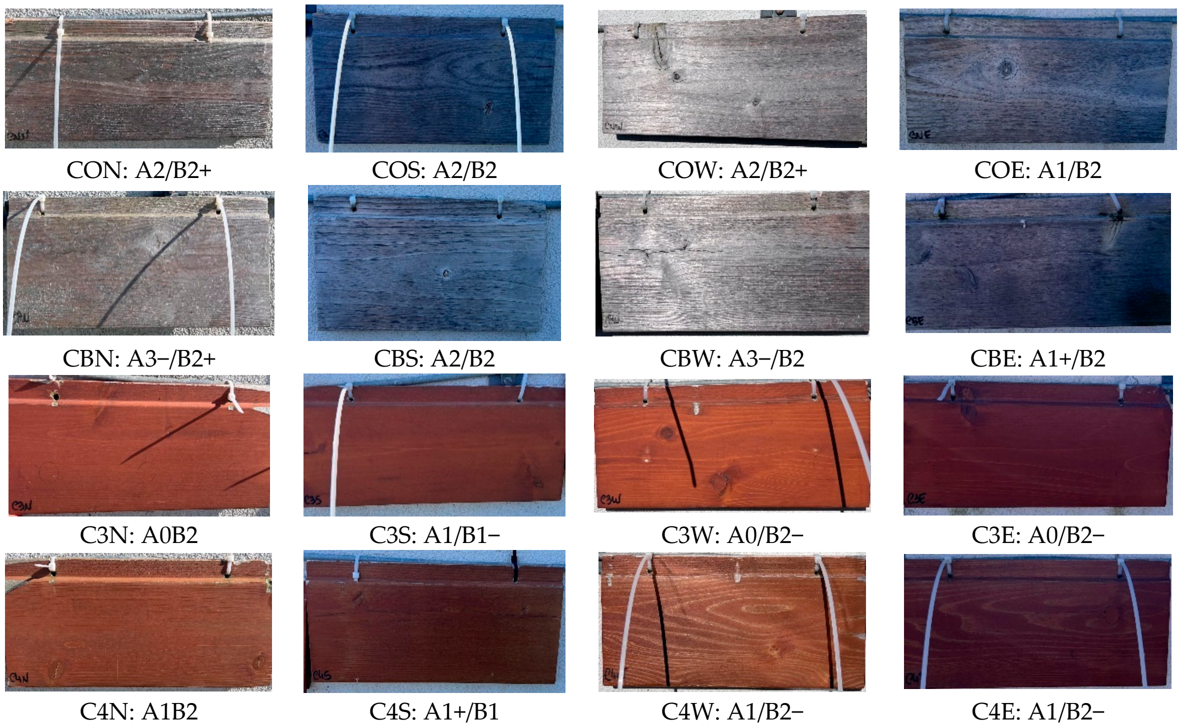

Figure 8. Images and condition of the Cryptomeria specimens after 2 years of study.

Evidence of both abiotic and biotic degradation was observed within the initial two months of exposure. During this early phase, abiotic degradation reached Level 1 for treatments 3 and 4, whereas treatments O and B exhibited higher susceptibility, reaching Level 2. In contrast, biotic degradation remained negligible for treatments 3 and 4 during the first two months, with only minor occurrences noted in the north- and south-oriented

Pine specimens under treatment 3. Following two years of exposure, abiotic degradation for treatments 3 and 4 remained stabilized at the maximum level of 1, while treatments O and B progressed in some cases to Level 3. Biotic degradation after 2 years varies between levels 2 and 3.

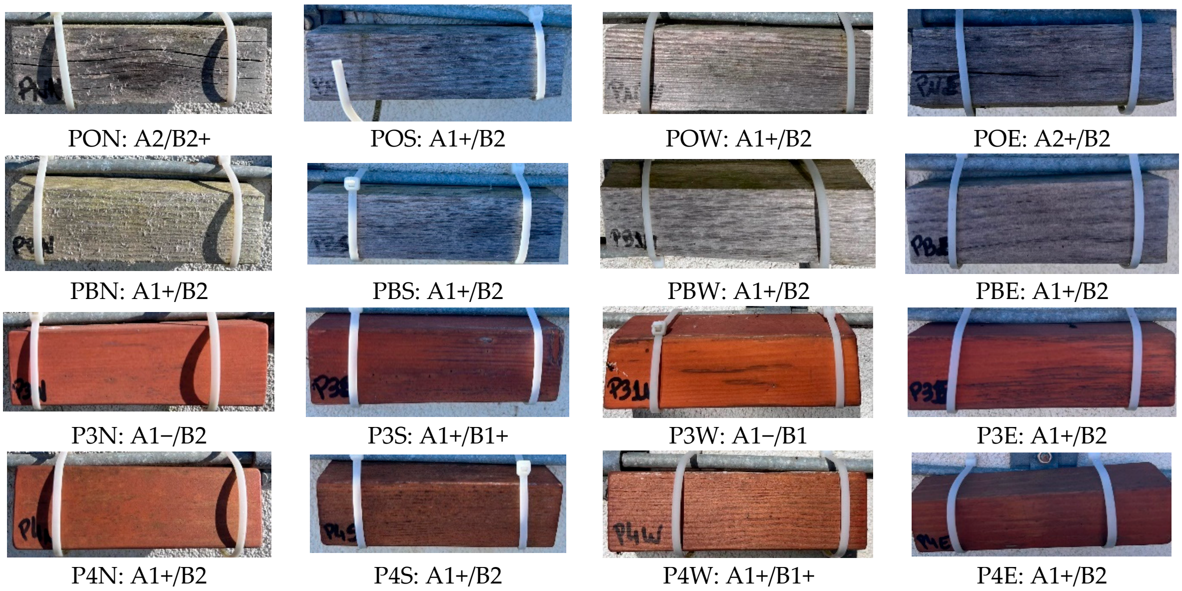

Figure 9. Images and condition of Scots pine specimens after 2 years of study.

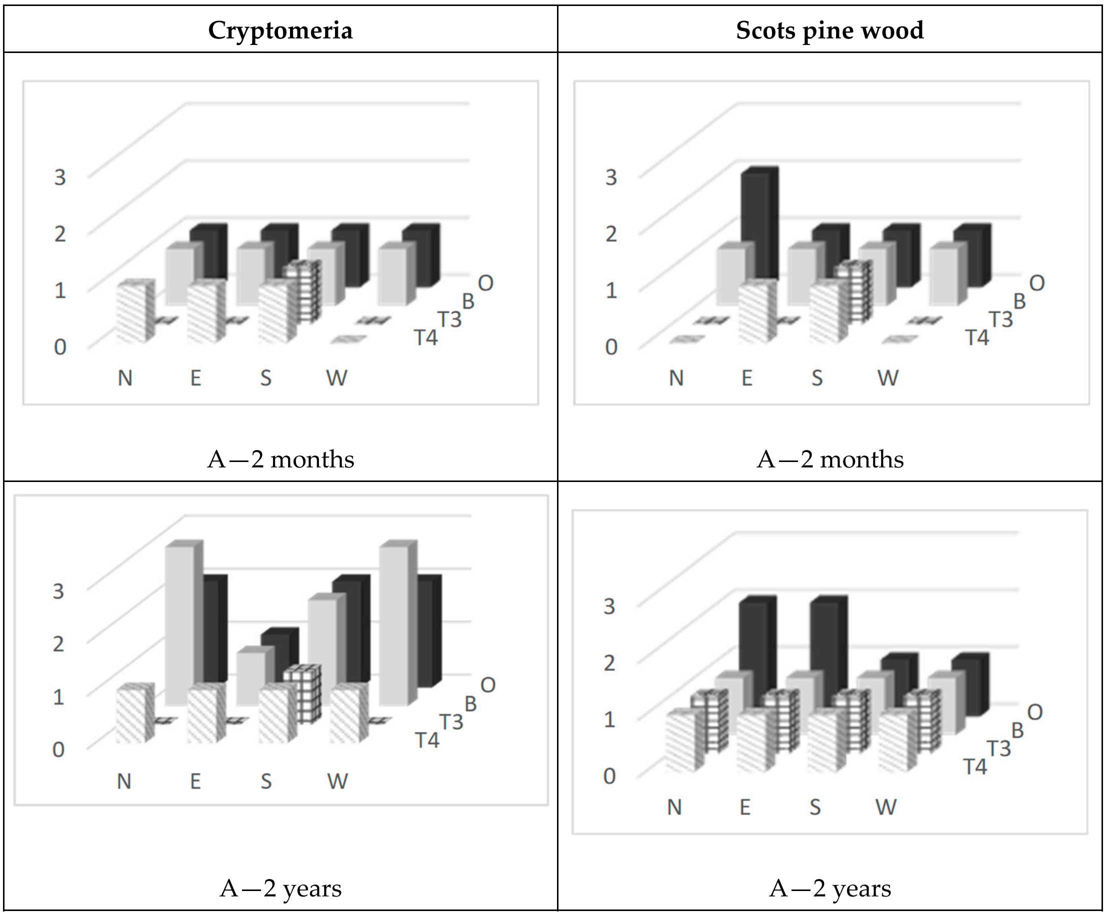

Figure 10. Visual classification results for wood degradation by abiotic agents—Parameter A.

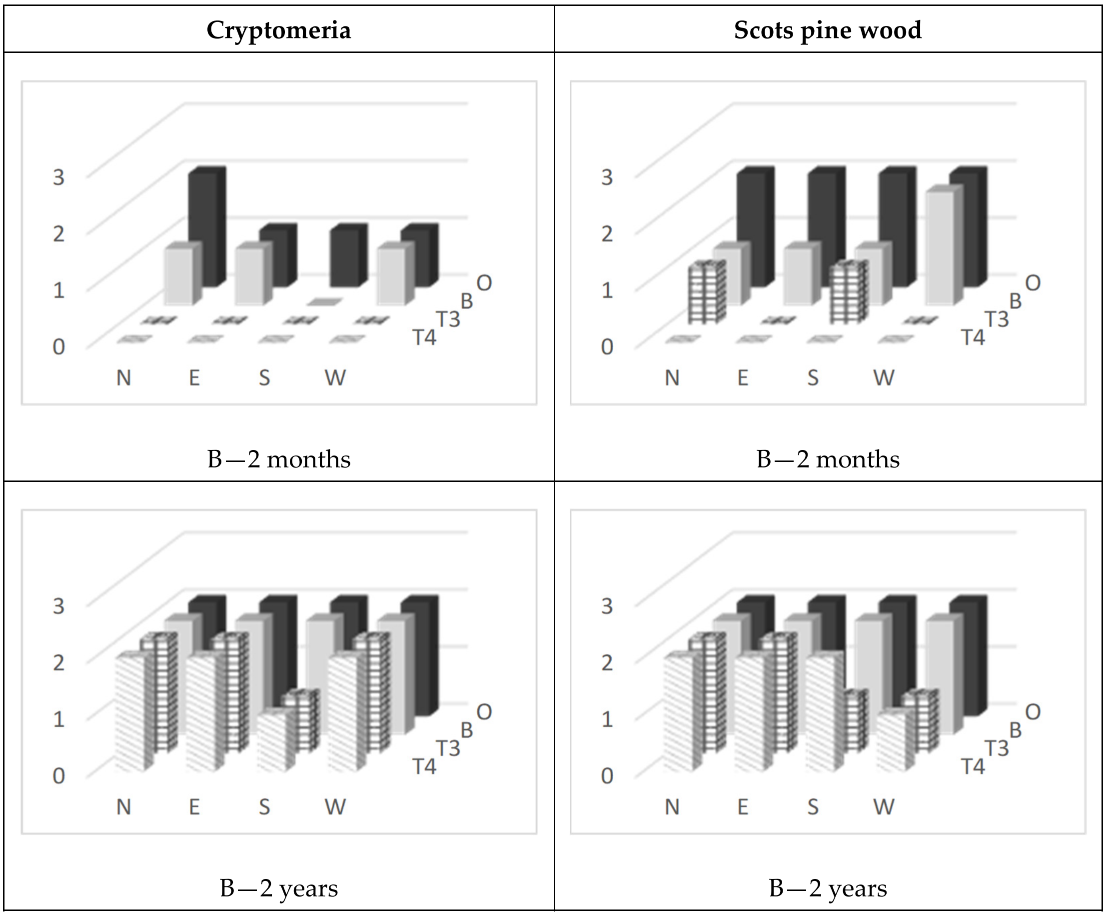

Figure 11. Visual classification results for wood degradation by biotic agents—Parameter B.

Overall, considering that the worst performance on the scale corresponds first to the highest B level and subsequently to the highest A level, specimen degradation progressed significantly between the initial and final assessments, with classifications increasing by up to two levels across all treatment types during the 22-month interval. At the two-month mark, the most severe deterioration (A2B2) was observed in untreated north-oriented Pine. By the end of the two years, the most critical state recorded was A3B2, found in Cryptomeria specimens treated only with biocide (B) and oriented north and west. For the fully treated specimens (T3 and T4), the maximum degradation observed after two years was A1B2 for T4 across both species. Treatment T3 yielded superior performance, with a maximum degradation of A1B2 in north-and west-oriented Pine. It should be noted that the north orientation maintains a slight inclination toward the north-northwest (NNW).

Regarding solar orientation, after two years of exposure, treatments 3 and 4 showed a higher propensity for biotic degradation in north and west orientations, while abiotic degradation appeared to show a slightly worse performance in south-facing specimens. In the control (O) and biocide-only (B) groups, the observed degradation showed no discernible variation that would allow strong conclusions regarding its relationship with orientation. This suggests that north-facing orientations are more susceptible to biotic agents due to reduced diurnal solar radiation, which maintains higher moisture levels on the substrate surface [46].

Comparative analysis of the two species indicates a slightly higher rate of degradation in Pine relative to Cryptomeria. However, it is essential to consider the influence of specimen geometry; the relatively small dimensions of the test samples, compared to standard structural timber, resulted in a higher surface-to-volume ratio and greater proximity to the permeable end-grains. Consequently, these experimental conditions represent a more severe exposure scenario than would typically be encountered in situ. Given that building components are designed for significant service lives, these findings underscore the importance of proactive maintenance and the early reapplication of protective treatments.

Furthermore, a very close analysis of the surfaces instead of an overall analysis of a facade—as was reported in a previous study—might suggest that the use of artificial intelligence to analyze images of a wood facade could be interesting to obtain a more reliable analysis of the degradation situation of the wood and consequent maintenance needed.

4.4. Analysis of Color Variation Results

Following the commencement of the study, colorimetric measurements were performed on 29 July 2022 and 18 April 2024. These dates correspond to exposure intervals of approximately two months and two years, respectively, relative to the June 2022 baseline.

The substantial divergence between the initial and final colorimetric assessments is consistent with the slow kinetics of lignin photodegradation, which typically requires more than two months to manifest significant surface alterations [47,48]. As shown in Tables 7 and 8, as well as illustrated in Figure 12, Japanese Cryptomeria demonstrated greater chromatic stability than Pine throughout the exposure period. In both species, the most pronounced color shifts were observed in the control (O) and biocide-only (B) groups. A comparison of treatments 3 and 4 reveals that while their performance was broadly similar, treatment 3 generally provided superior color retention for both species, with the singular exception of east-oriented Cryptomeria at 23 months.

Table 7. Average values of *L*, *a*, and *b*, with the respective standard deviations, and color variation in Cryptomeria specimens for 2 months and 2 years.

Cryptomeria Specimens		**2 Months**							**2 Years**						
		L	*Stand. Dev.*	*a*	*Stand. Dev.*	*b*	*Stand. Dev.*	**ΔE**	*L*	*Stand. Dev.*	*a*	*Stand. Dev.*	*b*	*Stand. Dev.*	**ΔE**
Treatment O	**CON**	68.73	1.58	7.62	0.53	25.18	1.44	**3.69**	53.67	1.29	0.16	0.18	10.86	0.56	**24.12**
	COS	70.12	0.61	6.67	0.18	24.22	0.79	**1.57**	45.22	1.59	−1.82	0.04	4.23	0.10	**33.96**
	COW	73.02	0.89	5.16	0.10	17.92	0.73	**4.44**	53.60	0.67	−2.15	0.13	5.76	0.46	**23.43**
	COE	65.49	1.54	6.42	0.80	21.07	1.86	**3.86**	53.82	2.59	−1.83	0.22	7.35	0.16	**21.96**
Treatment B	**CBN**	69.88	0.11	7.36	0.21	23.81	0.56	**3.86**	54.79	1.68	−1.47	0.30	9.96	0.89	**24.01**
	CBS	69.07	1.39	4.94	0.26	16.91	0.32	**4.37**	57.60	0.73	−2.52	0.06	7.87	0.16	**19.23**
	CBW	70.77	0.87	6.04	0.19	22.09	0.62	**8.07**	49.35	1.05	−1.83	0.06	5.40	0.19	**30.15**
	CBE	70.18	0.39	5.65	0.15	19.81	0.31	**4.86**	48.02	0.84	−2.25	0.73	7.33	1.45	**30.22**
Treatment 3	**C3N**	44.09	0.12	18.00	0.08	24.67	0.10	**4.68**	37.50	0.12	12.08	0.17	15.84	0.19	**17.16**
	C3S	48.04	2.25	19.41	0.78	30.07	2.72	**1.27**	39.84	1.73	13.68	0.70	18.42	1.41	**15.78**
	C3W	45.89	0.59	19.02	0.03	27.50	0.76	**2.52**	37.09	1.20	12.79	0.63	15.79	1.01	**16.66**
	C3E	46.35	0.56	18.20	0.35	26.91	0.92	**2.89**	38.08	0.62	12.32	0.23	16.45	0.47	**17.30**
Treatment 4	**C4N**	45.70	1.00	16.68	0.28	26.54	0.75	**4.46**	36.05	1.18	8.34	0.29	14.08	0.61	**22.24**
	C4S	47.17	0.77	16.90	0.20	27.78	1.14	**1.43**	36.92	0.64	7.84	1.06	14.48	0.57	**20.30**
	C4W	45.58	0.88	15.93	0.38	26.03	0.99	**1.81**	36.44	0.50	6.57	0.33	13.72	0.16	**19.40**
	C4E	45.02	1.36	15.44	0.36	24.75	1.25	**1.80**	36.50	0.75	7.73	0.26	14.18	0.48	**17.04**

Regarding solar orientation, untreated Cryptomeria exhibited peak color change in the south orientation, whereas those under treatment 3 were most affected in east orientations. For Pine, the control group (O) showed maximum color variation when south-facing, while biocide-only specimens (B) were more susceptible in the north orientation. No statistically significant differences related to solar exposure were detected in Pine for the remaining treatment schemes.

Table 8. Average values of *L*, *a*, and *b*, with the respective standard deviations, and color variation in Scots pine specimens for 2 month and 2 year.

Scots Pine Specimens		2 Months							2 Years						
		L	*Stand. Dev.*	*a*	*Stand. Dev.*	*b*	*Stand. Dev.*	ΔE	*L*	*Stand. Dev.*	*a*	*Stand. Dev.*	*b*	*Stand. Dev.*	ΔE
Treatment O	**PON**	60.09	4.04	7.32	1.82	20.84	4.19	**18.01**	35.13	4.09	−1.47	0.13	6.09	0.39	**47.59**
	POS	68.47	0.66	6.56	0.23	20.59	0.65	**10.63**	49.18	0.76	−2.02	0.17	5.49	0.36	**35.51**
	POW	67.24	2.87	7.13	0.27	22.66	1.43	**11.84**	45.29	1.34	−2.13	0.34	7.42	1.07	**37.97**
	POE	60.07	0.78	4.01	0.18	14.53	0.18	**24.03**	39.00	1.37	−1.56	0.11	5.50	0.12	**47.15**
Treatment B	**PBN**	68.23	0.44	6.99	0.16	22.17	0.55	**8.39**	54.28	0.61	−4.23	0.18	14.12	0.85	**28.46**
	PBS	65.25	1.12	6.44	0.28	20.41	0.68	**12.61**	43.34	1.71	−1.90	0.20	4.44	0.05	**40.89**
	PBW	66.55	0.61	3.18	0.15	13.57	0.44	**20.61**	47.04	0.56	−2.14	0.08	5.70	0.13	**37.21**
	PBE	62.77	0.45	5.82	0.31	18.40	0.50	**21.09**	42.37	0.41	−1.64	0.04	5.02	0.09	**44.27**
Treatment 3	**P3N**	50.04	0.76	20.93	0.08	34.32	0.89	**3.72**	38.55	0.34	13.26	0.08	17.09	0.25	**39.99**
	P3S	48.75	0.48	18.85	0.50	30.78	0.96	**6.13**	35.07	0.42	9.19	0.27	13.79	0.06	**44.61**
	P3W	51.50	0.29	20.71	0.05	35.40	0.31	**3.71**	39.75	0.82	12.82	1.08	17.75	0.89	**40.26**
	P3E	50.95	0.25	20.04	0.18	34.58	0.41	**5.31**	36.70	1.18	9.28	1.75	14.84	1.40	**46.90**
Treatment 4	**P4N**	51.29	0.25	18.69	0.30	33.14	0.33	**6.70**	36.49	0.31	7.50	1.29	14.30	0.38	**42.26**
	P4S	52.58	0.17	17.82	0.22	34.32	0.17	**4.30**	38.81	0.90	5.36	0.35	14.90	0.08	**40.52**
	P4W	51.11	0.53	17.70	0.27	31.85	0.27	**6.01**	41.26	3.97	6.38	0.23	15.29	0.78	**38.54**
	P4E	50.94	0.65	16.98	0.46	31.05	0.24	**7.88**	39.32	1.00	7.30	1.05	15.83	0.40	**43.93**

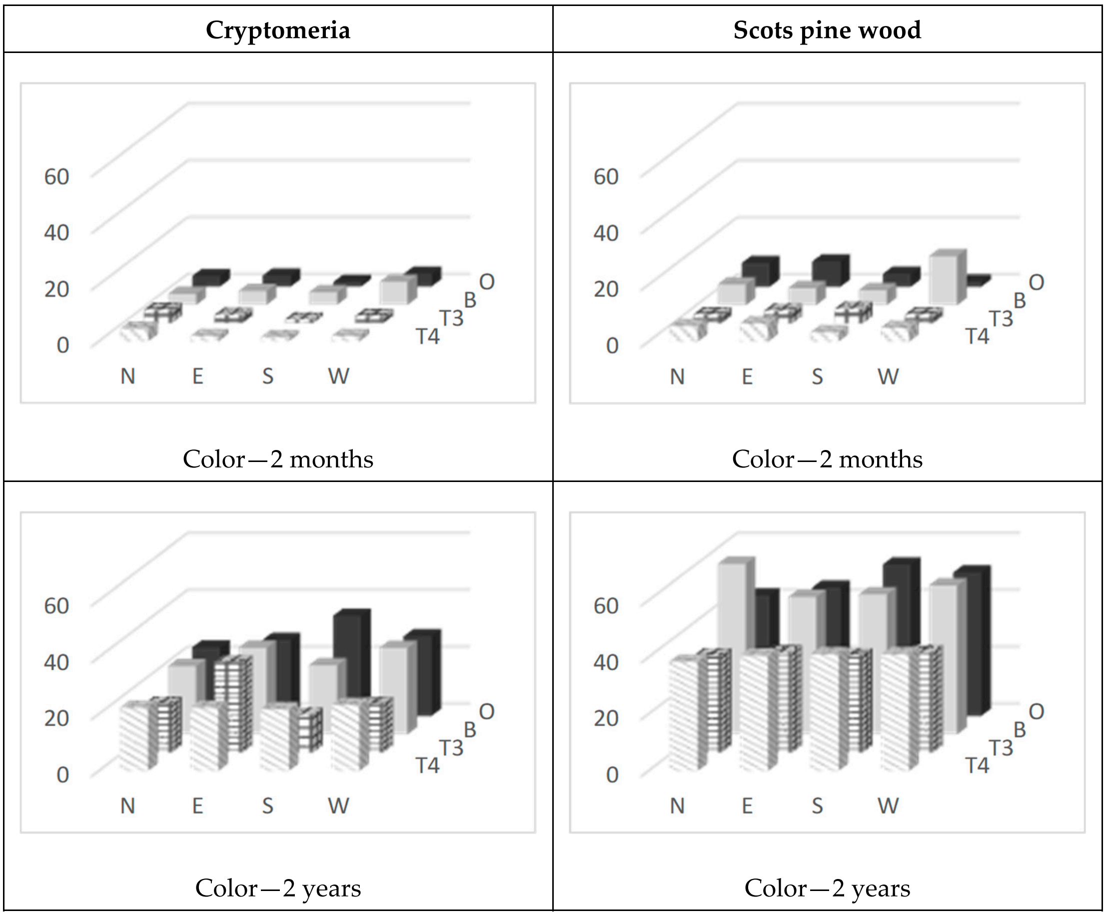

Figure 12. Color variation in both specimens for 2 months and 2 years.

The experimental results indicate a positive correlation between total color change (Δ*E**) and the qualitative degradation classification of the timber specimens. Specifically, specimens exhibiting the most significant chromatic shifts were consistently associated with advanced stages of degradation.

Considering the completely treated samples (treatments 3 or 4) after two years of environmental exposure, the most pronounced color alterations were recorded in specimens oriented towards the east. This trend was particularly evident in Cryptomeria with treatment 3, where the degradation was classified as A1B2. Considering all samples after two years of exposure, the maximum color variation for each wood type was observed in Original towards south (at A2B2 degradation) and in biocide treatment with north exposure (at A1B2 degradation), respectively, for Cryptomeria and Pine. This is consistent with greater abiotic degradation in the south and greater biotic degradation in the north.

The magnitude of the color change phenomenon was heavily contingent upon the preservative protocol employed. As hypothesized, untreated control samples—devoid of biocides or protective coatings—demonstrated the highest susceptibility to both esthetic shifts and structural degradation. This confirms that the absence of chemical stabilization significantly accelerates the weathering process under field conditions.

5. Conclusions

This study underlines the significant challenges concerning timber durability within the maritime climate of Northern Portugal. Longitudinal monitoring over 2 years reveals that while degradation is driven by synergistic weathering factors—including solar radiation, wind action, and precipitation—the preservative treatment protocol seems to remain one of the most important aspects of material performance.

The tests carried out over 2 years show that wood degradation is influenced by exposure to the different weather conditions (such as sunlight, wind and rain), but mainly by the treatments applied. In addition, some signals of degradation appear even in the first months and years of service life.

Treatment 3, characterized by the application of an anti-tannin impregnant, proved most effective in mitigating structural and esthetic decay. However, even treated specimens reached Level 2 on the biotic degradation scale before the two-year threshold. This underscores the suggestion of frequent maintenance cycles to reinforce chemical barriers and extend the service life of exterior wood components.

Specimens exposed to the north tend to be more subject to degradation caused by biotic agents, and specimens exposed to the south tend also to be subject to degradation caused by abiotic agents, but.

The degradation does not exhibit a strong correlation with geographical orientation, although it is broadly consistent with north-facing exposure being predominantly associated with biotic agents due to higher equilibrium moisture content (EMC) that promotes fungal and bacterial colonization, while south-facing exposure is mainly influenced by abiotic weathering, where increased prolonged UV exposure contributes to accelerated photochemical degradation and surface checking.

Contrary to expectations regarding its higher density, Scots pine exhibited more pronounced colorimetric shifts compared to Japanese Cryptomeria. In Cryptomeria, the east (E) orientation was the most detrimental to color stability. In Scots pine, orientation-dependent variation was less significant after 2 years.

However, it is important to note that the observed degradation rates may be accelerated due to the geometry of the specimens. The high surface-area-to-volume ratio and the proximity of permeable end-grains—which lacked the structural shielding (e.g., eaves or flashings) typical of full-scale architectural elements—likely increased vulnerability to moisture ingress and biotic attack compared to in situ building components.

Considering that the building materials under analysis are expected to have a much longer life span, these results show that it is very important to carry out maintenance to replace their treatments from a very young age.

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