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Original Research

Experimental Investigation of a Lignin-based Adhesive Layer for Biodegradable Composite Material Made With Wood Veneer and Hemp Fabric

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Abstract

Background: The current adhesives for textile laminates are generally fossil-based, with corresponding disadvantages for recycling of the composite and biodegradability in the environment. Together with cellulose, lignin is one of the main structural components of wood and is generated in large quantities as a by-product of the paper manufacturing industry. With suitable processing, lignin can be applied as a bio-based adhesive in textile composites. **Methods**: In this study, lignin was applied as a thermoplastic adhesive interlayer to bond wood veneer and hemp fabric. The resulting composite ("flexwood") was evaluated in terms of its mechanical properties (tear resistance, delamination strength), durability under accelerated dry heat and wet ageing, and biodegradability through soil burial tests in an outdoor field. Reference composites made of cotton and synthetic textiles were used for comparison. These were bonded to the same wood veneer using polyurethane adhesive. **Results**: Flexwood showed significantly higher tear resistance compared to conventional reference composites. Ageing tests demonstrated stable mechanical performance of flexwood over several weeks, although its adhesive strength decreased under prolonged humid conditions. Soil burial experiments revealed that both flexwood and the cotton-based reference degraded almost completely within 211 days, whereas the synthetic-based composite showed no relevant decomposition. **Conclusions**: The results demonstrate that lignin-based adhesives have strong potential for use in textile–wood composites due to their good mechanical performance and high durability for applications such as interior and automotive design. Flexwood is completely biodegradable, as confirmed by the soil burial experiments, contributing to more sustainable material cycles. Furthermore, it can replace petroleum-based polymers such as polyurethanes in textile-wood composites for various applications, thereby reducing both the carbon footprint of the products and microplastic pollution.

Keywords: textiles; composites; adhesive; lignin; wood veneer; hemp; soil burial test; biodegradation; microplastics

1. Introduction

1.1 Flexible Wood-Textile compound

The growing demand for sustainable materials in both interior design and the automotive industry has led to the development of numerous new products [1,2]. One emerging approach for the replacement of synthetic leather involves processing wood into a soft, fabric-like material through laser engraving within a textile composite (Fig. 1). As a renewable raw material, wood fulfills key requirements for circularity. However, the conventional adhesives and textiles employed in the fabrication of wood-based composites are typically derived from non-renewable sources and therefore lack environmental sustainability. Cotton and synthetic textiles are often used for lamination. Life cycle assessments show that conventional cotton and many synthetic textiles have different impacts compared to other fiber materials (jute, hemp, or recycled fibers) and have greater negative environmental impacts in terms of water use, pesticide/fertilizer requirements, energy consumption, and microplastic emissions [3,4].

To meet the growing demand for a more sustainable alternative, a key challenge is to manufacture such composites using adhesives and textiles that align more closely with circular economy principles. Identifying sustainable textile alternatives is not a major obstacle, as the market already offers a variety of environmentally friendly options. In the present study, we selected hemp fabric due to its favorable ecological profile and because its mechanical properties are comparable to conventional alternatives [5–7].

However, the adhesive layer remains a bottleneck for composite materials, with synthetic resins continuing to dominate. Despite decades of research as a wood adhesive [8–11], lignin has yet to achieve commercial breakthrough. Challenges include limited solubility, inconsistent performance, and the need for chemical derivatization (e.g., etherification, esterification, sulfonation) to improve bonding properties [12–15]. Commercial thermoplastic lignin polymers have shown the technology is technically feasible, although its use in veneer–textile laminates has yet to be thoroughly investigated.

Fig. 1. Highly flexible wood-textile composite with a laser-treated surface.

1.2 Lignin—A Biopolymer With Great Potential

Research in the field of bio-sourced materials is becoming increasingly important for the development of a green bioeconomy. As pointed out by Mili *et al.* [16], lignin is a particularly promising candidate due to its abundance, non-toxicity, and biodegradability. Numerous studies have confirmed the multifunctionality of lignin, with demonstrated applications as a binder in wood adhesives for fiberboard, particleboard and plywood, as well as in printed circuit boards. Lignin is also a promising green alternative in 3D printing and adhesive hydrogels, as a soil protectant, in lignocellulosic paper, in coatings, as well as in many other applications [16].

Increasingly, lignin is being investigated for possible applications in the textile sector. Studies have also explored its use as a flame retardant and as a dyeing agent [17]. Moreover, in the form of nanolignin, it has been identified as a promising UV blocker and antibacterial agent for linen textiles [18] Reports by Upton *et al.* [19], Antunes *et al.* [20], and Glasser [15] provide comprehensive overviews of derivatization strategies and functional applications for lignin.

These studies highlight the versatility of lignin and its potential for sustainable material design. However, most studies to date have focused on coatings, particulate incorporation, or chemical modifications in conventional wood or textile systems. The potential role of lignin as a continuous adhesive in hybrid composites is not well understood.

1.3 Research Gap and Aim of This Study

Previous research has demonstrated the functionality of lignin in coatings, wood adhesives, and textiles. However, there are no systematic studies on lignin films as adhesive layers in flexible, layered wood–textile composites. This knowledge gap concerns not only its adhesive performance, but also the long-term stability and biodegradability of such systems—key aspects for sustainable material design. To address this gap, the present work investigated a composite consisting of wood veneer, hemp fabric, and lignin film as the adhesive layer. Specifically, the focus of this study was:

(i) the bonding performance of lignin films;

(ii) their ageing behavior under controlled heat and humidity conditions;

(iii) the biodegradability of the resulting material in soil environments.

By clarifying these aspects, our study provides novel insights into the feasibility of lignin films as sustainable ad-

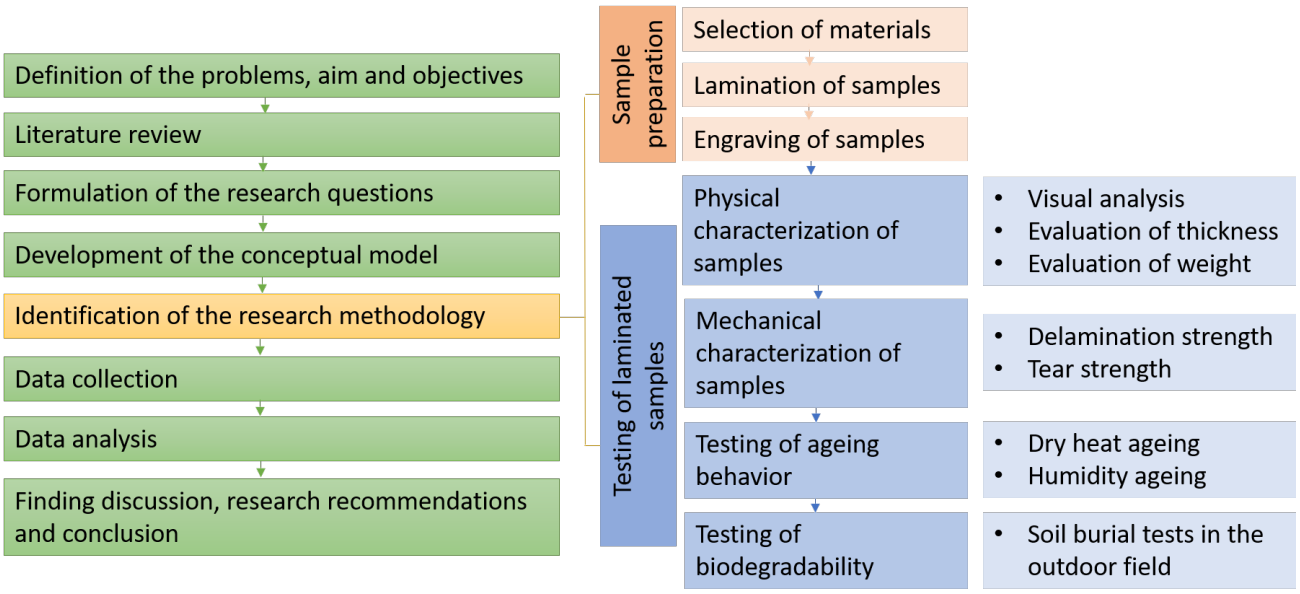


Fig. 2. Overview of the flowchart for this research study.

hesives for natural textile–wood composites, as well as their potential applications in interior and automotive design.

To achieve the stated objectives and close the research gap, we applied the extensive research methodology comprising the stages shown in Fig. 2. Following a thorough review of the literature on the use of lignin adhesives for textiles, the following research questions arose: "Which lignin and textiles should be used, and which references should be consulted? What method should be used to apply the lignin adhesive layer? Which properties are most important, and which preliminary and follow-up tests need to be carried out? How should the results be detected, evaluated, and interpreted?" The data collection involved lamination, physical and mechanical tests, as well as accelerated climate ageing and soil burial tests. The working concepts and methods were subsequently developed and are explained in more detail in section 2.2. The collected data was analysed with particular reference to maximum tear strength loss.

2. Materials and Methods

2.1 Materials

Textiles: The new fabric used in this study was Hanf-420, a 100% hemp canvas with a width of 150 cm and a weight of 420 g/m^2 (Inspiration Stoffe, Weissach im Tal, Germany). This new fabric was compared with two reference fabrics that are already used in the production of wood-textile compound:

- The first reference fabric was a black cotton drill fabric with a nominal width of 160 cm and a weight of 280 g/m^2 (Accoppiatura Expert s.r.l., Gravellona Lomellina, Italy). It was composed of 100% cotton, featuring a 3/1 twill weave.
- The second reference material was Mycro Dashboard CP1616 (Giardini S.p.a., Vigevano, Italy), a synthetic non-woven composed of 50% polyurethane (PU) and 50% polyamide (PA). It had a weight of 390 g/m^2 ($\pm$20 g/m^2) and a thickness of 0.95 mm ($\pm$0.15 mm).
- For the first lamination and delamination tests, a cotton fabric was used (DRILL MODENA GG, Busto Garolfo, Italy, 280 g/m^2).

Lignin: The lignin-based thermoplastic compound used here was a blend of hardwood-kraftwood lignin provided by Tecnaro GmbH, Ilsfeld, Germany. The lignin granulate exhibited a melt volume flow rate of 5 cm^3/10 min at 190 °C under a 2.16 kg load according to ISO 1133 [21], a heat deflection temperature of 41 °C according to ISO 75 [22], and an elastic modulus of 100 MPa measured at 1 mm/min according to ISO 527 [23].

Adhesives: For bonding the reference materials, the polyurethane (PU) dispersion KLEIBERIT 450.7 (Kleiberit SE & Co. KG, Weingarten, Germany) was used. The adhesive was applied at a rate of 100 g/m^2 using a Wirth LW 120 roller coater (Axel Wirth Maschinen GmbH, Oberkochen, Germany) to ensure uniform distribution.

Wood veneer: All experiments used 0.6 mm thick American walnut veneer (Juglans nigra). The veneer was produced by tangential slicing, resulting in a characteristic straight grain pattern and uniform surface texture. Prior to bonding, the veneer was left untreated to preserve the natural surface condition. The surface characteristics of all veneers used can be assumed as comparable. For bonding the veneer to the required sheet size, a UF-based glue was applied (Dynea Prefere 4452, Dynea, Lillestrøm, Norway). This wood was selected for its aesthetic appeal, durability, and widespread use in high-end interior and automotive applications.

Soil: For the soil burial experiments, a certified compost (RAL GZ 251, test no. 5117-174136-1) supplied by Döbler GmbH, Kirchheim unter Teck, Germany, was used to ensure constant quality and reproducible testing conditions. According to the supplier's specifications, this compost is an organic NPK (nitrogen (N), phosphorus (P), and potassium (K)) fertilizer containing trace elements and derived entirely from plant materials sourced from horticulture and landscaping. The soil had a grain size of up to 10 mm, a density of 600 kg/m^3, and dry matter of 64.8% with particularly high biological activity.

2.2 Methodology

The methodology used in this study can be divided into two main parts: sample preparation, followed by testing of the laminated samples. These are described in detail in the following sections.

2.2.1 Sample Preparation

2.2.1.1 Selection of Materials. Materials were selected for the preparation of three types of laminate samples: one newly developed sustainable alternative, and two commercially available reference materials. These differed in their composition with the exception of the wood veneer. They consisted of the following components, starting from the surface to the back:

(1) flexwood (the new composite material): wood veneer, lignin adhesive layer, hemp fabric in black.

(2) nuo_bw (first reference): wood veneer, PU adhesive layer, cotton fabric. Due to limited availability, a white version was used for the burial tests and a black version for all other tests. All properties of both color variants were identical.

(3) nuo_mf (second reference): wood veneer, PU adhesive layer, synthetic non-woven fabric. Due to limited availability, a white version was used for the burial tests and a gray version for all other tests. All properties of both color variants were identical.

2.2.1.2 Lamination of Samples. The lamination technique with a lignin adhesive layer was studied in detail for the new flexwood composite material, while the others were produced using standard production methods.

For the lignin-hemp composite samples, 100 g (flexwood_1) and 200 g (flexwood_2) of lignin film were manually deposited on the hemp fabric and subsequently laminated with the wood veneer for 40 seconds at 120 °C with a specific pressure of 5 N/mm^2 using an Italpresse SCF/10 (ITALPRESSE S.P.A., Bagnatica BG, Italy). Only flexwood_2 was used for the subsequent investigations, and this is referred to as "flexwood" in the following sections.

For the production of laminated reference samples, the wood veneer was first coated with PU dispersion KLEIBERIT 450.7 using a roller coating machine (Wirth LW 120, Axel Wirth Maschinen GmbH, Oberkochen, Germany) and subsequently bonded to the textile layers (cotton [nuo_bw] or synthetic [nuo_mf]) by hot pressing for 2 minutes at 120 °C and applying a pressure of 9.3 N/mm^2 using the same Italpresse SCF/10.

2.2.1.3 Engraving of Samples. Following lamination, the materials were sanded (Bütfering SCO 413, HOMAG Group AG, Schopfloch, Germany) to achieve a final thickness of 0.95 mm for the hemp and cotton composites, and 1.2 mm for the microfiber composite. After sanding, all samples were processed using an SEI Mercury ME603.03027 laser cutting machine (Sei S.p.a, Curno, Italy) to engrave softening textures into the wood veneer. An overview of these composite samples is shown in Fig. 3.

All three samples (flexwood, nuo_bw, nuo_mf) were first examined in terms of their mechanical and physical properties. The specific characterization methods are described in more detail in the next section.

2.2.2 Testing of Laminated Samples

2.2.2.1 Physical Characterization. Visual analysis: Fig. 3 shows macroscopic images (Olympus SZX16 High-End Stereo Microscope, Model SZX2-ILLTQ, Evident Corporation, Nagano, Japan) of the cross-section and surface of the back side (textile side) of the prepared composite samples.

Evaluation of thickness: The laminate thickness was determined with an accredited thickness gauge (Käfer Messuhrenfabrik GmbH & Co.KG, Villingen-Schwenningen, Germany) and with a measuring interval of 0.01 mm, accuracy of 0.015 mm, and a measuring plate diameter of 10 mm.

Evaluation of weight: The laminate weight was determined with a laboratory scale Mettler PM 200 (Mettler Toledo GmbH, Gießen, Germany).

2.2.2.2 Mechanical Characterization of Samples. Delamination strength: A peel test using non-lasered laminated samples was applied to assess delamination. Test specimens with a length of 30 cm and width of 9 cm were used. The first 7 cm of each specimen were kept unbonded. The test was carried out using a universal testing machine (TiraTest 28025, TIRA GmbH, Schalkau, Germany) equipped with a load cell of up to 2.5 kN. For the 180° peel test, the wood and textile samples were secured in the testing machine and separated at a constant rate of 10 mm/min. The initial clamping length at the start of the test was 8 cm. The maximum peel force was documented, as well as the average force measured between 3 cm and 18 cm of the bonded length.

For laser-treated samples, the delamination strength could not be evaluated using the standard peel test due to the non-continuous surface structure. As an alternative, adhesion was assessed using a tape pull-off test. A PE tape

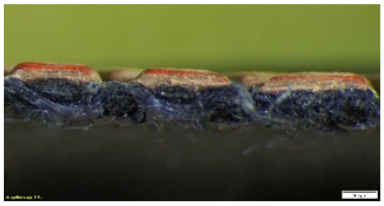
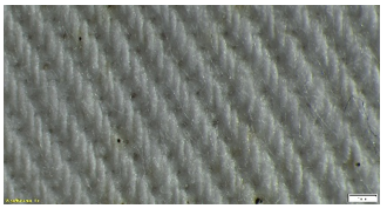
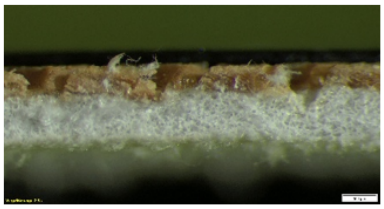
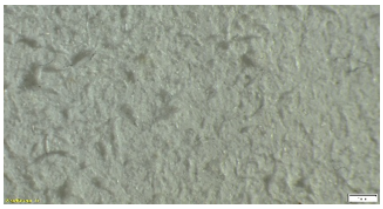
Sample	Bottom left side, top right side	Cross-section of the composite material	Textile surface (back side of the composite material)
flexwood			
nuo_bw			
nuo_mf			

Fig. 3. Overview of the prepared composite samples.

(HPX Duct Tape 1900, Temse, Belgium) with a width of 48 mm was applied to the laser-treated wood surface over a 7 cm length. The tape was firmly pressed onto the wood and left in place for 5 minutes to ensure appropriate contact. Afterwards, the tape was removed in one continuous motion. The amount of wood fiber adhering to the tape was then evaluated visually. A percentage value (in increments of 10%) representing the area of removed wood fiber transferred to the textile surface was recorded as the delamination result.

Tear strength: Tear properties of the samples were measured according to ISO 13937-2:2000 Textiles—Tear properties of fabrics—Part 2: Determination of tear force of trouser-shaped test specimens (single tear method) [24], where a test specimen was cut to form trouser-shaped legs. The tear force measured was the force required to propagate a previously initiated single tear when the force was applied parallel to the cut, with the fabric tearing in the direction of the applied force.

The tests were conducted with the tensile testing machine Zwick 1455, ZMART PRO (Zwick Roell, Ulm, Germany). The samples were fixed between two ZZW No. 3 clamps equipped with SRM. Tests were performed using a measuring head of 1000 N and a testing speed of 100 mm/min. At least 5 tests were performed for each sample.

2.2.2.3 Testing of Ageing Behavior. Accelerated ageing tests by both oxidation (dry heat ageing) and hydrolysis (humidity ageing) were conducted to simulate the effects of naturally occurring ageing conditions relevant to application in a car interior. The tests were carried out in accordance with standards DIN EN ISO 2440:2020-03 [25] and DIN EN 12447:2021-11 [26].

A climate chamber (WK 340/70/5, Weiss Technik GmbH, Reiskirchen, Germany) with forced air circulation and a tolerance of ±0.5 °C for temperature and ±3% for relative humidity (measured in the center of the usable space) was used for the tests (Fig. 4). The samples for dry heat

Fig. 4. Placement of the composite samples in the climate chamber: dry ageing on metal grids (left); dry and wet ageing in glass vessels (right).

ageing were placed flat on a grid to ensure exposure to the environment from all sides. For humidity ageing, the samples were immersed in water inside a sealed glass vessel. The size of the glass vessel was selected so that the total volume of the specimens did not exceed 10% of the free air volume and the specimens were not under tension. The specimens were cut to 6 × 20 cm, matching the size used for the subsequent mechanical tests, and conditioned for 48 h in the textile testing laboratory at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 2%.

All tests were conducted at a controlled temperature of 70 °C. Samples were taken after 2, 4, 7, 14 and 28 days over the total test period of 28 days. After each sampling, the samples were reconditioned by drying them at 70 °C for 3 h in a climate chamber (MK240, BINDER GmbH, Tuttlingen, Germany), with a temperature fluctuation of ±0.1 to 0.5 °C depending on the set value. The samples were then reconditioned in the textile testing laboratory at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 2%. After reconditioning, the tear strength of the aged samples was measured as described in Section 2.2.2 b.

2.2.2.4 Testing of Biodegradability. The biodegradability of the samples was investigated using outdoor soil burial tests. The experiments were conducted from 23.07.2024 to 19.02.2025 on site in DITF Denkendorf, Germany with coordinates 48°41′ N 9°20′ E. The composite samples were buried at an approximate depth of 30 cm and in direct contact with the soil in the field at a specially chosen site with sufficient solar radiation and rainfall. Over a 211-day burial period, 5 samples each of flexwood and nuo_bw, and 7 samples of nuo_mf were extracted from the soil, cleaned and treated with an ethanol/water (70/30 vol.%) solution for approximately 10 min before conditioning under textile testing laboratory conditions (20 ± 2 °C/65 ± 2% relative humidity). The mechanical properties of the samples were then characterized, as described in Section 2.2.2 b.

3. Results

3.1 Lamination

Table 1 summarizes the physical parameters of the samples, including their thickness, weight per unit area, and the applied engraving patterns on a defined surface area. In addition to differences in thickness and weight, the samples also feature varying laser engraving designs. These engravings differ in shape and pixel density, but are solely decorative in purpose and do not affect the adhesive bonding behavior of the laminates.

Mechanical performance was assessed using a tear test based on the single tear method. Table 2 shows the results obtained for the three laminate materials, summarizing the maximum (F_{max}), minimum (F_{min}), and average tear forces, as well as the number of force peaks observed during testing. These peaks provide insight into the failure behavior and internal resistance of the laminate structure under tear stress. For comparison, the average force of the respective textile substrate without wood lamination is also shown. The results show clear differences in the mechanical response of the different laminate types, which are influenced by both the material composition and the laser engraving.

3.2 Delamination Strength

In order to quantify the influence of the different parameters for the lamination process on the delamination

Table 1. Physical properties of the samples.

Sample	Thickness [mm] (stamp 10 mm)	Weight [g/m^2]	Engraving type and number of pixels on a sample area of 64 mm^2
flexwood	1.19 s = 0.024	723.13	Triangle shape, 16 Pixel
nuo_bw	0.79 s = 0.017	461.45	Rectangle shape, 32 Pixel
nuo_mf	1.32 s = 0.013	721.36	Rectangle shape, 32 Pixel

Table 2. Mechanical tear strength properties of the composite samples determined by the single tear method.

Sample/textile substrate	Fmax [N]	Fmin [N]	Average force [N]	Number of peaks	Average force [N] of the respective textile substrate
flexwood/hemp fabric	70.8 s = 7.35	47.7 s = 6.16	60.0 s = 6.01	48 s = 31	164 s = 4.53
nuo_bw/cotton fabric	15.5 s = 0.928	10.2 s = 0.884	13.2 s = 1.01	86 s = 4	20.4 s = 0.46
nuo_mf/synthetic nonwoven	24.2 s = 7.26	17.8 s = 6.81	17.4 s = 4.08	3 s = 2	57.8 s = 3.91

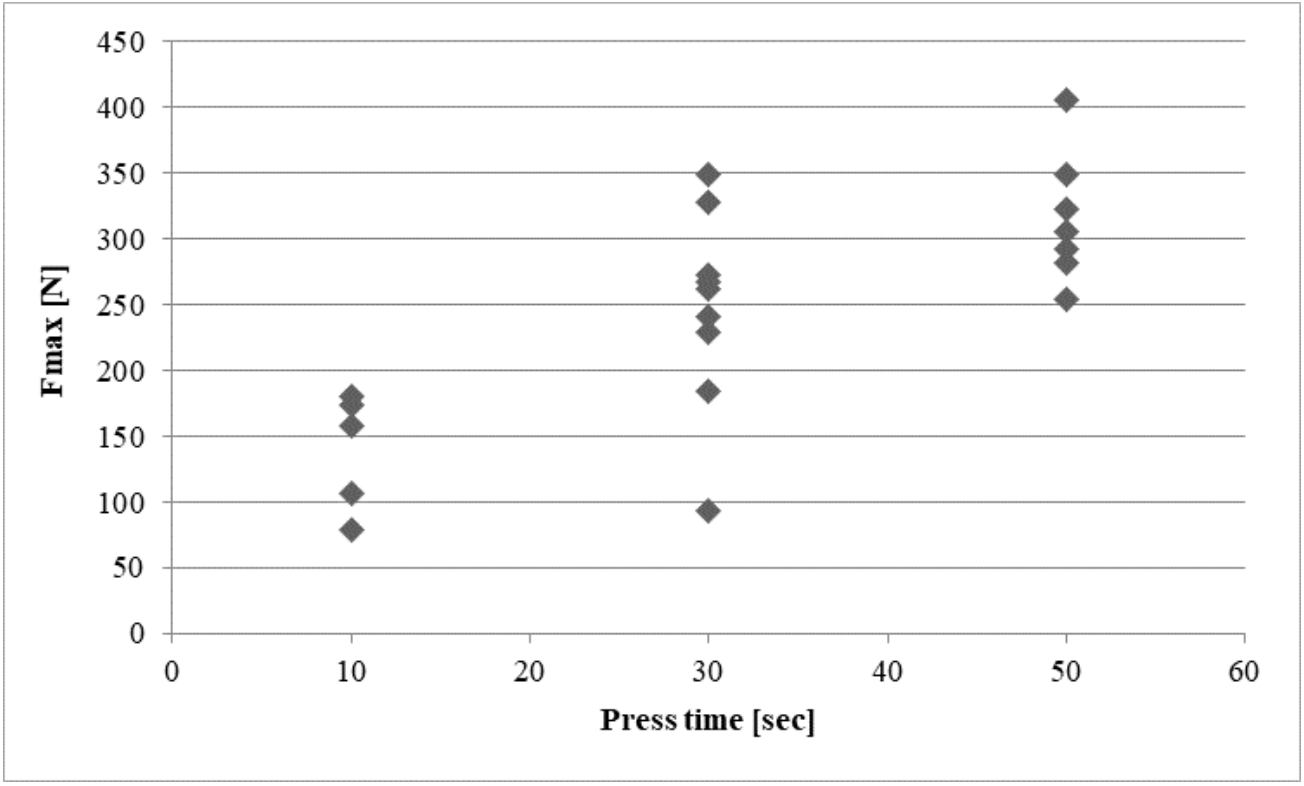


Fig. 5. Maximum peeling force (F_{max}) of samples with lignin bonding to cotton, according to pressing time.

strength of the composite material, test samples comprising cotton textile as a substrate, lignin as an adhesive, and the wood-veneer were prepared. Fig. 5 shows the results for the maximum peeling force of the model samples at different lamination times. The delamination tests revealed notable differences in the adhesion strength depending on the process parameter tested. Six samples could not be evaluated, as they repeatedly broke before testing due to mechanical failure during clamping. However, despite these missing data points, statistical analysis via Analysis of Variance (ANOVA) confirmed that the results remained significant (Table 3). It is important to note this analysis was based solely on the maximum delamination force rather than on the average peeling force. The force-displacement curves showed a high level of inhomogeneity, likely caused by irregular extrusion of the adhesive films leading to local variations in adhesion strength.

Table 3. Results of the delamination tests, showing the variance analysis of influencing factors.

Factor	F-value	*p*-value	Significance
Pressing time	9.83	0.0022	Significant
Pressing pressure	0.85	0.448	not significant
Adhesive thickness	0.0008	0.999	not significant

Table 4. Peel test results for the reference samples and for lignin-bonded specimens (flexwood_0.1 and _0.2 with adhesive film thickness of 0.1 and 0.2 mm, respectively).

Samples	Average peeling force F [N]	Standard deviation [N]
nuo_mf	214.7	14.2
nuo_bw	169.6	23.4
flexwood_0.1	93.8	23.2
flexwood_0.2 (= flexwood)	178.8	24.5

Statistical evaluation revealed that pressing time had the strongest influence on delamination strength, followed by pressing pressure, while the adhesive film thickness appeared to have minimal effect (Table 3). This indicates that sufficient heat activation and mechanical compression are crucial for achieving strong adhesion, whereas increasing the thickness of the adhesive layer beyond a certain threshold does not contribute significantly to bonding performance.

Based on the above results, the lamination process was optimized and the samples for this study were prepared. Among the reference samples, the cotton-laminated veneer (nuo_bw) exhibited a maximum delamination force of 169 N $\pm$ 23 N, while the nonwoven-laminated veneer (nuo_mf) had a significantly higher delamination force of 214 N $\pm$ 14 N. These values provide a benchmark for evaluating the lignin-based adhesive performance under different processing conditions.

The reference samples were compared to specimens bonded with hemp textile using lignin (Table 4). The parameters from previous bonding experiments with lignin were applied to ensure optimal adhesion. In addition, the amount of lignin adhesive was adjusted due to the varying porosity and absorption behavior of the hemp textile. The average peeling forces F [N] over the detachment path were evaluated in this analysis, with the results showing that microfiber textile exhibited the highest peeling force. However, no statistically significant difference (*t*-test, *p*-value = 0.70) was observed between veneer/hemp samples bonded by lignin (flexwood) and the reference sample on cotton substrate bonded by PU (nuo_bw). This suggests that a comparable bonding quality to both reference products was achieved.

3.3 Accelerated Ageing Tests

Visual assessments revealed the wood veneer exhibited a typical colour change in both dry and humid temperature conditions. The samples comprising natural fibre materials (flexwood and nuo_bw) did not show any colour or visual changes over the total test period of 28 days, whereas the nuo_mf comprising synthetic fibre substrate showed much lower colour fastness in both ageing conditions (Fig. 6).

The weight loss from the three materials during ageing in water (2.15–4.47%) was higher than under dry ageing conditions (0.2–2.34%), with all three showing very similar results. No significant change was observed in the average laminate thickness of all three material types during or after the ageing experiments under the different conditions (data not shown).

As shown in Fig. 7, the tear strength of the nuo_bw samples did not vary significantly under either dry or wet conditions. With nuo_mf, high temperature had a slight positive effect on tear strength, which remained unchanged even under wet conditions. In contrast, flexwood showed a significant decrease in tear strength after an initial increase under humid conditions. The sample taken at the end of the test period had a tear strength that was almost 30% lower than that of the untreated sample. Under dry conditions, slight changes were observed in each flexwood sample taken. Moreover, they exhibited slightly higher tear resistance compared to their initial state.

Delamination tests were performed on the aged samples. Adhesion of laser-treated samples was evaluated using the tape pull-off test (as described in 2.2.2 b) after storage under dry and humid conditions for 2, 4, 7, 14, and 28 days. The amount of wood fiber remaining on the adhesive layer after pull-off test was estimated as a percentage and used as an indicator of bonding performance, with the results summarized in Table 5.

Flexwood samples showed a noticeable decline in adhesion over time, particularly under humid conditions. The bonding strength decreased significantly after 14 days, with no adhesion observed after 28 days. In contrast, nuo_bw and nuo_mf samples maintained consistently high adhesion regardless of humidity, indicating superior bonding stability.

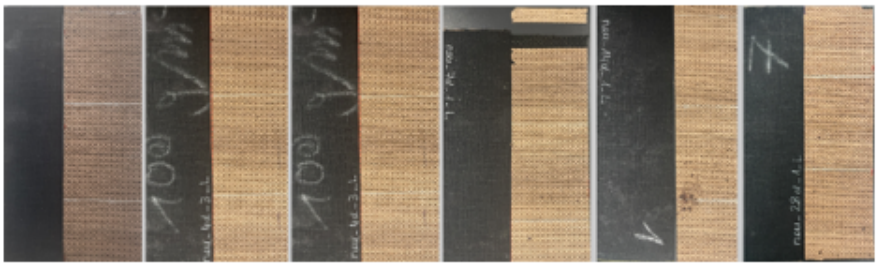
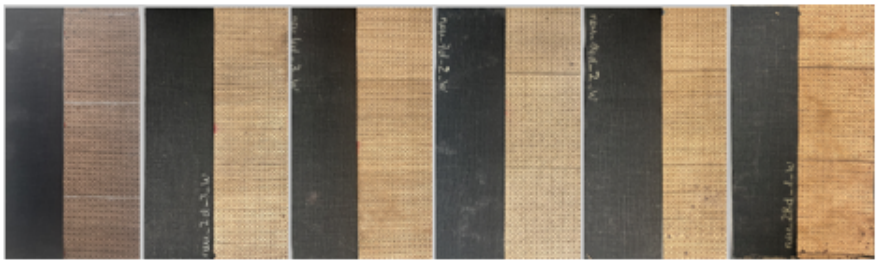
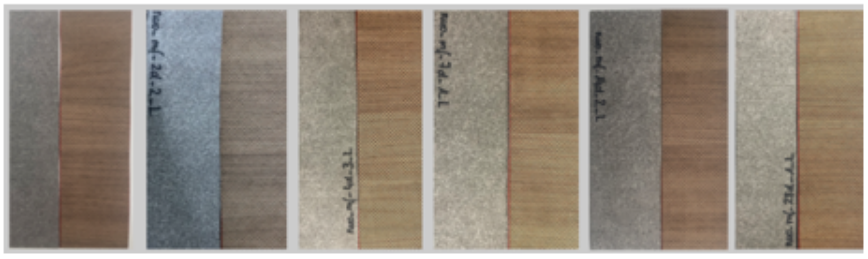
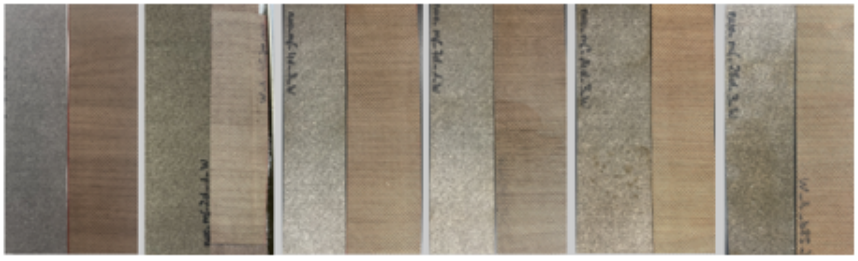
Sample		Samples original and taken after 2, 4, 7, 14 and 28 days (left to right)
flexwood	Dry heat ageing	
	Humidity ageing	
nuo-bw	Dry heat ageing	
	Humidity ageing	
nuo-mf	Dry heat ageing	
	Humidity ageing	

Fig. 6. Images of the aged composite samples.

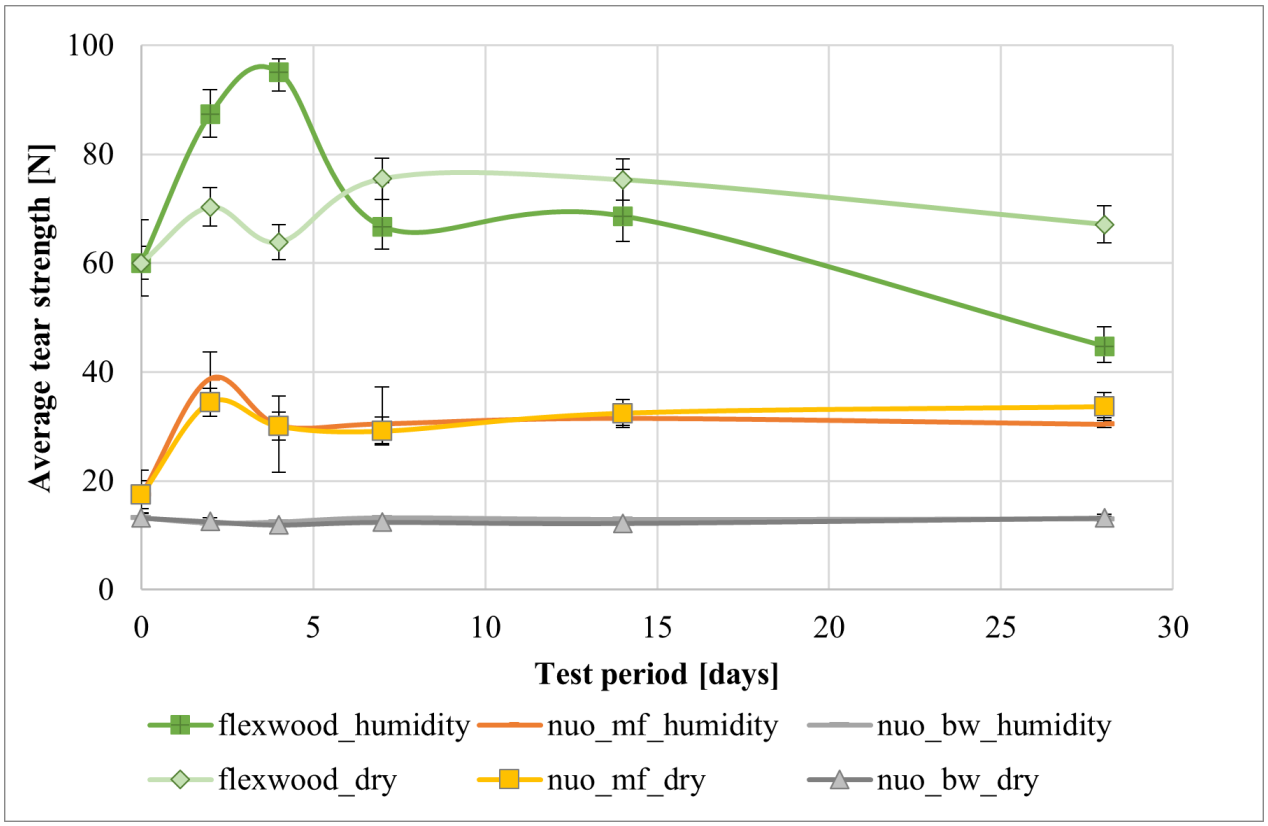


Fig. 7. Tear resistance of the aged composite samples.

Table 5. Remaining wood fiber during tape pull-off tests after 2, 4, 7, 14, and 28 days of storage under dry and humid conditions.

	day 2	day 4	day 7	day 14	day 28
flexwood_dry	100%	90%	90%	20%	0%
flexwood_humidity	100%	80%	80%	20%	0%
nuo_bw_dry	100%	100%	100%	100%	100%
nuo_bw_humidity	100%	100%	100%	100%	100%
nuo_mf_dry	100%	100%	100%	100%	100%
nuo_mf_humidity	100%	100%	100%	100%	100%

3.4 Soil Burial Tests in Outdoor Field

The soil burial field test revealed that flexwood composite material showed the most rapid decomposition, with complete degradation after 211 days in soil (Fig. 8). The nuo_bw material (laminated on cotton fabrics) degraded in a similar manner, but exhibited significantly slower degradation kinetics compared to flexwood (Fig. 9). In contrast, the synthetic variant nuo_mf remained almost completely resistant to decomposition over the test period of 211 days.

Macroscopic images of the textile side also showed clear biodegradation of the natural fiber textiles (flexwood and nuo_bw), whereas the synthetic nonwoven fabric from the nuo_mf sample remained almost unchanged. Because the PU-based adhesive is biodegradable, the entire nuo_bw composite material remained significantly more stable than the purely natural flexwood composite material. The PU adhesive retained the cotton fabric or part of the fibers in the composite system for longer.

The results of the tear strength tests on the samples taken at different time points during the soil burial test (Fig. 9) also correlate with the degradation speed, as presented visually in Fig. 8. All samples showed an initial increase in tear strength after 8 days of soil treatment, probably due to an increase in their moisture content. In the nuo_mf sample, this value remained almost constant throughout the entire test period of 211 days. The flexwood sample had the highest initial tear strength (60.0 N), but this decreased markedly by day 38 and was similar to that of nuo_bw, which had a very low initial strength (13.07 N). After the fifth sampling at day 125, mechanical tests were no longer possible on the flexwood and nuo_bw samples since only very small residues remained in the soil.

4. Discussion

This study was conducted within the framework of the research project “flexwood” (Grant number

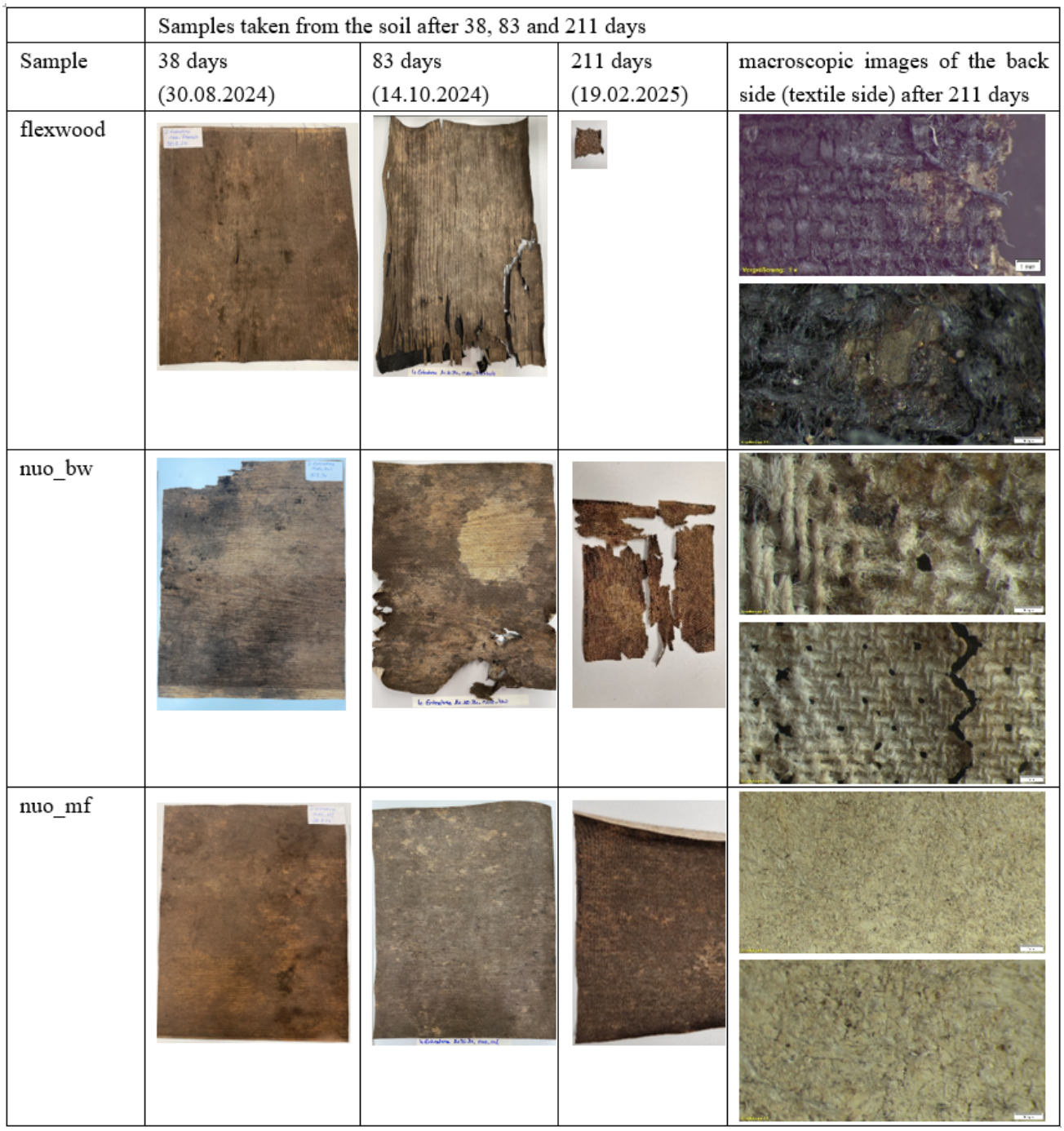


Fig. 8. Images of the composite samples taken from the soil in the outdoor test field.

BWIN330033), funded by the Ministry for Food, Rural Affairs and Consumer Protection of Baden-Württemberg. The aim of the project is to develop sustainable wood-based composite materials using textiles from natural fibers and bio-based adhesives. The results of the delamination tests using hemp as the textile and a lignin adhesive indicate the adhesion strength between the hemp fabric and the wood veneer meets the necessary quality requirements. The lignin adhesive effectively bonds the two materials, ensuring strong adherence without overpenetration into the textile. This finding aligns with a previous study that highlighted the importance of achieving a balance between adhesion strength and penetration depth in order to ensure optimal bonding performance [27].

The pressing time during the lamination of wood and hemp textile with a thermoplastic foil of lignin had a significant influence on delamination strength. This was likely due to increased adhesive flow and polymer chain mobility, which promote improved interfacial bonding with wood cell walls [15]. In contrast, the lamination pressure had

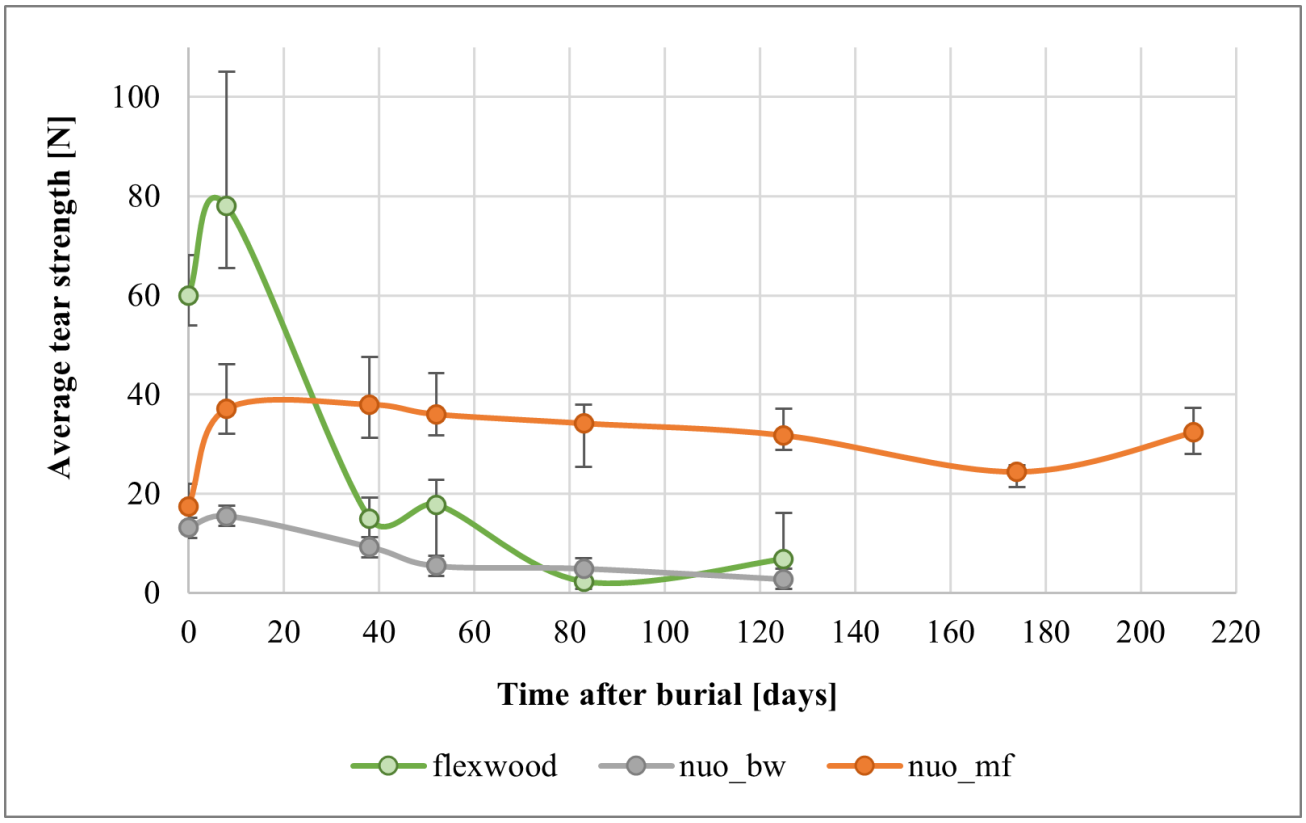


Fig. 9. Tear resistance of the composite samples as a function of burial time in the outdoor field test.

only a moderate effect, while film thickness above a certain threshold did not significantly enhance bond strength. These findings suggest that effective bonding is driven more by interfacial interactions than by the amount of adhesive applied [28,29].

Earlier research studies also support this interpretation, indicating that sufficient thermal activation and mechanical compression are essential for strong adhesion [30, 31]. Excessive thickness of the adhesive layer might hinder heat transfer or introduce internal stresses that negatively affect bonding performance.

A critical aspect that requires further investigation is the interplay between penetration depth and the distribution of adhesive. While deeper penetration can enhance the contact between adhesive and wood fibers, excessive infiltration into the textile may lead to the loss of a distinct glue line, thus compromising the quality of adhesion. Previous studies have shown that overpenetration can weaken the adhesive layer and reduce the mechanical integrity of bonded materials [32,33].

One potential solution to mitigate this issue is the application of a primer to the textile before bonding. Primers can act as barriers to control adhesive absorption into the textile, while simultaneously promoting adhesion to the wood. Surface treatments such as primer application or plasma treatment have been shown to enhance adhesive performance by modifying the surface energy and improving interfacial interactions [34,35]. Future studies should investigate which types of primers best optimize the balance between penetration and interfacial bonding.

The biodegradation tests showed that after an initial period of stability, flexwood completely decomposed and was broken down by bacteria, fungi, and enzymes in the soil. This composite laminate, comprised only of natural and renewable materials, therefore has good potential for the prevention of microplastic pollution in the environment. These results align with the goals of the research project, which are to develop environmentally friendly wood-textile composites.

Unexpectedly, the first measurement point after climate exposure and soil ageing showed a significant increase in tear strength. Although such a result may seem contradictory to the anticipated degradation trend, it has been reported previously under certain environmental conditions for natural, fibre–based composites. Such effects may be explained by several mechanisms: (i) moderate moisture uptake can improve fibre–matrix adhesion or relieve internal stresses, resulting in more effective load transfer between the fibre and matrix; (ii) thermally- or humidity-induced relaxation of residual stresses within the matrix may temporarily increase stiffness and strength; and (iii) partial swelling of the fibre surface can locally enhance consolidation before biological degradation becomes dominant [36,37].

5. Conclusions

In this study, the waste product lignin—one of the most available raw materials on earth—was applied as an adhesive layer in wood veneer and hemp fabric composite material. More than 80 million tons of lignin are produced annually as a by-product of lignocellulosic biorefineries and the pulp and paper industry. Lignin waste also poses an environmental problem, as it is usually disposed by burning as a low-grade fuel, leading to the release of CO_2 emissions and wasting natural resources [38]. Conversely, fossil resources are becoming increasingly scarce and the use of synthetic materials is causing environmental pollution. Therefore, in order to sustainably manage resources, it is important to increase lignin utilisation by developing new technological applications [39].

In terms of its life cycle, the new composite can be characterized by several attributes. Although its production from renewable raw materials (wood and hemp) requires machinery and processes (and therefore energy consumption), these processes generate significantly less CO_2 emissions than the extraction of synthetic materials from petroleum. The composite material itself can certainly be recycled in sufficiently large quantities, as the high-quality cellulose may be extracted from the composite material using solvents and separated from the used lignin. However, recycling will not be economically viable for small quantities. Instead, biological degradation, such as in anaerobic digesters, offers the possibility of producing biogas as an energy source. The remaining components can be returned to nature as fertilizer, thus closing the biological cycle.

In conclusion, this study demonstrates that lignin-based thermoplastic adhesive can be used between a hemp textile and wood. Furthermore, it can meet quality standards when the processing parameters are optimized. A well-defined glue line was observed, suggesting strong and consistent bonding. To further improve performance, future research should focus on surface modification techniques that regulate penetration of the adhesive, particularly into textiles. Such strategies could expand the use of sustainable lignin adhesives in textile-wood composites.

Availability of Data and Materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Conceptualization, methodology, validation, formal analysis, investigation, data curation, writing—original draft preparation, project management, CK and MH; funding acquisition, designing the research study, writing—review and editing, TS; designing the research study, resources, supervision GTG. All authors have read and agreed to the published version of the manuscript. All authors contributed to editorial changes in the manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

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Conflicts of Interest

All authors declare no conflicts of interest. Despite Markus Hauptmann from Schorn & Groh GmbH, the judgments in data interpretation and writing were not influenced by this relationship.

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