

Article

Hybrid Decorative Elements Inspired by Textile Heritage for Furniture: Design and Influence of Coating on the UV-Accelerated Aging Behavior

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Abstract

Integrating traditional textile heritage into contemporary furniture design offers an innovative way to preserve cultural identity through modern materials and decorative techniques. This study investigates the color stability of hybrid decorative plywood panels fabricated using mechanical perforation and sewing techniques inspired by traditional textile motifs. The samples were evaluated using UV-induced artificial aging, alongside color measurements before and after exposure, microscopic analysis, and Fourier Transform Infrared Spectroscopy (FTIR). The approach enables traditional decorative patterns to be transferred onto wood-based materials, creating contemporary furniture decorations, while preserving and reinterpreting the textile heritage. Results revealed distinct aging behaviors depending on the finishing system. Changes in total color difference (ΔE^*)—4.36 for red thread, 4.21 for unvarnished reference, 3.34 for oiled, 0.72 for water-based, 2.55 for nitrocellulose-based, and 0.52 for epoxy-coated samples—demonstrated that both the coated plywood substrate and the textile thread were affected by aging after 72 h of UV exposure. Epoxy resin and water-based coatings provided the greatest color surface stability, while oil- and solvent-based finishes exhibited varying degrees of chromatic alteration due to their different responses to ultraviolet radiation and moderate temperature. The stitch technique showed good structural compatibility with plywood and preserved the integrity of heritage-inspired motifs after artificial aging for 72 h of UV exposure relative to long-term furniture use, which is a limitation of the present study. However, the red cotton sewing thread was more sensitive to light exposure, showing a slight UV-induced discoloration, with effects varying according to coating type. FTIR investigations demonstrated that UV aging of the cotton thread resulted in some photo-oxidative degradation of cellulose, which may explain the minor incipient microstructural degradation phenomena observed by SEM.



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1. Introduction

Cultural heritage preservation has increasingly expanded beyond the conservation of original artifacts toward the modern reinterpretation and integration of traditional cultural expressions into contemporary design and manufacturing systems [1]. Among the various forms of cultural heritage, traditional textiles occupy a significant place due to their complex symbolic language, regional identity markers, craftsmanship techniques, and decorative richness [2,3]. Textile motifs, as part of cultural heritage, often embody historical

narratives and community memory, reflecting local cultural identities and artistic creation transmitted across generations [1,4]. However, the accelerated globalization of industrial production and the gradual disappearance of traditional crafts have contributed to the decline of vernacular textile practices and to the reduced visibility of textile heritage in contemporary living environments. Recent advances in digital fabrication, computer-aided manufacturing, and heritage-oriented design have enabled new strategies for preserving and valorizing traditional motifs and for providing digital restoration and reconstruction of heritage clothing [5–8], damaged textile cultural relics [9], or textile patterns [10]. On the other hand, 3D technologies, such as 3D scanning and modeling, as well as augmented and virtual reality, are often used to revive forgotten cultural heritage [11,12], or even reconstruct garments or fiber materials from artworks [8,13]. Lately, artificial intelligence has been used to replicate historical fashion to preserve fashion heritage and cultural identity [14–16].

Nowadays, new technologies are integrated into craft production: Computer-Aided Design (CAD), Computer Numerical Control (CNC), laser cutting and engraving, scanning, 3D printing, and digital design software applications [17]. These technologies and applications enable the transfer of heritage-inspired motifs onto a range of materials, including ceramics, fabrics, and wood-based surfaces [18]. They are nowadays included in modern furniture and interior design, becoming a promising approach to extending the cultural relevance of traditional patterns while adapting them to contemporary aesthetic and functional requirements [19–21]. Several studies have explored transferring textile ornaments onto wood furniture surfaces, using various design methods and processing techniques such as routing or laser engraving, thereby demonstrating the potential of interdisciplinary approaches that combine cultural heritage, materials science, and product design [22–25]. Such approaches contribute not only to the conservation of heritage but also to the creation of innovative design languages that reconnect users with traditional cultural values.

Wood is traditionally used in furniture design for its aesthetic appeal, ease of crafting, durability, naturalness, and ecological benefits [26]. In contemporary furniture design, wood-based materials are well-suited to this type of cultural reinterpretation due to their versatility and machinability. Plywood, in particular, offers dimensional stability, superior mechanical properties, and better stress distribution [27], as well as ease of processing with traditional tools, laser cutting, and CNC milling [28]. Thus, perforating plywood and sewing textile-inspired motifs could create opportunities for hybrid decorative systems in which the decorative textile pattern is physically embedded as a tactile design feature within the structure of contemporary furniture components by combining materials and techniques. Cabinet fronts, chair backrests, tabletops, or other furniture elements are examples of possible applications.

The durability and long-term behavior of such hybrid decorative systems have not yet been investigated. Since furniture is subjected throughout its service life to environmental fluctuations and various aging factors, especially ultraviolet (UV) radiation from natural or artificial light sources, the performance of protective coatings is essential for maintaining the aesthetic quality, color stability, and structural integrity of the wood-based surface and of the sewn patterns. Oil finishes, nitrocellulose lacquers, and epoxy resins are coating categories with different chemical compositions curing mechanisms, and resistance to intensive use [29]. Understanding their behavior under accelerated-aging conditions is therefore necessary to evaluate their feasibility for long-term interior applications.

Accelerated aging methods simulate environmental degradation processes and assess the long-term performance of materials exposed to ultraviolet (UV) radiation, humidity, and temperature variations, including those from textile cultural heritage, such

as silk [30], cotton [31–33], linen [34], as well as other textile relics [35]. In these studies, the Scanning Electron Microscope (SEM) is an important investigation tool. When using wood-based materials, aging studies are important for both surface coatings and the wooden material itself, as they influence color stability and surface integrity over time [36–38].

Color change under the effect of light is one of the main consequences affecting the long-term performance, aesthetic appearance, and authenticity of artifacts [39,40]. Color measurement techniques based on the CIELab system are used to monitor aging processes, evaluate conservation treatments, and quantify degradation phenomena in historical textiles, dyed fibers, painted surfaces, and wood materials [37,41,42]. Wood color is also sensitive to UV light, and the effects are visible after a few hours of exposure [43–46]. Spectrophotometric color analysis enables the objective assessment of total color differences (ΔE^*), as well as variations in lightness (ΔL^*), red–green chromatic coordinate (Δa^*), and yellow++–blue chromatic coordinate (Δb^*), allowing detailed characterization of materials' aspect alterations induced by artificial or natural aging processes. The effect of UV light on color changes in wood samples coated with various types of varnishes was studied by researchers [36,37,47–49]. The results showed a decrease in the lightness (L^*) of coated wood surfaces, whilst the opposite trend was observed for the coordinates a^* and b^* , and chemical modifications.

Limited research has examined the color behavior of both coated and uncoated wood when combined with textile-sewn motifs used in decorative assemblies. In such hybrid systems, interactions among coatings, wood surfaces, textile fibers, and the dyes used to color the thread may result in distinct discolorations due to photodegradation and thermal degradation. Consequently, colorimetric investigations provide important information regarding the long-term preservation potential of such decorative assemblies.

The present study investigates the accelerated aging behavior of plywood samples, in which a combined drilling and sewing technique was used to create a hybrid, furniture-oriented decorative element inspired by motifs from traditional textile heritage, thereby supporting both cultural heritage preservation and contemporary design innovation. Four finishing systems—siccative oil, waterborne lacquer, nitrocellulose lacquer, and epoxy resin—were applied to evaluate their influence on the aspect and aging performance of the decorated elements. By analyzing the color responses of coated and stitched plywood samples under accelerated aging conditions, this research aims to evaluate color stability and is complemented by microscopy and chemical analyses. The present study contributes to the development of heritage-inspired furniture surfaces while promoting a new method for the preservation and reinterpretation of textile cultural heritage. Figure 1 presents an example of a furniture piece featuring a hand-stitched cross-stitch component, following a pattern derived from Romania's textile heritage.

Previous research found in the literature has addressed the preservation and digital reinterpretation of textile heritage [1–16], the application of textile-derived ornaments to wood furniture surfaces [22–25], and the separate aging behavior of wood coatings [36–38] and textile materials [30–35]. However, these approaches have generally considered the constituent materials or decorative motifs separately. In this respect, the combined use of a perforated plywood substrate and a sewn, heritage-inspired textile motif as a hybrid furniture decoration, together with an assessment of its color stability and degradation under accelerated UV exposure, has not been previously investigated. The present study addresses this gap by evaluating interactions among the plywood substrate, protective coating systems, and textile thread using colorimetric, microscopic, and FTIR analyses.



Figure 1. Table prototype featuring a hybrid integrated ornament, manually stitched on drilled plywood, developed to demonstrate the feasibility of the proposed research approach.

2. Materials and Methods

2.1. Sample Preparation

A traditional motif was selected from the textile heritage of the village of Prejmer, Brasov County [50]. It represents the model from a decorative towel stitched in 1795 with red cotton thread. The motif represents the North Star, the Mill Collar, or the Eight-Pointed Star. It serves as an essential guide, a fixed point, and an indispensable reference for shepherds and navigators, without which they could lose their way. In Romanian ethnographic research, the eight-pointed star frequently appears as a geometric “rosette”, interpreted as a cosmic and protective motif [51].

The model was first created in vector format using the professional graphics software CorelDRAW X7 (version 17, Corel Corporation, Ottawa, ON, Canada) on a square grid (Figure 2a). Next, the points required for stitching were marked (Figure 2b). Finally, the resulting vector CDR file containing only the markings (Figure 2c) was exported to AutoCAD LT 2017 (Autodesk, San Francisco, CA, USA) as a DXF file and then imported into VCarvePro 9.519 (Vectric Ltd., Alcester, UK).

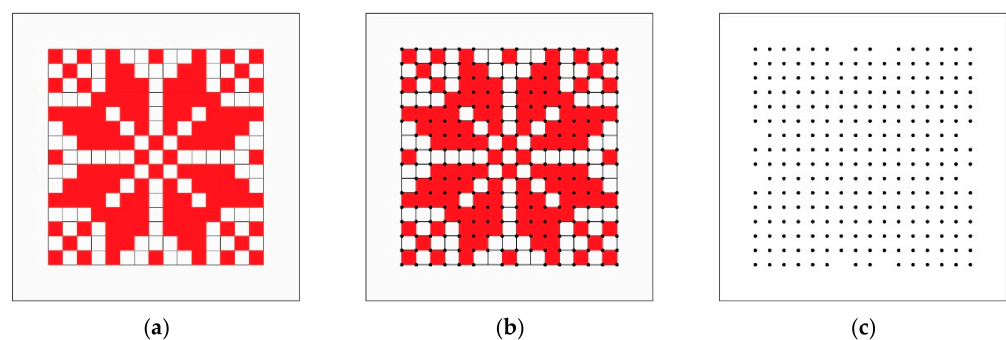


Figure 2. The selected motif: (a) Digital drawing. (b) Marking the points required for cross-stitching. (c) The points for perforation (red color represents the sewn red thread).

Two sets of five beech (*Fagus sylvatica* L.) plywood samples measuring 80 mm × 80 mm × 4 mm, with an average density of 810 kg/m³ and a moisture content of approximately

10%, were prepared. The first set was mechanically drilled according to the DXF file using a 3-axis CNC router (ISEL GFV, Eichenzell, Germany) equipped with a 1.5 mm drill bit and subsequently decorated by hand-stitching (Figure 3a) with sewing thread through the perforations (Figure 3b), whereas the second set remained unmodified. In both sets, four samples were finished using the same four finishing materials (one sample per finishing material), while the fifth sample was left uncoated and served as a reference.

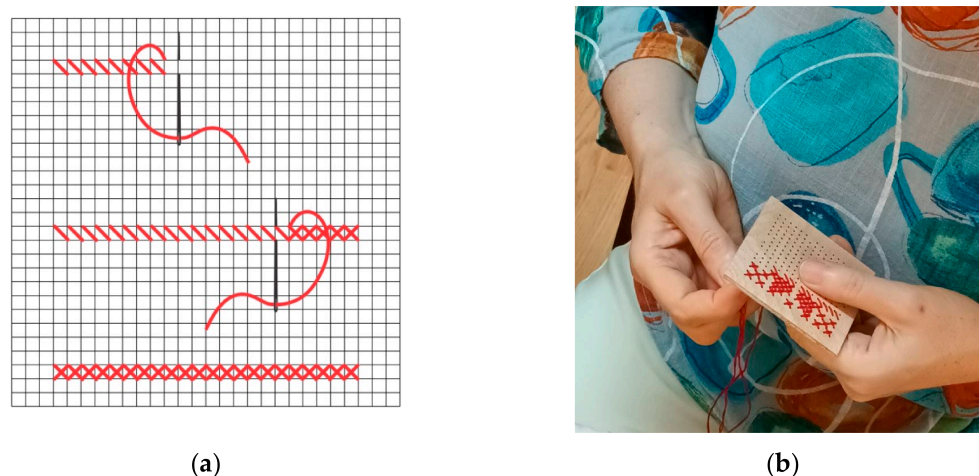


Figure 3. Cross stitch: (a) The technique used. (b) Hand-stitch of the sample.

The stitched samples (uncoated and coated in four variants) are presented in Figure 4a–e. The samples shown in Figure 4f–j were necessary for methodological monitoring of changes in the unfinished and finished substrates.

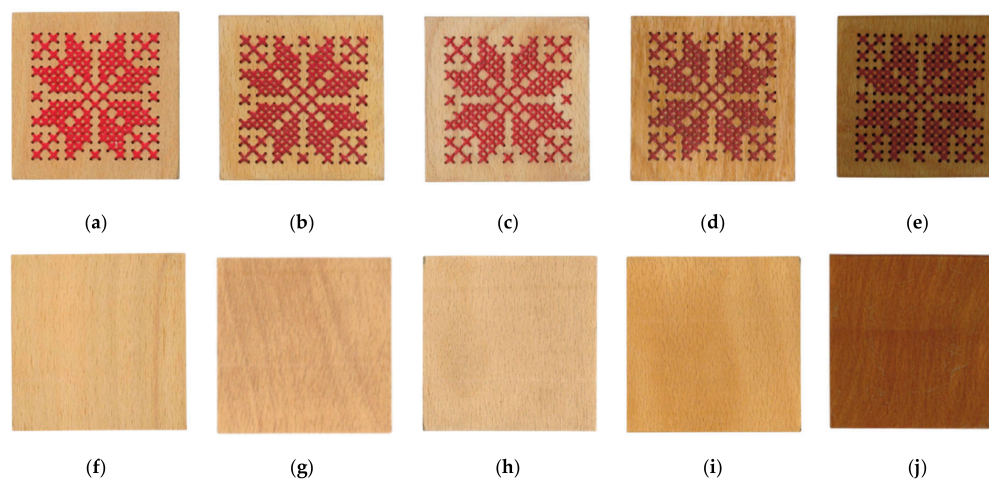


Figure 4. Stitched and unstitched samples before aging treatment: (a) Uncoated stitched reference. (b) Oiled stitched sample. (c) Waterborne lacquered stitched sample. (d) Nitrocellulose lacquered stitched sample. (e) Epoxy resin-coated stitched sample. (f) Uncoated reference sample. (g) Oiled sample. (h) Waterborne lacquered sample. (i) Nitrocellulose lacquered sample. (j) Epoxy resin-coated sample.

Four finishing systems with different composition and protective characteristics were applied on the samples: oil (Figure 4b,g), water-based lacquer (Figure 4c,h), nitrocellulose lacquer (Figure 4d,i), and epoxy resin (Figure 4e,j). Two samples remained uncoated as references (Figure 4a,f).

All test samples were finished manually following the same application procedure, except for the epoxy resin. For all finishing systems, a single layer was applied by brushing at an approximate rate of 110 g/m². The epoxy resin was poured onto the sample surface,

resulting in a final coating thickness of approximately 2 mm. Borma Hard Top Oil, with a coverage of 18–26 m²/L, is a coating material based on natural siccative oils in combination with synthetic resins and wax, specifically formulated for wooden countertops, providing a durable, water-resistant finish that enhances the wood's natural appearance. Ecolasure Extra Köber, with a coverage of 14.5–18 m²/L, is a waterborne-based, colorless wood glaze that forms a protective and decorative coating film with good vapor permeability and low volatile organic compound content. Nitrocellulose lacquer Vektor (125–160 m²/L) provides high surface coverage, gloss enhancement, and effective protection for indoor wooden substrates. Epoxy resin Epodex ECO Resin, with a density of about 1.1 g/cm³, viscosity of about 700 mPa·s, and Shore D hardness of about 87 after curing, shows good chemical stability, strong adhesion, and the ability to form a dense, mechanically resistant cross-linked polymeric film. The epoxy resin was poured onto the sample surface, resulting in a final thickness of 2 mm.

Approximately 25 m of sewing textile thread, Anchor Mouline red 0047 (Anchor, Mulhouse, France), was wound around a piece of plywood, as shown in Figure 5a, to create a continuous colored surface for measuring the thread's color before and after aging (Figure 5b).

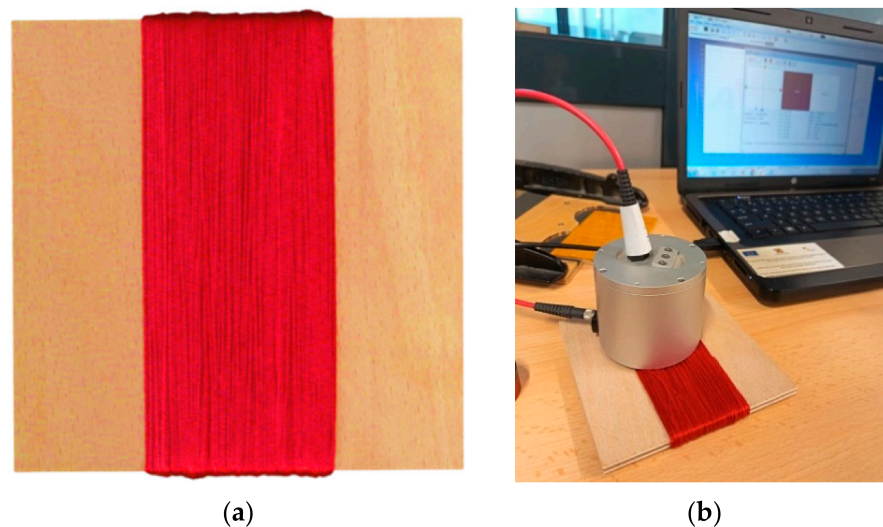


Figure 5. Color measurement for the textile sewing thread: (a) The sample prepared for the measurement. (b) Measurement method.

2.2. UV-Accelerated Aging

To evaluate the long-term behavior of the developed decorative systems, an accelerated cyclic aging test was performed for the read thread and the ten plywood samples under controlled environmental conditions using a Feutron 400 FKS climatic chamber (Feutron Klimasimulation–GmbH-Greiz, Langenwetzendorf, Germany). This was equipped with a UVA Spot 400 T lamp (Hönle UV Technology, Gilching, Germany) of 400 kW, fitted with an H2 glass filter to ensure exposure of the samples to UV–VIS radiation within the 295–600 nm wavelength range, and ensuring an irradiation level of 5 mW/cm² at a distance of 50 cm from the source, reproducing indoor daylight conditions due to natural light transmitted through window glass, consistent with previously reported methodologies [46]. Samples were mounted vertically on a support rack positioned 60 cm from the UV light source (Figure 6). Half of each sample was protected with black cardboard covered with aluminum foil to prevent light exposure and allow color comparison between the exposed and unexposed surfaces.

The use of successive 24 h exposure cycles was based on Method B of EN ISO 16474-3 for simulating the effects of daylight transmitted through window glass [52].

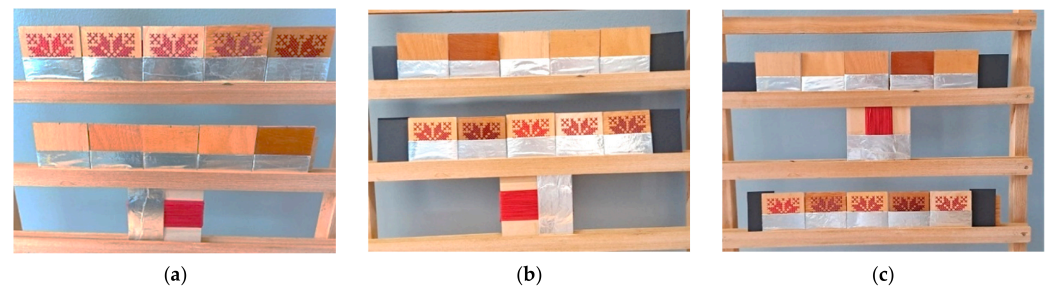


Figure 6. The position of the samples on the support rack for UV exposure in the climate chamber: (a) Before 24 h of UV exposure. (b) Before 48 h of UV exposure. (c) Before 48 h of UV exposure.

The exposure protocol is presented in Table 1.

Table 1. UV irradiation under accelerated aging behavior.

Step *	Stages of a 24 h UV Irradiation Cycle	RH (%)	T (°C)	UV Source	Time of Exposure (Hours)	Total Hours for a 24-h Cycle *
1	Initial conditioning	55 ± 5	20 ± 2	No	0.5	
2	UV irradiation stage 1	-	40 ± 2	5 mW/cm ²	6 h	26
	Dark period	55 ± 5	20 ± 2	No	0.5 h	
	UV irradiation stage 2	-	40 ± 2	5 mW/cm ²	6 h	
	Dark period	55 ± 5	20 ± 2	No	0.5 h	
	UV irradiation stage 3	-	40 ± 2	5 mW/cm ²	6 h	
	Dark period	55 ± 5	20 ± 2	No	0.5 h	
	UV irradiation stage 4	-	40 ± 2	5 mW/cm ²	6 h	
	Dark period	55 ± 5	20 ± 2	No	0.5 h	
3	Conditioning	55 ± 5	20 ± 2	No	24 h	

* Steps 2 and 3 are repeated two times for a UV irradiation cycle of 48 h and 3 times for a 72-h cycle.

The complete procedure was repeated three times, resulting in cumulative UV exposure durations of 24, 48, and 72 h. The selection of the 72 h cumulative exposure was based on a previously reported accelerated UV aging procedure employing the same Feutron 400 FKS climatic chamber, UVA Spot 400T lamp, and H2 glass filter, with radiation in the 295–600 nm range to simulate natural light filtered through window glass [36]. This methodology used successive 24 h exposure cycles and cumulative exposure durations of 24, 48, and 72 h and was subsequently applied to investigate light-induced color changes in wood surfaces [36,38]. The relevance of this accelerated exposure to prolonged indoor light aging can be contextualized by the natural aging study [37], in which the 72 h of accelerated exposure induces color changes of the same order of magnitude as those observed after seven years of natural indoor exposure. Therefore, the 72 h UV-aging exposure in this study was considered an accelerated simulation of prolonged indoor light exposure. Longer exposure periods are identified as an important direction for future work.

To maintain uniform irradiation conditions across all specimens, the position of the samples on the support rack was changed after each 24 h exposure period (Figure 6a–c).

2.3. Colorimetric Analysis

Colorimetric analyses using the CIELab system were conducted before and after aging for the sets of five unstitched plywood samples and the textile sewing threads (Figure 5b) to quantify chromatic changes and assess the influence of coating type on color stability.

The measurements were performed using an AvaSpec-2048 USB2 spectrometer (AVANTES, Apeldoorn, The Netherlands), coupled with an AvaLight-Hal light source and an integrating AVA sphere, with all components interconnected through optical fibers. This instrumental setup provided homogeneous diffuse illumination and enhanced measurement reliability throughout the analysis. The equipment was calibrated under the D65 illuminant, simulating daylight conditions, and according to the 2° standard observer. Data

acquisition and spectral processing were carried out using AvaSoft (version 7.7.2) equipped with the Color analysis module (AVANTES, Apeldoorn, The Netherlands). Measurements were collected through an 8 mm aperture, with ten readings taken at different locations across the red thread and each 50×50 mm wood sample surface, to assess local color variability. The recorded values were then averaged to determine the mean L^* , a^* , and b^* color coordinates, along with their corresponding standard deviations. The color variation before and after aging (24 h, 48 h, and 72 h) was quantified by calculating the color difference (ΔE^*), expressed as the Euclidean distance between their respective coordinates in the CIELab color space, according to Equation (1):

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

where ΔL^* corresponds to the difference in lightness, Δa^* represents the variation along the red–green chromatic axis, and Δb^* indicates the variation along the yellow–blue chromatic axis.

2.4. Microscopic Investigation

A microscopic analysis was performed using a Nikon Instruments NIKON SMZ 18 stereo microscope (Nikon Corporation, Yokohama, Japan), which offers magnification ranging from $22.5\times$ to $405\times$. Image acquisition, measurements, and data analysis were conducted using NIS-Elements Imaging Software. The objective of the analysis was to assess the thread's integrity after applying the aging protocol and to observe whether any changes resulted from this treatment. Measurements of thread thickness before and after UV exposure were conducted on the reference and varnished stitched samples.

Furthermore, SEM was employed to observe any microstructural changes in the sewing thread resulting from 72 h of UV aging. A Phenom XL Desktop SEM-EDS (Scanning Electron Microscope with Energy Dispersive Spectroscopy module), equipped with a high-sensitivity full BSD detector (Backscattered Electrons Detector), produced by Thermo-Fisher Scientific (Eindhoven, The Netherlands), was used for this purpose. Pieces of about 10 mm of unexposed and UV-exposed cotton thread were mounted on stubs with double-sided carbon adhesive pads and examined under low vacuum (60 Pa), 10 kV acceleration voltage, point imaging mode, at various magnifications, from $500\times$ to $3000\times$.

2.5. Fourier Transform Infrared Spectroscopy (FTIR) Investigation

An ALPHA Bruker spectrometer (Bruker Optics GmbH & Co. KG, Ettlingen, Germany) was employed to register the FTIR-ATR spectra of the red thread, before and after UV aging, in the range $4000\text{--}600\text{ cm}^{-1}$ at a resolution of 4 cm^{-1} and 24 scans/spectrum. For the aged thread, a sample was extracted from the exposed test sample. A total of five spectra were recorded for each sample type. All spectra were further processed using OPUS software version 7.2 (Bruker Optik GmbH, Ettlingen, Germany) for baseline correction and smoothing before computing an average spectrum for each sample type. These were further normalized (Min–Max normalization) and analyzed to highlight specific chemical features of the textile material employed and the chemical changes induced by aging. The assignment of characteristic absorption bands was based on references in the literature.

3. Results and Discussion

3.1. Colorimetric Analysis Results

The results of color measurements and images of the tested samples, including the thread before aging treatment and after 72 h of UV exposure, are presented in Figures 7–12.

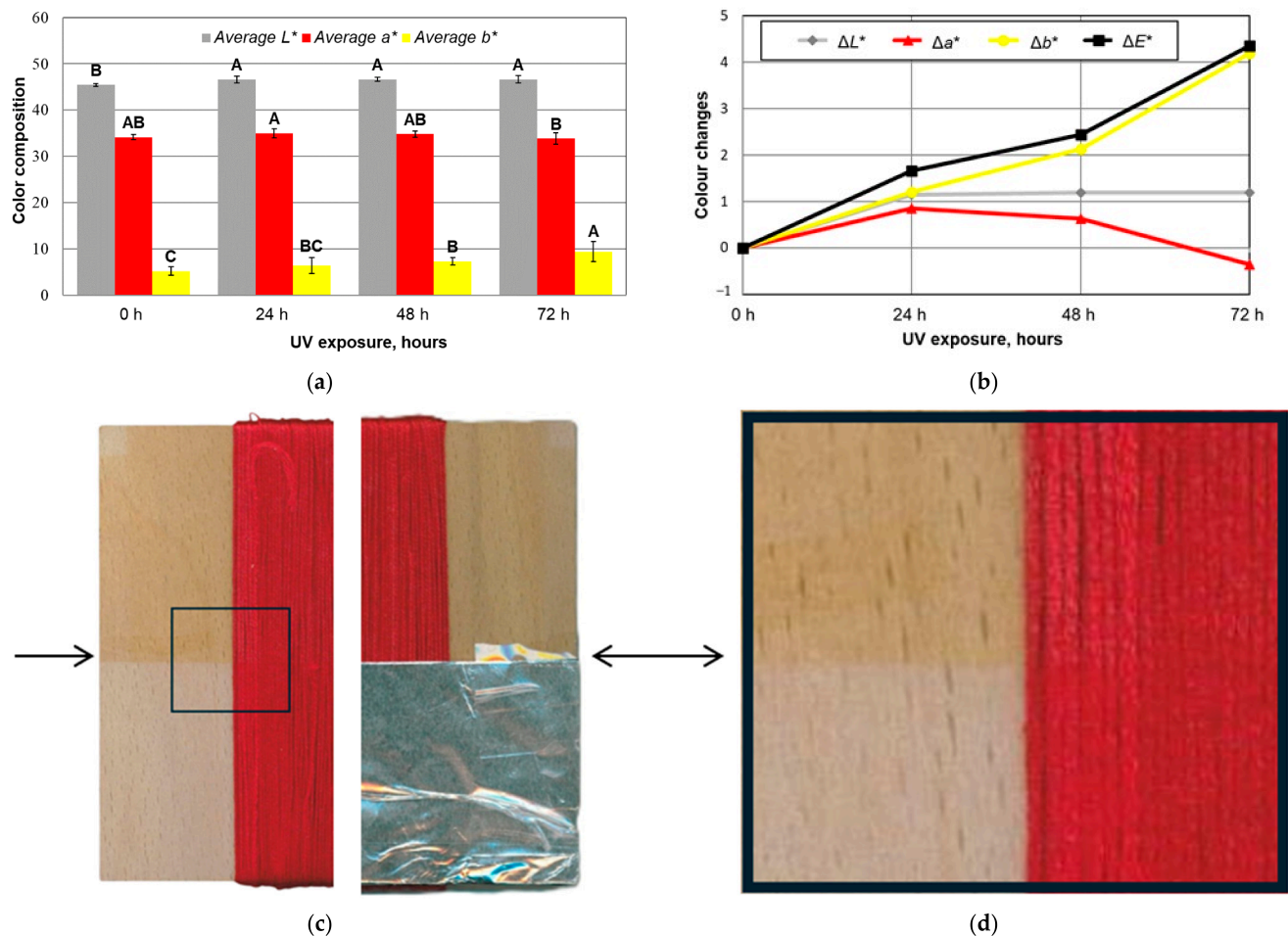


Figure 7. Color analysis of red thread: (a) Variation in L^* , a^* , and b^* color coordinates during UV aging. (b) Dynamics of color changes. (c) The sample after 72 h of UV exposure (left) and the half-protected sample before aging (right). (d) Marked detail in the “(c)” image, showing the color differences before and after 72 h of UV aging. Note: Different uppercase letters denote significant differences between mean values within each color parameter (L^* , a^* , or b^*) according to Tukey’s HSD test ($p < 0.05$). Means sharing the same letter are not significantly different.

The diagram in Figure 7a shows the recorded average L^* , a^* , and b^* color coordinates and their standard deviations for the red thread after 24, 48, and 72 h of UV exposure compared to the reference values before aging.

The overall pattern shown in Figure 7a indicates that UV exposure affected the color characteristics of the red thread. The L value increased slightly after 24 h ($p < 0.05$) and remained stable thereafter. The a^* value showed relative stability, with a significant decrease observed only after 72 h compared with 24 h. In contrast, the b^* value increased progressively throughout the exposure period, reaching significantly higher values after 72 h than at 0 h. These changes indicated that prolonged UV exposure made the thread lighter, slightly less red, and increasingly yellow. The dynamics of the color changes are depicted in Figure 7b. Variation in redness was very low and inconsistent over time, with a slight increase in the first 24 h (+1 unit) followed by a slight decrease (−1 unit) after 72 h. In contrast, a consistent increase in yellowness was observed, with no trend of flattening after 72 h, so that longer testing periods should be employed to conclude on the in-time evolution of this chromatic coordinate. The evolution of the calculated global color change, ΔE^* , follows the trend of Δb^* , suggesting that yellowing was the dominant factor in the global color change, reaching a value slightly higher than 4 after 72 h of UV exposure. The above color data are in good agreement with visual perception, with slight lightening

and a change in shade towards yellow visible in Figure 7c and more clearly in the detail in Figure 7d, where the arrows indicate the demarcation line between the exposed and unexposed areas.

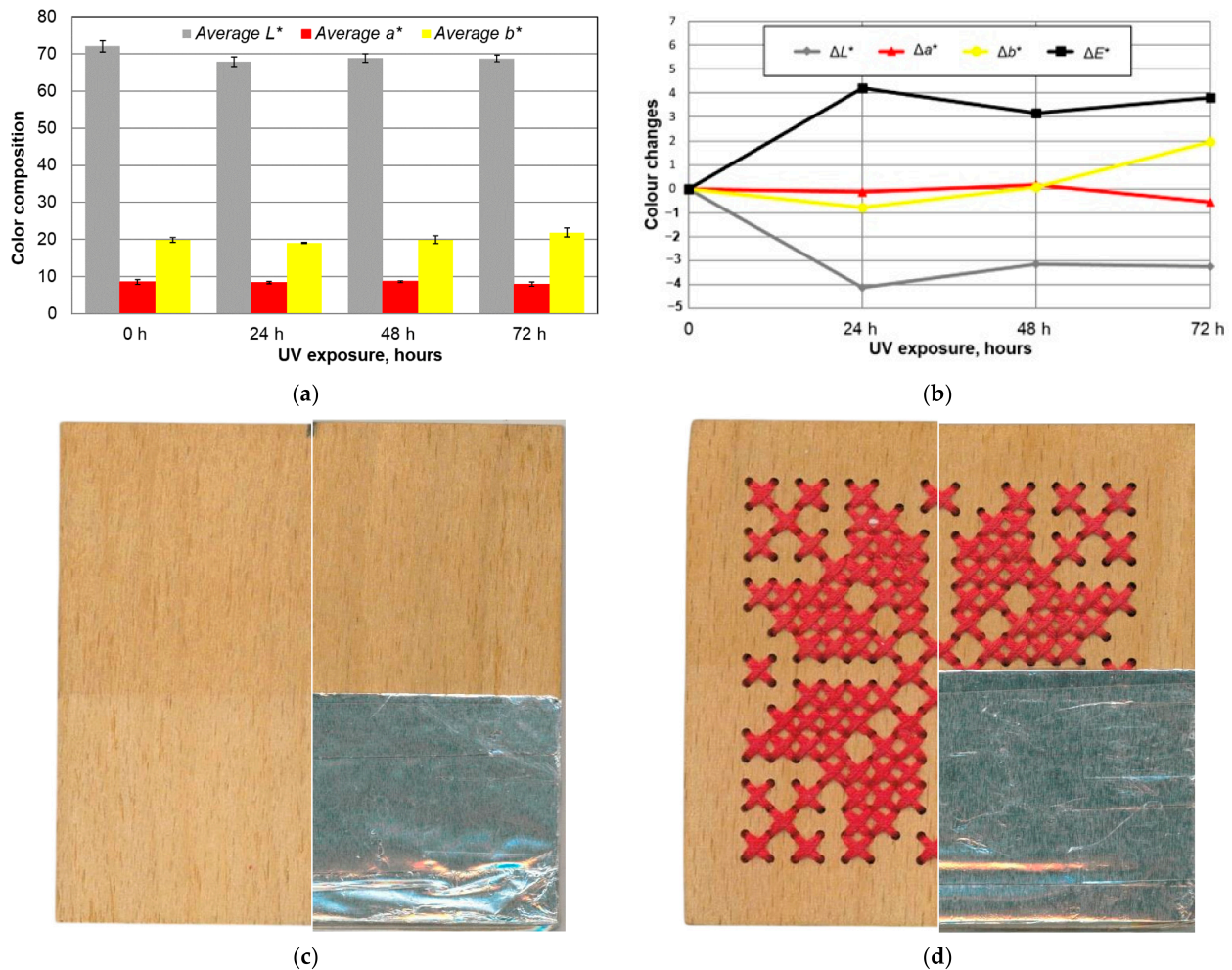


Figure 8. Color analysis of the uncoated reference wooden substrate: (a) Variation in the L^* , a^* , and b^* color coordinates during aging. (b) Dynamics of color change. (c) Color change after 72 h of UV exposure of the unvarnished plywood sample (left) and the half-protected sample after aging (right). (d) Color change in the stitched sample after 72 h of aging treatment (left) and the half-protected sample after aging (right).

For the uncoated reference samples (Figure 8a), the average lightness (L^*) values decreased from 72 to 68 after 24 h, indicating that UV exposure darkens the samples, which then stabilize, showing slightly higher but constant values after 48 and 72 h.

Average redness (a^*) values remained nearly constant during UV exposure, indicating that UV radiation has had little effect on the redness. The small increase in the average b^* values from 20 to 22 indicates a slight tendency for the material to become more yellow as UV exposure increases. These color-change dynamics are illustrated in Figure 8b, indicating a slight but sharp darkening in the first 24 h and a slightly delayed yellowing, as highlighted by positive Δb^* values after 48 h of UV exposure. The evolution of ΔE^* demonstrates sharp and rapid color changes in the first 24 h, reaching the maximum value of 4 units, followed by a slight trend of reverse evolution in the following 24 h (decrease by 1 unit), to slightly increase afterward (back to 4 units) due to the increase in yellowness. As shown in Figure 8b, there were only minor color changes after 72 h of UV exposure, consistent with visual perception (Figure 8c,d).

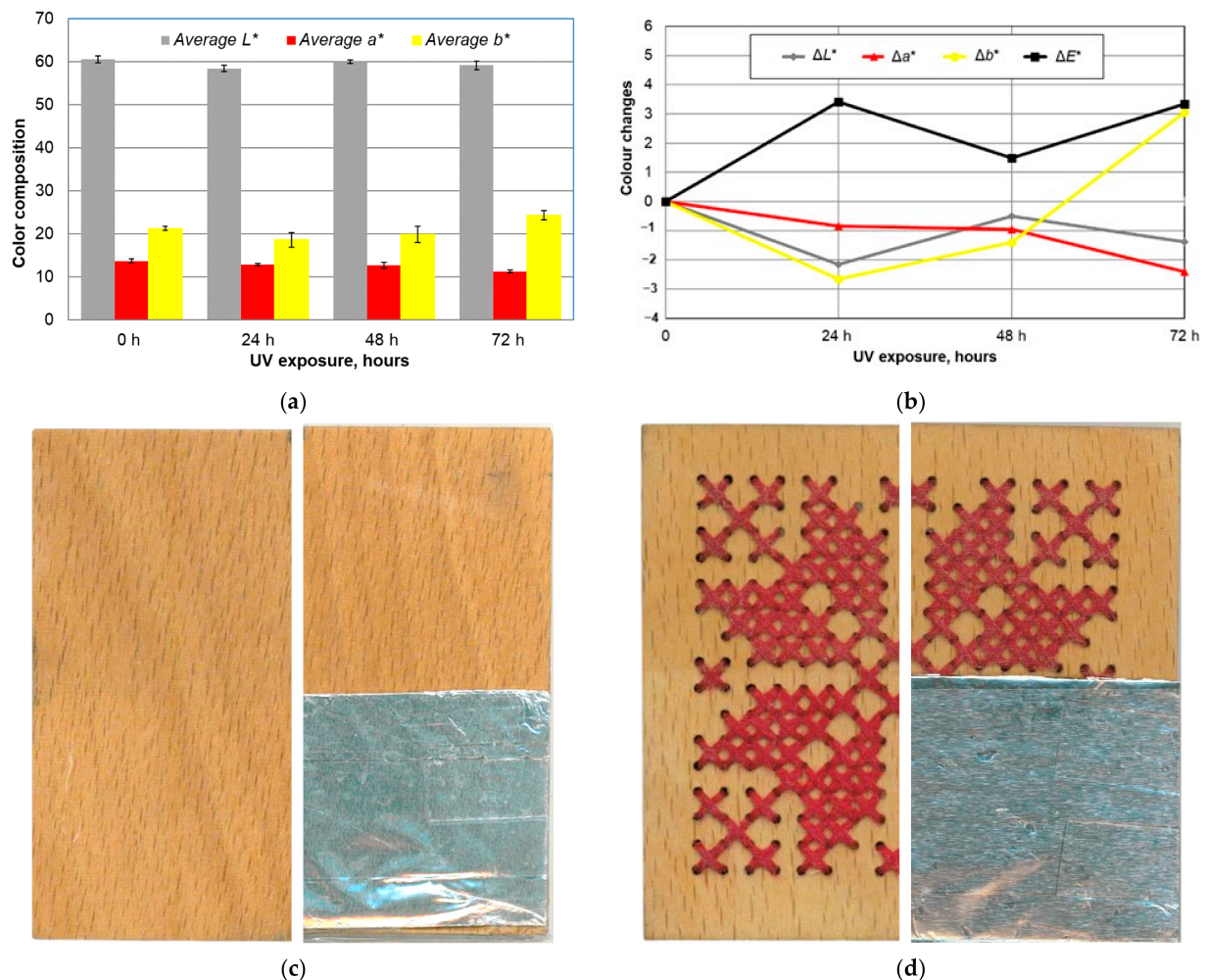


Figure 9. Color analysis of oiled samples: (a) L^* , a^* , and b^* color coordinates during the aging treatment. (b) The dynamics of color change. (c) Color change in the oiled plywood sample (left) and half-protected sample (right) after 72 h of aging treatment. (d) Color change in the stitched sample (left) and half-protected sample (right) after 72 h of aging treatment.

This pattern of UV-induced color evolution for the beech plywood, employed as substrate in this research, with rapid and sharp lightness changes in the first 24 h, followed by a possible reverse evolution and relative trend of levelling after 72 h, occurring in parallel with a clear increase in yellowness by this exposure period and a less important and more wavy evolution of redness, is quite common for wooden substrates, though clearly influenced by the wood species and their natural color, due to the extractives content [36,37,44–46]. Also, finishing of wooden substrates with various clear, colorless coatings will affect both their initial color and, further, their color stability when exposed to UV light, with possible protective effects or, contrarily, accentuated light-induced color changes, depending on the type and composition of the coating materials [36–38,48,49].

For the oil-finished samples (Figure 9a), a lower average L^* value and a negative ΔL^* (Figure 9b) were observed after 72 h of UV aging, indicating slight darkening of the wood surface. Average a^* and negative Δa^* values suggest a decrease in redness, while Δb^* shifting from negative to positive values and a final increased average b^* indicate a variation and increase in yellowish coloration. The variation in ΔE^* shown in Figure 9b confirms the visible color changes induced by UV radiation after 48 h of exposure, followed by a return to the initial state after 72 h, indicating a small change in the color of the wood surface. The slight darkening of the wood surface is observed in Figure 9c for the oiled

plywood sample and in Figure 9d for the stitched sample. The minimal color differences observed between the protected and unprotected UV-exposed areas, resulting in a barely distinguishable boundary between them, suggest that the oil varnish provides a certain degree of protection against color changes in the wood surfaces.

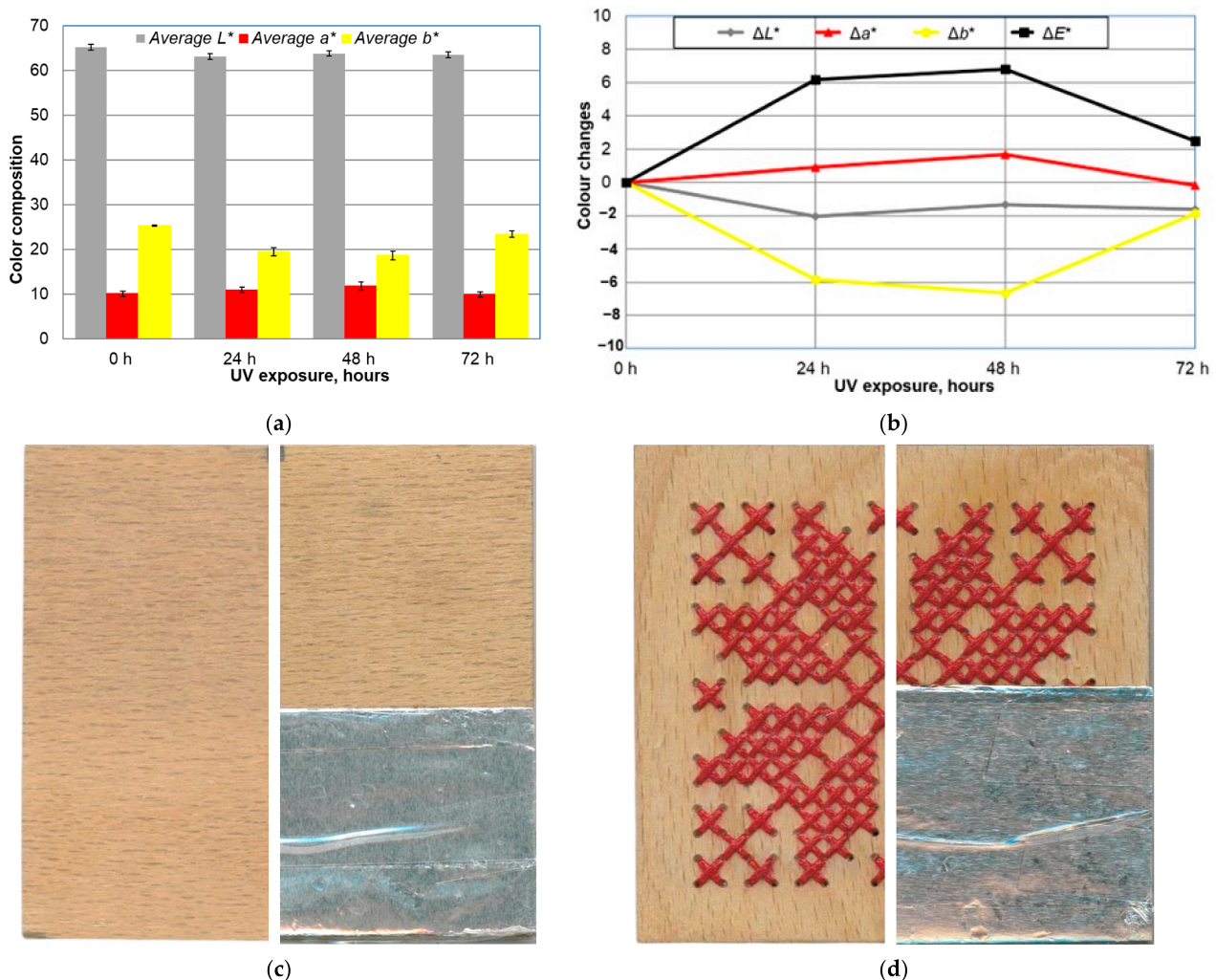


Figure 10. Color analysis of waterborne varnished sample: (a) L^* , a^* , and b^* color coordinates during the aging treatment. (b) The dynamics of color change. (c) Minimal change in color of the wood surface (left) and half-protected sample after 72 h of UV exposure. (d) Minimal change in color of the stitched sample (left) and half-protected sample (right) after 72 h of UV exposure.

The diagram in Figure 10a shows the recorded L^* , a^* , and b^* color coordinates of the waterborne varnished sample after 24, 48, and 72 h of UV exposure, and the dynamics of color change are shown in Figure 10b.

Decreased L^* value and negative ΔL^* in Figure 10a,b indicate slight darkening of the samples throughout the aging treatment after 24 h of UV exposure, which appears to be reduced after 72 h. An increase in the a^* and Δa^* after 48 h and their reverse evolution to the initial state after 72 h indicate the stabilization of red color. A negative trend was also noticed after 48 h of exposure for b^* and the Δb^* variations, partially recovered after 72 h (by more than 4 units). The variation in ΔE^* indicates a pronounced color change after 48 h of UV exposure, followed by a reverse trend after 72 h, as shown by the images in Figure 10c,d, where the limit between exposed and protected areas is hard to distinguish. The results show that water-based varnish is an effective solution for UV protection of the wood surface.

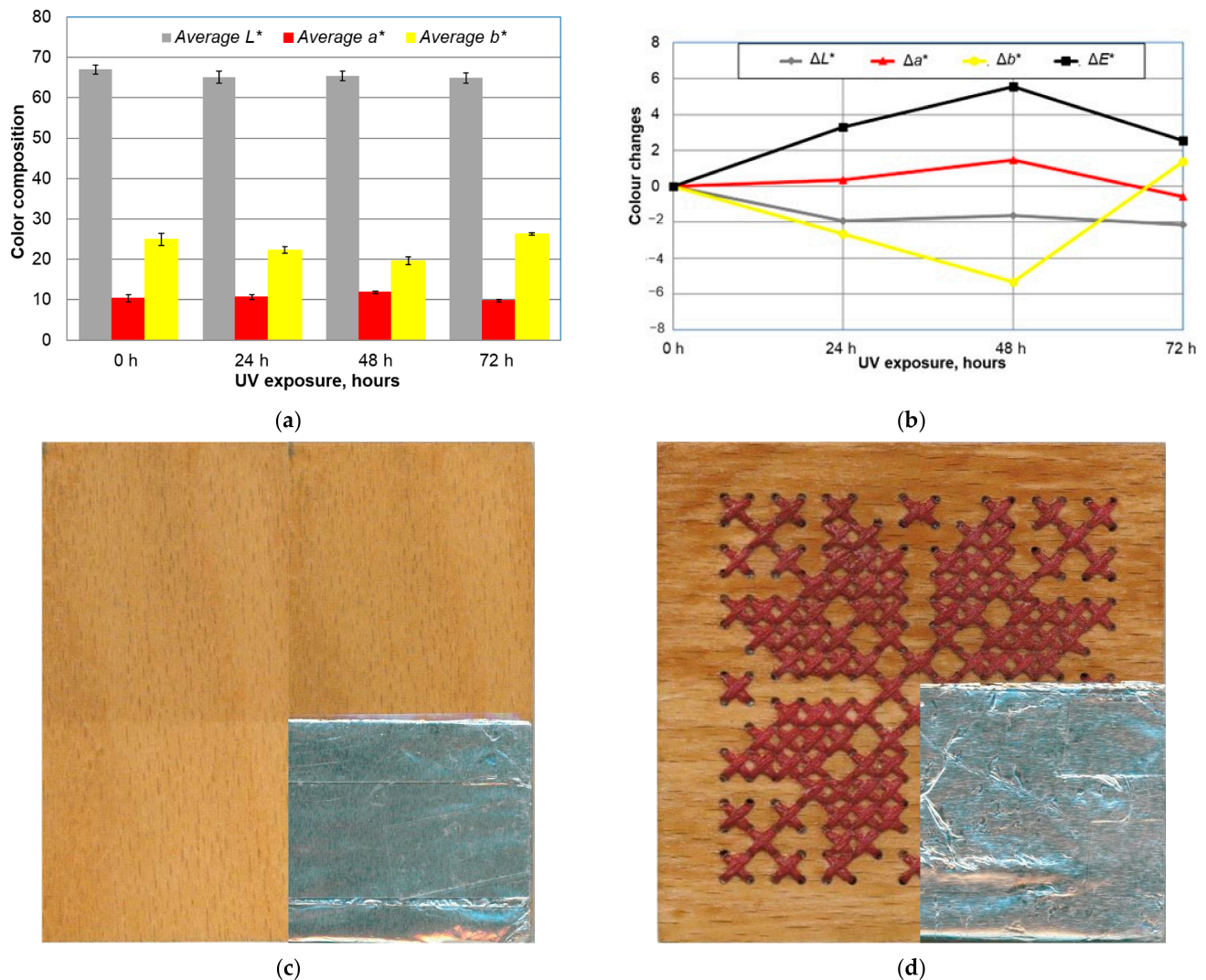


Figure 11. Color analysis of nitrocellulose varnished sample: (a) L^* , a^* , and b^* color coordinates during the aging treatment. (b) The dynamics of color change. (c) Change in color of the wood surface (left) and half-protected sample after 72 h of UV exposure. (d) Change in color of the stitched sample (left) and the half-protected sample (right) after 72 h of UV exposure.

For the solvent-based varnished samples (Figure 11), the slight decrease in L^* color coordinate from 67 to 60 after 72 h of UV exposure (Figure 11a) and a negative ΔL^* (to -2 units) noticed in Figure 11b indicate that the samples darkened slightly. The increase to 6 units of ΔE^* after 48 h shows an accentuated color change, due to a 2-unit increase in Δa^* to a positive value and a 5-unit decrease in Δb^* to a negative value, which indicates that the wood surface turned a faded blue. After 72 h of UV exposure, the color change was attenuated, but ΔL^* remained at a negative value of approximately 3 units, thus explaining the demarcation line observed in Figure 11c (left) and also on the stitched sample in Figure 11d (left).

The color analysis of the epoxy resin-based varnished samples is presented in Figure 12. The initial lightness (L^*) value of approximately 52 (Figure 12a) indicates that these samples are darker than those discussed previously, which is also evident from the images shown in Figure 12c,d. After 72 h of UV exposure, the L^* value decreased to approximately 50, while the negative ΔL^* value of about -1.7 (Figure 12b) indicates a slight darkening of the surface due to artificial aging. The ΔE^* value (Figure 12b) increased to almost 8 units after 48 h but decreased to less than 2 units after 72 h of UV exposure, indicating only minor

overall color changes. This is consistent with the images in Figure 12c,d, where the color difference between the exposed and unexposed areas is barely perceptible. The reversal to the initial value of the b^* parameter after 72 h, together with the slightly negative Δb^* value, suggests little change in color. These changes contribute to the slight darkening of the surface, which remains difficult to distinguish visually from the unexposed area.

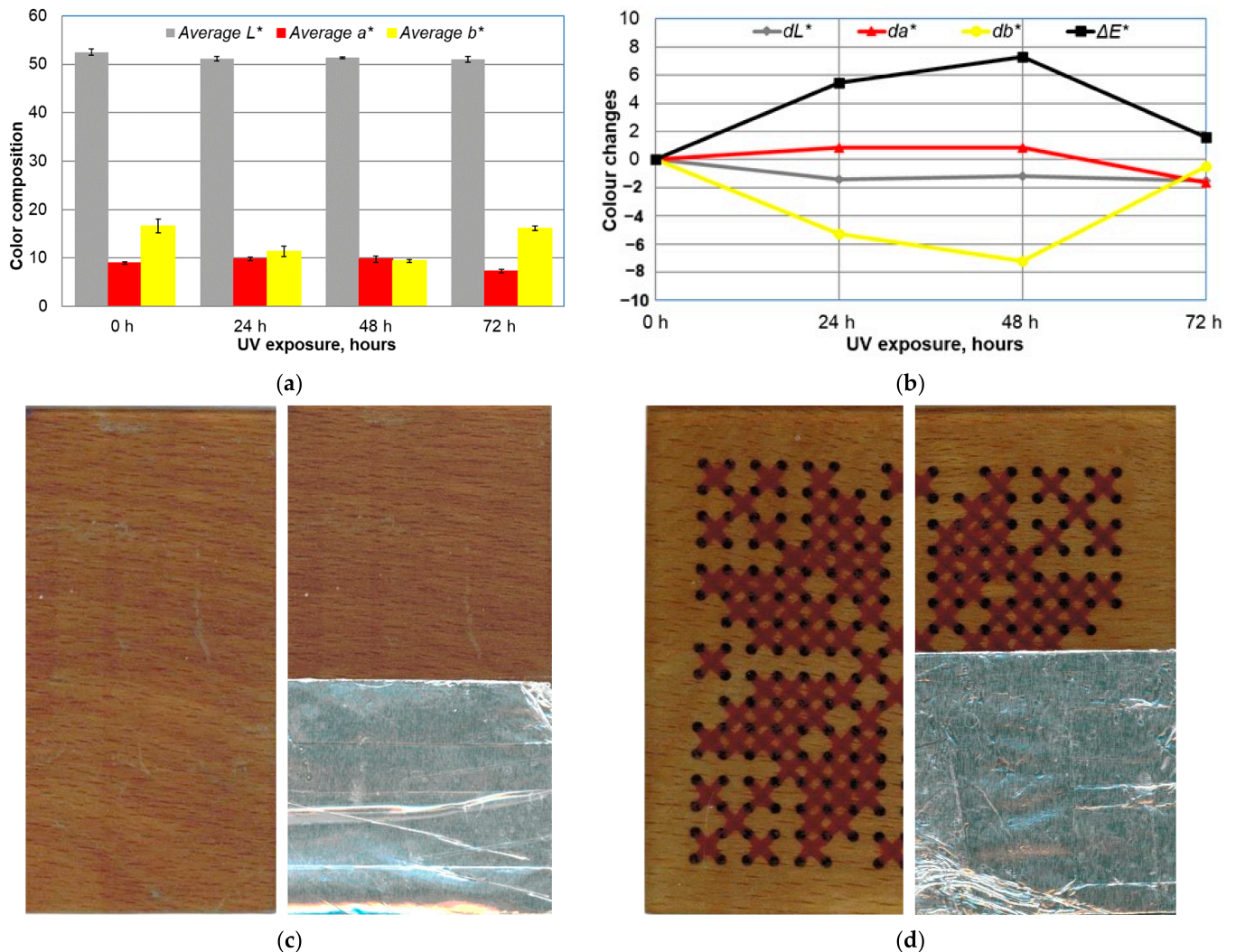


Figure 12. Color analysis of epoxy resin-based varnished sample: (a) L^* , a^* , and b^* color coordinates during the aging treatment. (b) The dynamics of color change. (c) Change in color of the wood surface (left) and half-protected sample after 72 h of UV exposure. (d) Change in color of the stitched sample (left) and the half-protected sample (right) after 72 h of UV exposure.

The color difference (ΔE^*) for all coating systems is shown in Figure 13. The exploratory Tukey HSD analysis showed no significant differences among the investigated systems after 24 h or 72 h of UV exposure, as all samples belonged to the same statistical group (A). After 48 h, two groups were identified: the water-based and epoxy-coated samples belonged to group A, whereas the uncoated plywood and oil- and nitrocellulose-coated samples belonged to groups B and AB, respectively. This indicates that the greatest differentiation in color response occurred at the intermediate exposure time of 48 h. However, because only one physical specimen was tested for each system, the statistical grouping should be regarded as exploratory rather than as evidence of differences between independently replicated samples. Future research will statistically test significance using a sufficient sample size, and chemical characterization of the individual components and their degradation mechanisms is also a valuable direction for future research.

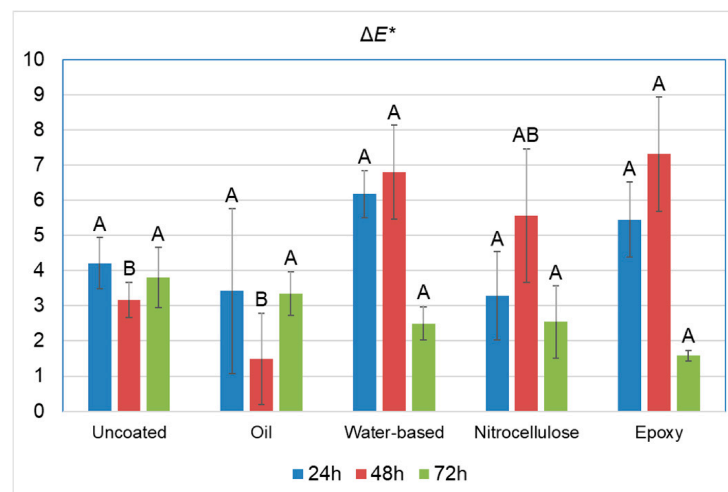


Figure 13. Color differences across all coating systems after 24 h, 48 h, and 72 h (A, B, and AB are statistics groups).

The comparison with other results from the literature (Table 2) shows that ΔE^* is higher for uncoated than for coated wood surfaces and varies with wood species. FTIR analysis of various coated and uncoated wood surfaces under artificial UV aging shows that degradation occurs mainly during the first 24 or 48 h of exposure, via lignin degradation and photooxidation, and significant light-induced color changes can occur during relatively short accelerated exposures. ΔE^* values obtained in the present study after 72 h of UV aging are of the same order as those obtained in other studies for coated wood surfaces, mainly with oil and waterborne coatings, including samples coated with wax and subjected to 7 years of natural indoor light.

Table 2. Comparison of light-induced degradation results with the literature data.

Material	UV Exposure Conditions	Time of Exposure	Color Change (ΔE^*)	Results and Relevance to Present Study	Reference
- Beech plywood with red cotton thread; 4 coating systems: oil; waterborne; nitrocellulose; epoxy resin; uncoated (reference)	- 295–600 nm; - 5 mW/cm ² (at 50 cm); - 40 °C and 55% RH during irradiation.	24 h 48 h 72 h	1.59–3.81 (after 72 h)	- Epoxy resin- and waterborne varnishes provided the highest color stability after 72 h of UV exposure ($\Delta E^* = 1.59$ and 2.49, respectively); - FTIR: slight increase of carbonyl absorption and photooxidation; - SEM: rougher surface and incipient micro-fissures.	Present study
- Maple - Ash - Walnut (uncoated and waterborne coating materials)	Same conditions as in the present study.	24 h 48 h 72 h	Uncoated wood: 6.20–9.36; Coated surfaces: 2.25–7.70. (after 72 h)	- Polyurethane film-foaming resin applied on ash wood: $\Delta E^* = 2.25$ (72 h), close to the value for waterborne varnish used in the present study for beech plywood surface. - Statistically significantly higher color differences were obtained for the uncoated samples—maple (9.36 units), ash (8.39 units), walnut (6.20 units)—compared to the coated ones.	[38]
Maple Walnut Coated with Shellac, clove and thyme essential oils	Same conditions as in the present study.	24 h 48 h 72 h	maple: 1.63–4.53; walnut: 2.39–3.58 (after 72 h)	- Minor chemical changes in coating systems; - The values of ΔE^* of the oiled samples are broadly comparable with those reported in the present study.	[36]

Table 2. Cont.

Material	UV Exposure Conditions	Time of Exposure	Color Change (ΔE^*)	Results and Relevance to Present Study	Reference
Maple Walnut, uncoated and wax-coated	Natural indoor daylight	7 years	11.66–12.54 (uncoated) 4.79 (coated with Chinese wax) 6.44 (coated with beeswax)	- Surface chemistry changed during prolonged indoor exposure. - Accelerated exposure from the present study induces color changes of the same order of magnitude as those observed after seven years of natural indoor exposure. - The 72 h UV-aging exposure in the present study was considered an accelerated simulation of prolonged indoor light exposure.	[37]
23 wood species	UVA-340 nm irradiation 0.89 W/m ² , 60 °C	2–336 h	Rapid color changes especially during 16–48 h	- FTIR: lignin/hemicellulose degradation and formation of carbonyl chromophores.	[45]
- Uncoated fir, pine, larch, ash, cherry and walnut samples.	Same conditions as in the present study.	6 h 12 h 18 h 24 h	min. 7.05 (ash); max. 15.93 (pine) (after 24 h)	- FTIR: lignin degradation and photooxidation with formation of carbonyl-containing chromophores, detectable after 6 h. - Larger ΔE^* values than in the present study (strong influence of wood species and coating substrate).	[46]
Poplar wood	Solar Box chamber; 550 W/m ² , 55 °C, UV filter at 280 nm.	504 h	Largest color variation during the first 24 h	- FTIR: lignin degradation occurred mainly during the first 48 h; color variation correlated with wood degradation; - Strongly supports the use of short exposure periods for detecting the initial stages of photodegradation and the combined interpretation of color and FTIR results.	[53]
Scots pine	Accelerated simulated sunlight	24–500 h	20–22 (after 24 h)	- Most color change occurred within the first 24 h; - Significant light-induced color changes can occur during relatively short accelerated exposures.	[54]

3.2. Microscopic Investigation Results

Microscopic investigation of the thread before and after UV exposure is presented in Figure 14. The magnification used to measure the thread thickness was 60 $\times$, whilst the magnification used to measure the thread thickness on the varnished and unvarnished stitched plywood was 22.5 $\times$. The thread was collected from the sample shown in Figure 7c, from both the unexposed and exposed areas. The marked crosses from the stitched samples were analyzed by microscopy and measured before and after UV exposure. They are shown in Table S1 in the Supplementary Material.

Microscopic examination of the red textile thread revealed an 18–22% decrease in thickness after the UV exposure, indicative of shrinkage.

Following UV exposure, as shown in the Supplementary Material and observed visually, the thread on the uncoated specimen exhibited a more irregular morphology, characterized by loose fibers and non-uniform thickness along the seam. The application of the varnishes caused noticeable microscopic changes in the textile thread. The thread appeared more frayed, flattened in the central region, and thinner near the perforations, while its color also differed from that of the unvarnished thread (Table S1 in the Supplementary Material).

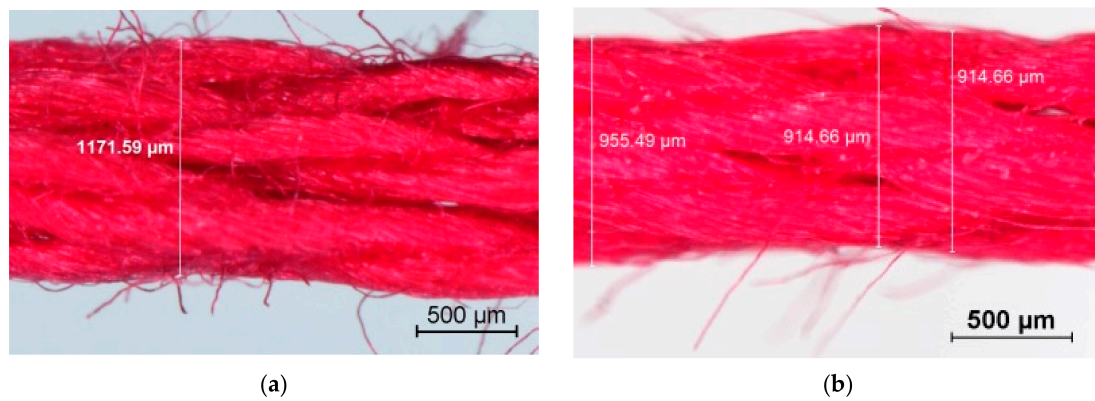


Figure 14. Microscopy of the red thread: (a) Before UV exposure. (b) After UV exposure.

The images in Figure 15a,b show the general structural aspect of the red cotton thread, which is made up of bundles of twisted fibers. A deeper insight at 3000 $\times$ magnification reveals the so-called “wrinkle-like” or “wrinkled” fibrillary structure, resulting from the structure of the vegetal cell wall of cotton fibers and their subsequent processing from raw material to finished cotton thread [32,55].

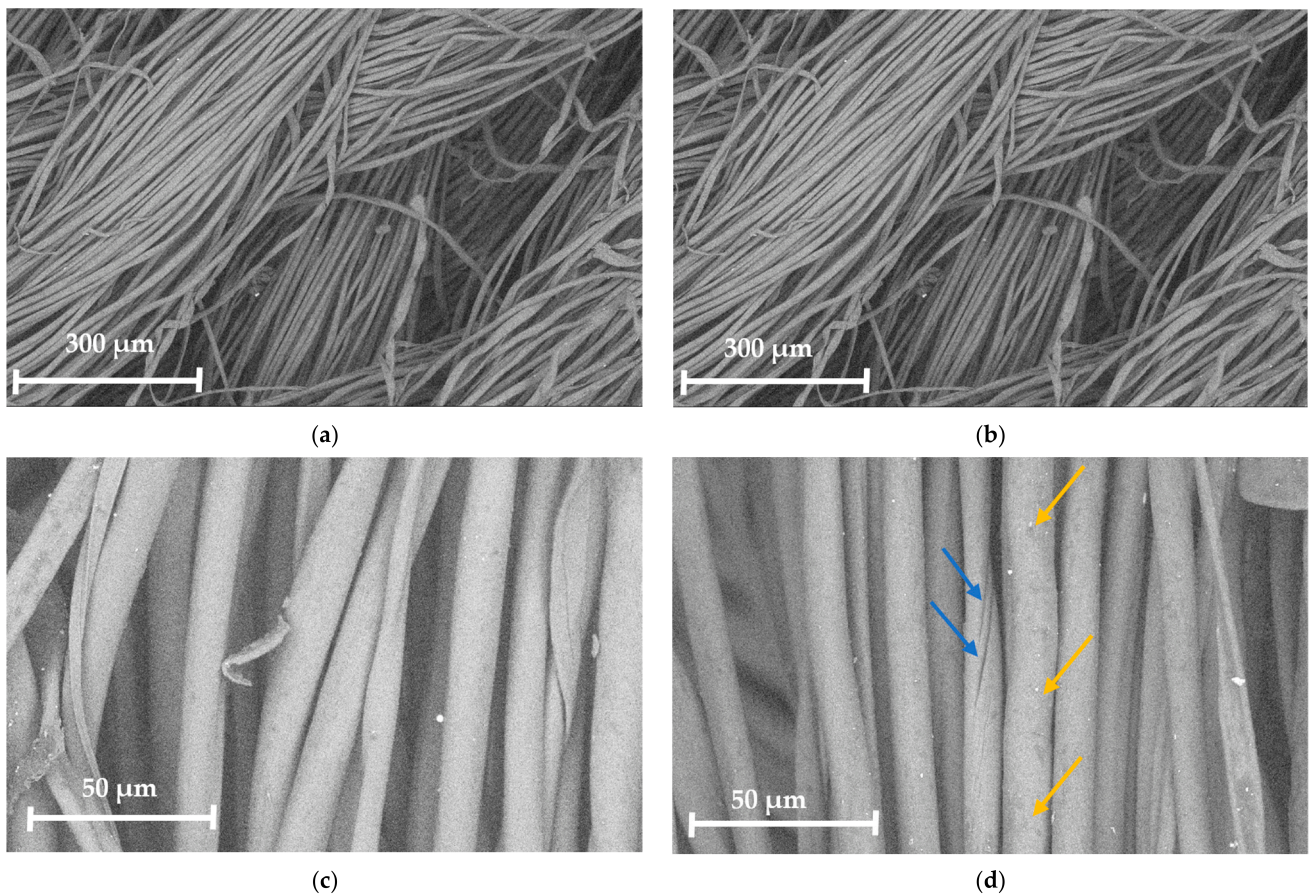


Figure 15. SEM microscopy of the red thread: (a,c) Before UV exposure. (b,d) After 72 h UV exposure, at magnifications of 500 $\times$ (a,b) and 3000 $\times$ (c,d). Blue arrows indicate incipient micro-fissures; orange arrows indicate rougher areas on the fiber surface.

Cotton is a seed hair fiber in the form of a single cell, emerging from the epidermis of the cotton seed when cotton grows on the plant. The cells are hollow, moisture-filled cylinders that transform into a flattened, twisted ribbon as water in the central lumen evaporates, causing the cell walls to collapse. These natural twists are called convolutions,

which visually mimic tiny, random wrinkles along the length of the cotton thread. Moreover, the spiral orientation of the cellulose microfibrils in the S2 layer of the cotton fiber cells, with directions that change randomly from S to Z shapes, alongside H-bonding between cellulose chains, contributes to the specific microscopic pattern of cotton fibers [55]. Exposure of the cotton thread to UV radiation for only 72 h in this research did not bring major structural changes, but a rougher, eroded surface of the twisted fibers, observed as circular or uneven areas, alongside some incipient fissures, possibly along the cellulose fibrils helicoidally oriented, is visible (Figure 15d). Previous research on the photo-degradation of cotton fabrics exposed to UV radiation at 35 W/m^2 , for periods of time from 150 h [32] up to 750 h [31], showed that SEM revealed a coarser and cracked texture of the fibers as the exposure time increased, with dramatic erosion on the fiber surface after 750 h. Thus, it seems reasonable to conclude that in the present research, only an incipient phase of photodegradation of the cotton thread was observed and that longer UV exposure times would be necessary in future research to achieve a more relevant evaluation.

3.3. FTIR Investigation Results

The spectra of the red thread before and after aging are presented in Figure 16 for the fingerprint region, while the spectra in the whole registered mid-IR domain are presented in the Supplementary Material (Figure S1).

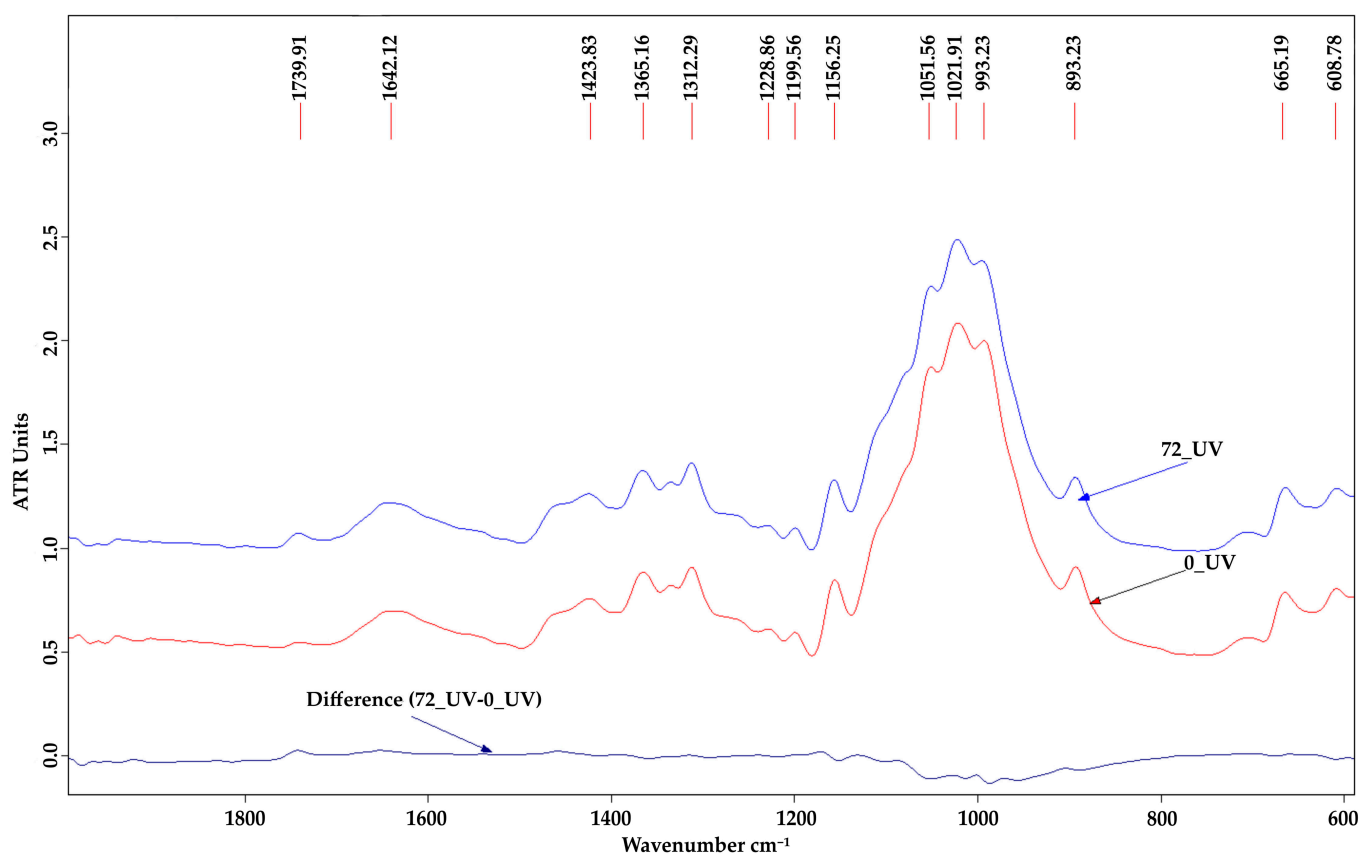


Figure 16. FTIR comparative spectra for the red thread before (0_UV) and after aging (72_UV) on an enlarged view of the fingerprint region $1800\text{--}600 \text{ cm}^{-1}$.

At a first analysis in its initial state (0_UV), the cellulosic nature of the material became clear, due to the presence of all the characteristic important features of their chemistry, revealed by specific IR absorptions, as follows: 3300 cm^{-1} (intense and broad band), assigned to stretching vibration of the H bonded -OH hydroxyl groups; $2914\text{--}2851 \text{ cm}^{-1}$ (compound sharp band with three max values), assigned to C-H symmetri-

cal and asymmetrical stretching vibration; 1642 cm^{-1} (small broad peak), usually assigned to the in-plane bending of -OH groups in the adsorbed water; 1423 cm^{-1} , 1365 cm^{-1} and 1228 cm^{-1} (a group of vibrations of lower intensity) assigned to H-C-H, O-C-H, C-H and C-OH bending at C6 of the anhydro-glucopyranose units; 1199 cm^{-1} (very small) and 1156 cm^{-1} (small), assigned to symmetrical and asymmetrical C-O-C glycosidic bonds between the glucopyranose units; 1021 cm^{-1} (broad and intense combined absorption band with secondary peaks at 1051 cm^{-1} and 993 cm^{-1}), assigned to C-C, C-OH, C-H vibrations of pyranose ring and side groups (-OH, -CH₂-OH); and 893 cm^{-1} (small band), assigned to stretching of glucose ring and β -glycosidic linkages [56–58]. According to the literature, the band at around $1420\text{--}1430\text{ cm}^{-1}$ (currently identified at 1423 cm^{-1}) is associated with the amount of the crystalline structure of the cellulose, while the band at around 898 cm^{-1} (currently identified at 893 cm^{-1}) is assigned to the amorphous region in cellulose, the ratio between the two being defined as an empirical crystallinity index [57,59].

A very small absorption at around 1740 cm^{-1} , assignable to unconjugated carbonyl groups in esters and acids, which is not characteristic of cellulose, was also detected. This might indicate an impurity originating from the cellulose source and dependent on the performance of the extraction procedure, such as residues of hemicelluloses, wax, or pectin [58]. Also, it should be considered that the spectrum of the analyzed sample may contain signals from the treatments applied during processing from raw cellulose to colored and finished thread, possibly including carbonyl-containing chemicals.

The accelerated UV aging procedure applied in this research resulted in only minor changes in the FTIR spectra, as can be observed by a direct visual comparison of the spectra 0_UV and 72_UV in Figure 16. To highlight these changes, a difference spectrum was calculated by subtracting the initial spectrum (0_UV) from the final spectrum (72_UV). Accordingly, the main alterations observed were: an increase in the absorption in the region $2920\text{--}2850\text{ cm}^{-1}$ of C-H absorptions in the aliphatic backbone of the carbohydrate units, occurring in parallel with a slight decrease in the absorptions in the region $1200\text{--}900\text{ cm}^{-1}$ of the various C-O, C-H, C-OH, C-O-C vibrations due to the characteristic features of cellulose structure, including glycosidic bridges C1-O-C4 linking the constitutive glucose units. These indicate changes in the chemical structure of the pyranose ring and the side -OH, -CH₂-OH groups, alongside chain scissoring by cleavage of the glycosidic bridges. Also, in the fingerprint region, a slight increase in the absorption of the unconjugated carbonyl groups at 1740 cm^{-1} is visible, which might be associated with photo-oxidative degradation, a phenomenon characteristic of organic polymers, including cellulose.

Indeed, photooxidative degradation of cellulose results in a decrease in degree of polymerization by chain scissoring, concurrently producing chromophore groups, such as carbonyl, carboxyl, and hydroperoxide groups within the polymer [60]. A more recent FTIR and UV/VIS study of oxidative degradation of model paper demonstrated an oxidative route of cellulose degradation during artificial aging of paper in air at $90\text{ }^{\circ}\text{C}$ and RH 59%, leading to the formation of various carbonyl groups. These are either single ketones on C2 and C3 transforming into conjugated diketones in the next oxidation step or into aldehydes and finally carboxylic groups on C6, which explain the increased absorptions for conjugated and unconjugated carbonyl groups at around 1640 cm^{-1} and 1740 cm^{-1} . Also, an oxidative cleavage of the glycosidic bond was proposed and supported by charge distribution calculations [61].

This complex, multi-route, oxidative process leading to the formation of ketones at C2 and C3 and aldehyde or carboxyl groups at C6 is the reason for the depletion of HO-C-H and -CH₂-OH structures, explaining the decrease in the C-H absorption in the range $2914\text{--}2850\text{ cm}^{-1}$, occurring in parallel with an increase in the absorption at 1740 cm^{-1} , as observed in the research presented in this paper. These changes may explain the minor

micro-structural changes in the cotton fibers observed by SEM. This is in good agreement with other research showing that the photodegradation mechanism of cotton fibers resides in oxidation of hydroxyl side groups and rupture of glycosidic bonds between cellulose units, leading to microstructural damage to the fibers' integrity and mechanical strength losses in cotton fabrics, alongside yellowing [31].

To conclude, the FTIR results are in line with current knowledge and the literature data, demonstrating some photo-oxidative degradation of the cellulose structure as a result of UV aging of the red thread under the experimental conditions of this research, which correlates with SEM investigation. Without any supporting information from the thread producer or an uncolored reference thread, the possible chemical alterations in the dye/finishing products, leading to minor fading and color shade modification, could not be identified.

The colorimetric, spectroscopic, morphological, and dimensional results provide complementary evidence of red cotton thread degradation under UV exposure. The progressive increase in ΔE^* , reaching 4.36 after 72 h, occurred concomitantly with chemical modifications detected by FTIR, particularly the slight increase in the absorption around 1740 cm^{-1} , consistent with the formation of unconjugated carbonyl groups during photo-oxidative degradation. These chemical changes were accompanied by morphological deterioration, as evidenced by incipient micro-fissures in SEM images and an approximately 18–22% reduction in measured thread thickness. Taken together, these observations suggest that UV-induced photo-oxidative modifications of the cellulose structure are associated with progressive physical deterioration and color alteration of the cotton thread.

4. Conclusions

After 72 h of UV exposure at $40\text{ }^{\circ}\text{C}$, the red sewing thread exhibited visible color changes ($\Delta E^* > 4$), with yellowing as the determining factor in the overall color change, in good agreement with visual perception, with slight lightening and a shift towards yellow being visible. Microscopic analysis also revealed thread shrinkage, with a thickness reduction of approximately 18–22%.

Among the investigated finishing systems, epoxy resin and waterborne varnishes provided the highest color stability, limiting color change in both the wood substrate and the decorative thread. Oil varnish also provided satisfactory protection, whereas the nitrocellulose finish was more susceptible to UV-induced discoloration.

Microscopic observations showed no significant structural degradation of the sewing thread in the coated specimens after aging.

FTIR investigations demonstrated that UV aging of the cotton thread resulted in photo-oxidative degradation of cellulose, with carbonyl group formation and chain scission, consistent with the color change, the approximately 18–22% reduction in thread thickness, and the incipient microstructural degradation observed by SEM.

Overall, the results demonstrate the technical feasibility of decorating drilled plywood by sewing heritage-inspired textile motifs for contemporary furniture applications. The 72 h accelerated aging test revealed limited changes in color, chemical structure, and microstructure, supporting the potential of this approach for the contemporary reinterpretation of textile heritage. Longer UV exposure periods are recommended in future research to further evaluate the aging behavior of the decorative systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16178721/s1>, Figure S1: FTIR comparative spectra for the red thread before and after UV-aging (72 h) on the whole IR registration range $4000\text{--}600\text{ cm}^{-1}$; Table S1: Microscopic analysis of the samples before and after 72 h of aging treatment.

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