

RESEARCH

Open Access



Non-twist flax fibre reinforcement of lightweight plywood

Marcus Cordier^{1*}, Ole Gonnens² and Carsten Mai¹

*Correspondence:
Marcus Cordier

marcus.cordier@stud.uni-goettingen.de

¹Wood Biology and Wood Products, University of Goettingen, Buesgenweg 4, 37077 Goettingen, Germany

²Application Center for Wood Fiber Research HOFZET®, Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI, Heisterbergallee 10A, 30453 Hannover, Germany

Abstract

Using lignin-phenol-formaldehyde (LPF) impregnated flax fibres is a little-studied method for reinforcing plywood through natural materials with only a modest increase in density. The main objective of this study was to assess the effects on the mechanical properties of small-leaved lime (*Tilia cordata*) veneer-based lightweight plywood (density $<600 \text{ kg m}^{-3}$) by inserting non-twist flax fibre fabrics pre-impregnated with lignin-phenol-formaldehyde resin. Two types of composite materials were compared—fully impregnated flax fibre fabric ('Fullpreg') and pre-impregnated flax fibre fabric ('Prepreg') inserted beneath the top layers of five-layered plywood boards. A 5-layered plywood without insertions served as a reference. Plywoods with insertions of pre-impregnated flax fibre fabrics (81.7 N mm^{-2}) exhibited up to 9.4% higher modulus of rupture (MOR) compared to the reference (74.7 N mm^{-2}), while fully impregnated insertions (83.9 N mm^{-2}) achieved 12.3% higher MOR than the reference in the grain direction of the top layers. Simultaneously, the modulus of elasticity (MOE) decreased for both variants due to the insertion, with reductions of 5.7% parallel and 10.3% perpendicular to grain direction. The surface soundness was 1.56 N mm^{-2} for the 'Fullpreg' variant and 1.47 N mm^{-2} for the 'Prepreg' variant, compared to 1.25 N mm^{-2} for the 'Reference' variant. The mean thickness swelling was 8.7% for the 'Fullpreg' variant and 8.8% for the 'Prepreg' variant, while the mean water uptake was 23.9% for both variants, compared to the reference of 22.2%. Considering the resulting properties, the insertion of LPF pre-impregnated flax fibre fabrics can be an appropriate technique for improving the properties of plywood using natural materials.

Keywords Plywood, Reinforcement, Lignin-phenol-formaldehyde, Flax fibre

1 Introduction

The bending properties, both under static and dynamic loads, are among the most important material properties for plywood in construction and structural use [1]. Simultaneously, the importance of combinations of renewable materials, such as natural fibres and bio-sourced adhesive systems, is increasing [2, 3]. Improving the bending properties is possible through several approaches, such as veneer densification [4], utilising a combination of different wood species [5], or reinforcing with fibres [6, 7]. Fibre reinforcement is a well-discussed method for enhancing plywood, which also



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

maintains its favourable strength-to-weight ratio (SWR), but its utilisation in industrial plywood production is low. The increasing relevance of reinforcing plywood with renewable, eco-friendly fibres such as flax (*Linum usitatissimum*) fibres is highlighted in the context of a growing global demand for plywood [8] and an expanding supply of low-grade wood resources. The increasing scarcity of large-diameter, high-quality logs suitable for the production of high quality plywood necessitates the investigation of alternatives, including the use of juvenile and lower quality logs for plywood manufacturing. Various inorganic materials, including carbon, glass, aramid and basalt, as well as a range of fibre-based products like roving, woven and non-woven fabrics, have been employed for fibre-reinforcement, often in combination with epoxy resins [9–16]. Vijayan et al. [17] highlighted that natural fibre-based composites have effectively demonstrated their fundamental potential as weight-saving materials. However, the current scientific challenge is to make them practically applicable. Correspondingly, the endeavour to use largely or entirely bio-based material combinations in the long term, along with bio-based adhesives, is the subject of ongoing research in various fields of materials science [18]. Bachmann et al. [2] pointed out the often poor interfacial bonding properties between hydrophilic natural fibres and hydrophobic polymers, which lead to low mechanical properties. Building upon these challenges, Lau et al. [19] point out that replacing synthetic fibres with natural fibres in structural components is a complex undertaking. The presence of moisture inside the composites (at the laminar level) and at the bonding interface can notably alter interfacial adhesion properties, thereby affecting their mechanical performance. In light of these considerations, Saal et al. [20] suggested that the wider adoption of fibre-reinforced plywood, especially in load- and impact-bearing applications, would greatly contribute to enhanced durability and longevity of the material whilst also allowing for more sustainable use of raw wood material. They elaborated that better management of wood resources is a key factor, and although plywood and other contemporary wood-based composites are already models of resource efficiency, they hold potential for further improvement in this category through fibre reinforcement [20]. However, besides various organic fibre-reinforcement materials like kenaf (*Hibiscus cannabinus*), date palm (*Phoenix dactylifera*), and hemp (*Cannabis sativa*) [21, 22], flax fibre is widely employed [23] in combination with several adhesives, including urea-formaldehyde (UF), melamine-urea-formaldehyde (MUF), polyurethane (PU-K), isocyanate MDI-based pre-polymer (PU-AN), and epoxy resins [24, 25]. Karri et al. [26] demonstrated that lignin-phenol-formaldehyde resin is suitable for bonding five-layer poplar plywood. They also used this adhesive system with short hemp fibres as a reinforcing material. Although research on fibre-reinforced plywood has made important contributions, the way in which bidirectional flax fibre fabric pre-impregnated with phenol-formaldehyde (PF), one of the most widely used adhesives in plywood manufacturing, and its modified adhesives such as lignin-phenol-formaldehyde (LPF), influence both static and dynamic bending properties of plywood remains undressed. This study examines methods for assessing these properties under both static and dynamic conditions, discusses the factors influencing them and investigates the practical implications for applications. Five-layered plywood was manufactured from rotary-cut veneers of small-leaved lime (*Tilia cordata*), incorporating LPF-pre-impregnated bidirectional flax fibre fabric beneath the top layers. The flax fibres were not spun into yarns, but were instead woven as rovings (without undulation), referred to as

non-twist. A lignin-phenol-formaldehyde adhesive, where 50% of the petroleum-based phenol was replaced by lignin, was utilised in order to meet sustainability aspects. The study assesses modulus of rupture (MOR), modulus of elasticity (MOE), impact bending strength (IBS), thickness swelling (TS), and includes evaluations of surface soundness (SS) and strength-to-weight-ratio (SWR) as well as stiffness-to-weight ratio. This analysis illuminates the role of LPF-pre-impregnated non-twist flax fibre fabrics in enhancing the static and dynamic load-bearing capabilities of plywood. It also contributes to the challenges and opportunities related to assessing the quality of bonding achieved with PF-pre-impregnated bidirectional flax fibre fabric. Finally, this study underscores the importance of optimising plywood-fibre compositions and design strategies to enhance its performance in the face of varying loads, ultimately contributing to the advancement of safer, more sustainable, and economically viable structural solutions.

2 Materials and methods

2.1 Materials selection and preparation

Small-leaved lime (*Tilia cordata*, Mill., 1768) is a native hardwood species in Central Europe with suitable properties for veneer and plywood production, but it is rarely used for material applications in practice. Rotary-cut veneers (Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI, Braunschweig, Germany) with a nominal thickness of 2 mm were used to manufacture five-layered plywood. The veneers measured 500 mm × 500 mm ($l \times w$) in nominal size. The wood originated from forest stands in Lower Saxony (Braunschweig, Germany) and was provided by the Niedersächsische Landesforsten (Lower Saxony State Forests, public forestry administration). Veneers were obtained from three different trees and randomly mixed before specimen preparation.

The lignin-phenol-formaldehyde adhesive Prefere 14W451 (Prefere Resins Germany GmbH, Erkner, Germany) was used for both the impregnation of flax fibre fabric and the bonding of the veneer layers. Prefere 14W451 is a two-component system, consisting of the adhesive Prefere 14W451 and the powder hardener EXPH 9500 [27, 28]. According to the manufacturer (Prefere Resins Germany GmbH), this system contains lignin as a partial replacement for petroleum-based phenol, with a substitution ratio of 50% phenol by lignin. However, detailed lignin specifications (e.g., origin, molecular weight, purity) were not disclosed by the manufacturer due to proprietary formulation. The viscosity at 20 °C was 300 mPa s, the non-volatiles content at 105 °C was 48%, and the density at 20 °C was 1.21 g cm⁻³ [27].

The selection of fibres and matrix components was the same for both of the 'Fullpreg' and 'Prepreg' variants. A commercial bidirectional flax (*Linum usitatissimum* L., 1753) fabric, ampliTex® 5040 (Bcomp Ltd., Fribourg, Switzerland), featuring fibres aligned at both 0° and 90° with a fabric weight of 300 g m⁻² and a twill 2/2 weave [29], was employed as fibre material [29]. The fabric cuttings were 500 mm × 500 mm ($l \times w$) in size. The lignin-phenol-formaldehyde adhesive, Prefere 14W451 (Prefere Resins Germany GmbH, Erkner, Germany), was used as the matrix. The matrix resin was applied to both sides using a roller with a total of 520 g m⁻² of adhesive applied. Both reinforcement approaches were selected to be technically compatible with existing plywood production lines. However, considerations regarding industrial implementation were beyond the scope of this study.

Fullpreg: The adhesive-treated fabrics were subjected to a hot-pressing process at a temperature of 140 °C, applying a specific pressure of 0.65 N mm⁻² and a set point force of 162.5 kN for a duration of 6 min. After each pressing cycle of 60 s, 120 s, 180 s and 240 s, the press was ventilated for 10 s. A HSP 250 (Gottfried Joos GmbH & Co.KG, Pfalzgrafenweiler, Germany) was employed for hotpressing. Subsequently, single Fullpregs were covered with press paper and allowed to cool to the ambient temperature of 22 °C over a 24 h period and both sides were sanded with 80 grit.

Prepreg: The adhesive-treated fabrics were pre-cured in a HSP 250 hot press (Gottfried Joos GmbH & Co. KG, Pfalzgrafenweiler, Germany), which was heated to 100 °C. The press was not fully closed and had an open gap of 20 mm between the heated pressing surfaces, so no pressure was applied. Heat was applied to the underside of the prepregs through contact with a pressing plate, while the top side was heated by the ambient temperature. The dwell time of the prepregs in the press was 6 min.

2.2 Sample fabrication and testing

Five-layered plywood was produced using two of the manufactured Fullpregs or Prepregs and Prefere EXP 14W451 to bond the remaining veneers. Prepregs were inserted between 90° cross laid veneer layers 1–2 and 4–5 without additional adhesive application. Veneer layers 3 and 4 were manually glued on the top side by approximately 120 g m⁻² adhesive (Fig. 1). Prior to utilisation, the prepregs' remaining moisture content in percentage was assessed using two Sartorius MA 160-1 (Sartorius Lab Instruments GmbH & Co. KG, Goettingen, Germany) Moisture Analysers operating at a temperature of 140 °C. Hotpressing was carried out with an HSP 250 (Gottfried Joos GmbH & Co.KG, Pfalzgrafenweiler, Germany). The stacked layers were hotpressed to

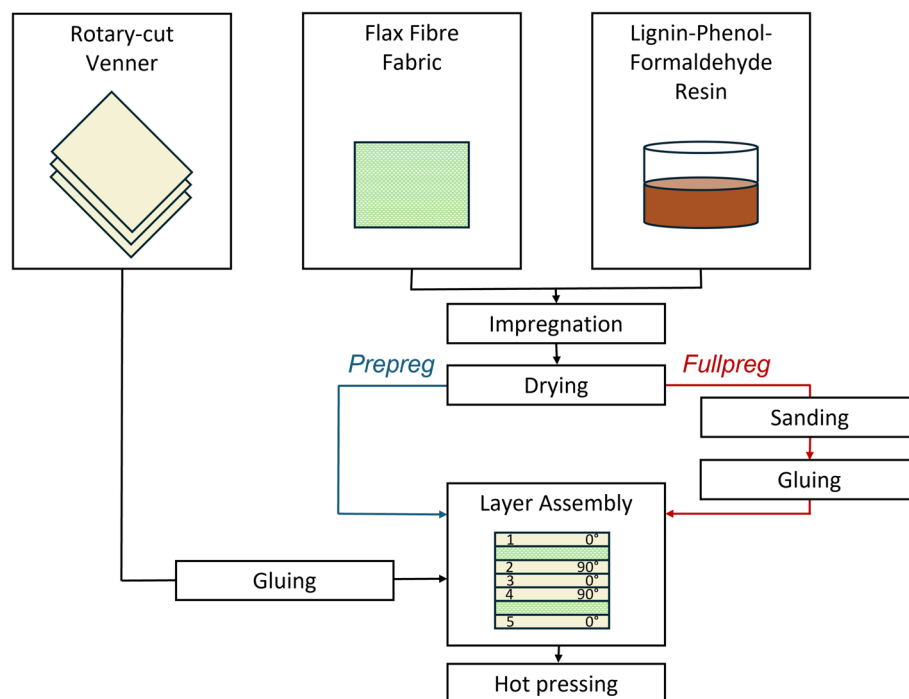


Fig. 1 Schematic representation of the plywood manufacturing process. Layer assembly simplified for clarity. Numbers indicate veneer layer order, degree values indicate grain direction. Fullpreg and Prepreg shown in distinct colours; each board contains only one reinforcement type

plywood boards with a specific pressure of 1 N mm^{-2} and a set point force of 250 kN for 10 min at a temperature of 130°C . Ventilation steps of 10 s were interposed after 60 s, 120 s, 180 s and 240 s. Cooling occurred within an unheated press, maintained at 0.5 N mm^{-2} , for a duration of 24 h to avoid deformation. One reference was produced for this study. The reference was created using the same process as described, but without reinforcement material. Instead of employing prepregs, adhesive was manually applied to the top sides of veneer layers 2 and 5, as was the case with the method used for the other veneers. Three boards were manufactured per variant. For a selective comparative analysis of the 'Prepreg' and 'Fullpreg' effects, a five-layered plywood variant was manufactured with birch veneer top layers and three small-leaved lime core layers, following the identical manufacturing parameters as applied to all other plywood specimens in this study. This birch-faced variant was not part of the primary test series and is therefore not included in the full evaluation. However, selected results are used for orientation when interpreting the mechanical performance of the flax-reinforced plywood. All manufactured boards measured $500 \text{ mm} \times 500 \text{ mm}$ ($l \times w$) in size, with thicknesses of 9 mm for the reference boards and 10 mm for the boards containing prepregs or fullpregs.

Cooled plywood boards were cut into the required test specimens. Before testing, all specimens were conditioned at 20°C and $65 \pm 5\%$ relative humidity (RH) until their mass stabilised, with no substantial variation observed over two consecutive days.

The density ρ (kg m^{-3}) of conditioned specimens was determined according to EN 323 [30]. Density profiles were obtained using a GreCon Densityprofiler (Weinig GreCon GmbH & Co. KG, Alfeld, Germany). Operating conditions for density measurements included a 0.1 mm s^{-1} feeding rate, 32.686 kV voltage, and 525 μA electric current.

Microscopy images were captured using a 3D reflected-light microscope (VHX-7000, KEYENCE Corporation, Osaka, Japan). The thicknesses of the flax fibre insertions were measured, and the mean thickness was determined based on 10 measurements per specimen, with five measurements taken for each flax fibre layer.

Modulus of rupture (MOR) f_m (N mm^{-2}) and modulus of elasticity (MOE) E_m (N mm^{-2}) were determined through three-point bending tests according to EN 310 [31]. The tests were conducted using a ZwickRoell universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) equipped with a 10 kN load cell. The specimens had dimensions of $230 \text{ mm} \times 50 \text{ mm}$ ($l \times w$), with thicknesses corresponding to their respective board thicknesses, and were tested with a span of 180 mm between the supports. For each variant, a total of 12 specimens were tested: 6 in the parallel ($\parallel$) direction and 6 in the perpendicular ($\perp$) direction, with 2 specimens taken from each of 3 boards.

Impact bending strength (IBS) ω (kJ m^{-2}) was determined using a Resil Impactor (CEAST GmbH, Martinsried, Germany) pendulum machine, following a modified version of DIN 52189-1 [32] with adjusted specimen size. A pendulum hammer with an energy of 15 J was used to transmit the dynamic impulse to the specimens. The specimens had nominal dimensions of $150 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$ ($l \times w \times t$), with a supporting span of 115 mm. The actual height of the samples corresponded to the thickness of the specimen. Tests were conducted both parallel and perpendicular to the grain of the top layers. IBS (ω) was calculated based on the recorded energy W (J) using Eq. (1) where w is the specimen width and t is the specimen thickness, both in millimeters.

$$\omega = \frac{(1000 \times W)}{(w \times t)} \quad (1)$$

For each variant, a total of 60 specimens were tested: 30 in the parallel direction ($\parallel$) and 30 in the perpendicular direction ($\perp$), with 10 specimens taken from each of 3 boards.

The strength-to-weight ratio (SWR) σ (N mkg^{-1}) was calculated using the method established by Hao et al. [33] to quantify the reinforcement effect using Eq. (2) where ρ is the density in kg m^{-3} , F_{max} is the maximum force at failure obtained in three-point bending test in N, and l , w and t are the dimensions of the specimen in m.

$$\sigma = \frac{1}{\rho} \times \frac{3 \times F_{max} \times l}{2 \times w \times t^2} \quad (2)$$

The stiffness-to-weight ratios (E/ρ) in N mkg^{-1} were calculated to determine the effect of the reinforcement on the plywood stiffness according to Eq. (3) where E_{max} is the modulus of elasticity (MOE) obtained in three-point bending test in N m^{-2} and ρ is the density in kg m^{-3} .

$$E/\rho = \frac{1}{\rho} \times E_{max} \quad (3)$$

The surface soundness (SS) between the top layers and the impregnated flax fabric beneath was assessed using a modified surface soundness test procedure based on EN 311 [34] to determine the bonding quality of the plywood. The cutting depth of the top layers was set to 1 mm. For each variant, a total of 15 specimens were tested (5 specimens from each of 3 boards)

Thickness swelling (TS) and water uptake (WU) tests were conducted on specimens with dimensions of $50 \text{ mm} \times 50 \text{ mm} \times \text{board thickness}$. For each variant, a total of 24 specimens were tested (8 specimens from each of 3 boards). TS was determined according to EN 317 [35]. Measurements were taken after 2 h and 24 h of water immersion. Additionally, WU was calculated using Eq. (4) where m_w is the wet mass of the specimen after water immersion, and m_d is the initial dry mass of the specimen.

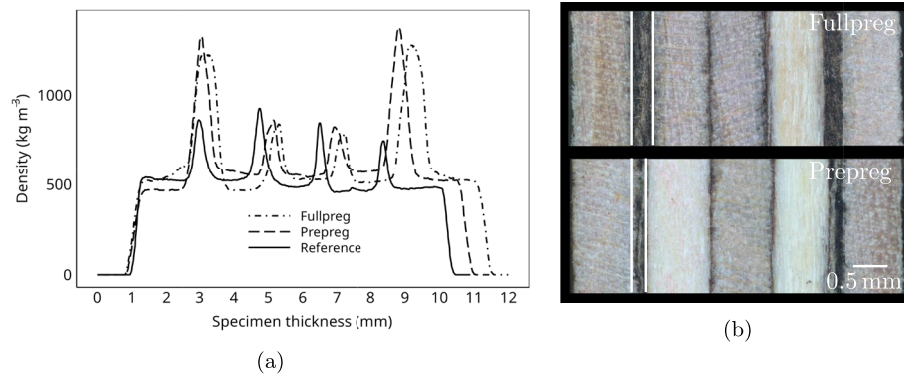
$$WU = \frac{m_w - m_d}{m_d} \times 100 \quad (4)$$

2.3 Data analysis

Statistical analysis and data visualisation were conducted using R (version 4.2.2, R Core Team, 2022) through the RStudio interface (version 2024.09.0+375, Posit PBC, Boston, Massachusetts). The data analysis focused on descriptive statistics and graphical representation methods to examine data distributions comprehensively due to limited sample size ($n = 3$ boards per variant) and variations in impregnation and veneer quality. To visualise the data distribution, boxplot diagrams were employed. The statistical analysis utilised R's built-in functions to calculate key descriptive measures including median values, interquartile ranges, extrema (minimum and maximum values), means (where applicable), and standard deviations, providing a comprehensive numerical characterisation of the data distribution to complement the visual analysis.

Table 1 Mean densities and standard deviations of plywood specimens, measured parallel (||) and perpendicular (⊥) to the grain of the top layers in kg m^{-3}

Plywood variant	Density (kg m^{-3})	
		⊥
Reference	563 ± 11	567 ± 9.3
Fullpreg	638 ± 22	641 ± 17.7
Prepreg	647 ± 6	650 ± 16.4

**Fig. 2** Representative density profiles of selected plywood specimens **(a)** and cross-sectional microscopy images **(b)** showing the flax fibre distribution in 'Fullpreg' and 'Prepreg' plywood variants. Vertical white lines indicate the extent of individual fibre layers. Microscopy images taken at 50× objective magnification

3 Results and discussion

3.1 Mechanical and physical properties

The insertion of impregnated flax fibre fabrics results in a moderate increase in density compared to the 'Reference' variant in both directions (Table 1). Based on the median values, the actual densities increased by 13.3% for the 'Fullpreg' variant and by 14% for the 'Prepreg' variant compared to the 'Reference' variant (Table 1). For comparative purposes, it may be noted that using birch veneers as top layers (own data, variant not shown) increased the median density by 17.75% compared to the 'Reference' variant. The observed density increase can be attributed to both the inherent weight of the flax fibre fabric itself (with a fabric weight of 300 g m^{-2}) and the additional adhesive content, contributing to the overall composite mass.

The density profiles of 'Fullpreg' and 'Prepreg' specimens reveal different characteristics despite the use of identical base materials. 'Prepreg' specimens exhibit higher, more pronounced density peaks, while 'Fullpreg' specimens demonstrate a broader region of elevated density with lower peak values (Fig. 2a). Microscopy measurements determined a flax fibre insertion thickness of $577 \mu\text{m}$ (5.8 % of total thickness) for 'Fullpreg' and $284 \mu\text{m}$ (2.9% of total thickness) for 'Prepreg' specimens.

The observed differences in density profiles can be attributed to two primary factors: the pre-curing state of 'Fullpreg' and the additional adhesive content. The 'Prepreg's' uncured state allows for enhanced resin flow and mobility during processing, resulting in higher mean density and considerably lower standard deviation, indicating more uniform compaction. In contrast, the 'Fullpreg's' partially cross-linked resin structure restricts material flow and compression. The additional adhesive in 'Fullpreg' acts as a spacer between fibres, contributing to the broader density distribution. These findings

strongly suggest that the pre-cured state of the 'Fullpreg' matrix is the dominant factor affecting density distribution. The partially cross-linked resin resists complete compression due to its reduced mobility, resulting in a broader density profile with lower peaks. The additional adhesive contributes to a wider spacing between fibres, leading to a broader density profile. This effect outweighs the influence of the additional adhesive, as evidenced by the lower overall density in 'Fullpreg' specimens despite the added material. The markedly lower standard deviation in 'Prepreg' specimens ($SD = 6$ vs. $SD = 22$) demonstrates that uncured material allows for more uniform compaction during processing. The microscopy images of the cross-sections highlight the higher compaction of the flax fibre fabric inserts in the 'Prepreg' variant compared to the 'Fullpreg' variant (Fig. 2b). The choice of pre-impregnation method markedly influences not only the final density but also its distribution throughout the material. These findings align with previous studies on wood-based composites, where processing parameters have been shown to influence density profiles [36]. The density profiles exhibit the typical characteristics of plywood, with higher density in the adhesive joint areas [9, 37]. Jorda et al. [38] found similarly shaped density profiles for plywood reinforced with unidirectional flax fibre. The observed density increases in the present study are 4.0% to 13.0% lower than those reported for synthetic fibre reinforcements such as carbon and basalt, which range between 17.0 and 27.0% [10], supporting the potential of flax fibres for lightweight applications. This assessment's focus on density characteristics is limited to standard climate conditions (20 °C, 65 %RH) and specific pressing parameters. The influence of varying processing conditions, such as different pressing temperatures or pressures, might yield different density distributions and warrants further investigation. For industrial applications, 'Prepreg' systems might be preferable when uniform density distribution is crucial, despite their slightly higher overall density. The broader density distribution in the 'Fullpreg' variant might be advantageous in applications where gradual property transitions are desired. Future research should investigate the long-term stability of these density distributions under various environmental conditions and the relationship between density profiles and mechanical properties.

The median MOR and MOE measured in the three-point bending test showed a pronounced increase compared to the 'Reference' variant. This increase was observed in both directions, parallel ($\parallel$) and perpendicular ($\perp$) to the grain of the top layers, taking into account the actual densities (Fig. 3a–d).

The increase in MOR $\parallel$, compared to the 'Reference' variant, was $\Delta 12.3\%$ for the 'Fullpreg' variant and $\Delta 9.4\%$ for the 'Prepreg' variant, based on the actual density of the specimens. The increase in MOR $\perp$, compared to the 'Reference' variant, was $\Delta 20.5\%$ for the 'Fullpreg' variant and $\Delta 36.6\%$ for the 'Prepreg' variant. In contrast to the increase in MOR, the MOE showed varied results. For the 'Fullpreg' variant, there was a decrease of $\Delta -5.7\%$ in the parallel direction and $\Delta -10.3\%$ in the perpendicular direction. For the 'Prepreg' variant, however, an increase was observed: $\Delta 4.6\%$ in the parallel direction and $\Delta 15.4\%$ in the perpendicular direction. Clearly, the 'Fullpreg' variant had the highest standard deviations in both MOR and MOE, in both directions.

The 'Prepreg' specimens consistently required an approximately 23.4% higher standard force compared to the 'Reference' specimens when subjected to comparable deformation (Fig. 4). In contrast, some of the 'Fullpreg' specimens exhibited remarkably different behavior, undergoing very high deformation (up to 35 mm) without experiencing

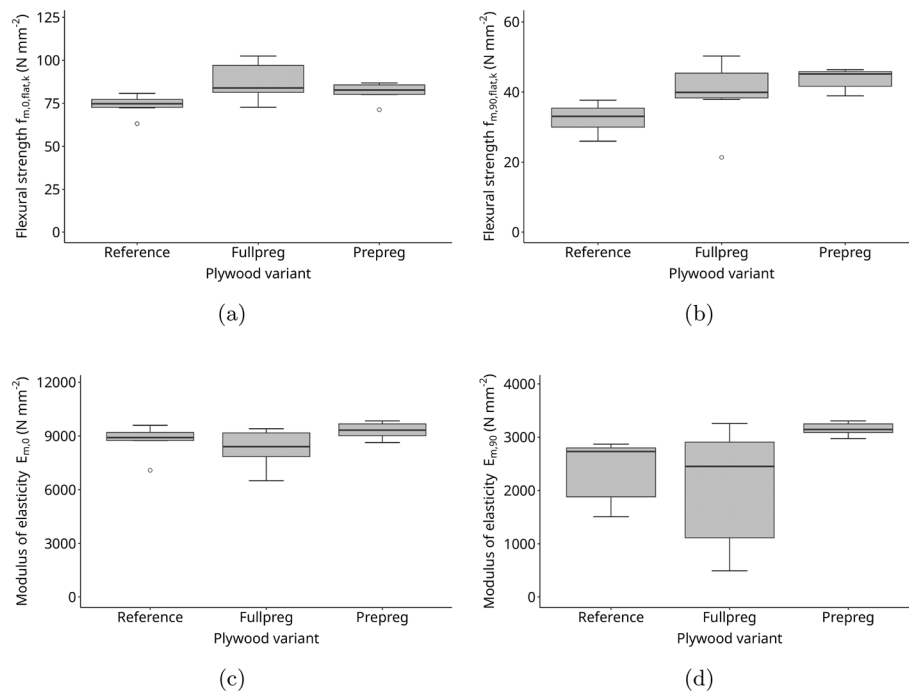


Fig. 3 Modulus of rupture (MOR) and modulus of elasticity (MOE) measurements parallel (||) and perpendicular (⊥) to the grain of the top layers. Each boxplot represents 6 measurements (3 boards × 2 specimens). The grain direction (||, ⊥) is specified in the y-axis labels of each subplot

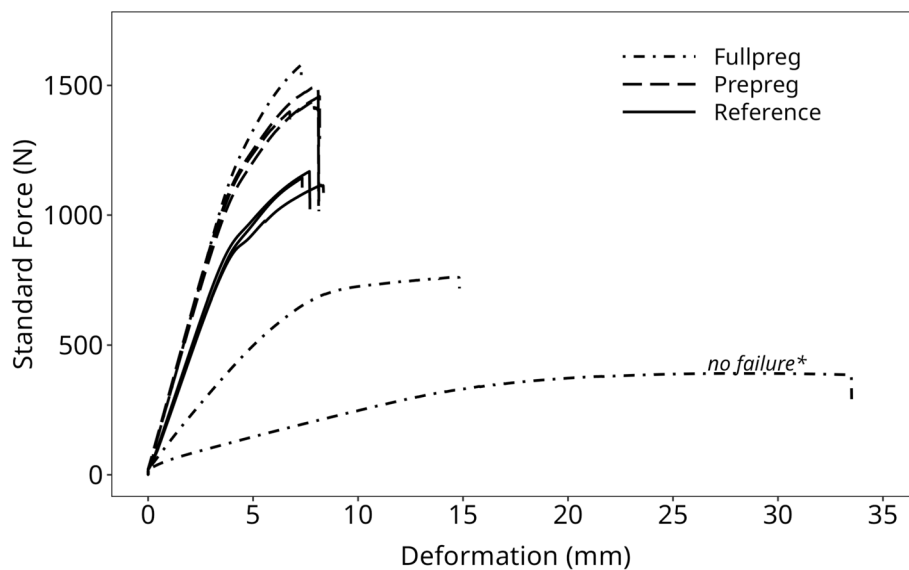


Fig. 4 Force-deformation diagram during three-point bending strength tests of selected specimens parallel to the grain of the top layers. Specimens denoted by * showed no failure during testing

failure during testing. These specimens displayed a notably lower force (approximately 500 N) compared to the reference specimens (typically around 1200 N). A notable trade-off between ductility and strength was observed, particularly in the 'Fullpreg' specimens. The performance of the 'Prepreg' reinforcement indicates its effectiveness. The higher standard force observed in 'Prepreg' specimens at comparable deformation levels suggests an increase in the load-bearing capacity of the plywood. This finding indicates that

the 'Prepreg' method may be more efficient in facilitating stress transfer between the flax fibres and the wood matrix, resulting in improved mechanical properties. The 'Fullpreg' specimens presented more complex behaviour. The wide range of behaviors observed in these specimens points to inconsistency in the reinforcement process. This variability raises questions about the consistency of the fullpreg reinforcement method. While 'Prepreg' appears to enhance strength without dramatically altering the failure mode, 'Fullpreg' in some cases, seems to fundamentally change the material's behavior, possibly introducing a more ductile failure mode. Comparing these results with existing research, some discrepancies are notable. A previous study found no significant influence of flax fibre reinforcement on the MOR and MOE of beech plywood [25]. One potential explanation for this discrepancy is the utilisation of disparate flax fibre fabrics. While Jorda [25] employed fabrics with spun yarns, the present study utilised fabrics with non-twist yarns, which allow for a more optimal exploitation of the fibre strength due to the absence of fibre ondulation [39, 40]. The results are somewhat similar to those of Borri et al. [41], who found that wooden beams made of high-quality wood did not show significant increases in load-bearing capacity when reinforced with natural fibres embedded in an epoxy matrix, but indicated increased ductility of the wooden elements. The results are limited by the high standard deviations observed, particularly in the 'Fullpreg' variant, indicating higher variability in the reinforcement's effects. This variability could be attributed to inconsistencies in the impregnation process or inherent variations in the natural materials used. A study of plywood reinforced with carbon and basalt fibres, showed similar results to this study in that both the maximum load and maximum deflection of the plywood increased compared to the reference plywood [10]. The choice between 'Prepreg' and 'Fullpreg' reinforcement methods may ultimately depend on specific application requirements. 'Prepreg' might be preferred for applications demanding higher strength and more predictable behaviour, while 'Fullpreg' might find advantages in applications where high deformation without catastrophic failure is desirable.

The increase in MOR can be attributed to the increased density; the SWR shows only partial improvement of the plywood through the incorporation of impregnated flax fibre fabrics, depending on the loading direction. In the parallel direction, both reinforcement strategies show limited influence on the strength-to-weight ratio (SWR), with 'Fullpreg' slightly increasing and 'Prepreg' slightly decreasing performance compared to the 'Reference' (Table 2). In contrast, the perpendicular direction shows substantial improvements for both treatments, with the 'Prepreg' variant demonstrating the most pronounced enhancement. This directional dependency suggests that partial pre-impregnation may be particularly effective under transverse loading, likely attributable to the biaxial fibre orientation (0° and 90°) within the flax fabric layers. Although the improved strength values indicate reinforcement effectiveness, baseline density increases due to fibre incorporation must be considered when evaluating material efficiency. For orientation, additional data from a birch veneer treatment (own data) indicate superior performance in the parallel direction but inferior values in the transverse direction compared to both flax-reinforced variants. For stiffness-to-weight ratios, the 'Fullpreg' variant exhibits decreased values in both directions. By contrast, the 'Prepreg' variant marked directional dependency: modest reduction parallel to the grain but substantial improvement transversely. These distinct performance differences underscore the critical influence of impregnation methodology on reinforcement effectiveness and indicate that partial

Table 2 Strength-to-weight ratio (SWR) and stiffness-to-weight ratio of different treatments in longitudinal and transverse direction. Percentage changes (Δ) relative to the baseline values of the Reference treatment. *Data for birch veneer are included for orientation only and were not part of the main study focus

Property	Treatment	Direction	Value (N mkg ⁻¹)	Change Δ vs. Reference (%)
SWR	Reference		167 178	–
	Fullpreg		175 850	+5.2
	Prepreg		162 835	-2.6
	Birch veneer*		190 884	+14.2
	Reference	⊥	73 022	–
	Fullpreg		77 196	+5.7
	Prepreg		86 553	+18.6
	Birch veneer*		68 735	-5.9
Stiffness-to-weight	Reference		1.54×10^7	–
	Fullpreg		1.27×10^7	-17.5
	Prepreg		1.46×10^7	-5.2
	Reference	⊥	4.04×10^6	–
	Fullpreg		3.65×10^6	-9.7
	Prepreg		4.85×10^6	+20.0

pre-impregnation provides selective mechanical advantages under perpendicular loading conditions.

These findings indicate that the weight penalty of incorporating flax fabrics outweighs potential stiffness gains in the parallel direction, suggesting the need for selective reinforcement strategies. The effectiveness of flax fibre fabrics for stiffness-to-weight ratios is highly direction-dependent, with pre-impregnated flax fabrics being particularly valuable in applications where perpendicular stiffness is crucial. The scope of the investigation was focused on specific pre-impregnation methods and fabric configurations. The marginal differences observed in SWR between the reinforced and reference variants suggest that the current impregnation techniques or fabric properties may not be optimised for maximising the strength-to-weight ratio. Similarly, for the stiffness investigation, the study focused specifically on pre-impregnated flax fabrics with defined material parameters in a lignin-phenol-formaldehyde matrix, and the observed effects might vary with different fibre configurations or impregnation methods. When placing these results in the context of existing studies [2, 17, 19, 20, 24, 25, 38], it becomes evident that the effectiveness of pre-impregnated flax fibre fabrics as a reinforcement material may be more limited than anticipated, particularly when considering the strength-to-weight ratio. The choice between using LPF pre-impregnated flax fibre fabrics or alternative top layer materials should be based on the primary loading direction in the intended application, with prepregs being particularly beneficial where perpendicular loading resistance and minimal weight increase are prioritised.

The median impact bending strength (IBS) in the perpendicular direction of the top layers increased with the insertion of pre-impregnated flax fibre fabrics (Fig. 5).

In the perpendicular direction, both the 'Fullpreg' and 'Prepreg' variants showed increased IBS, with the 'Prepreg' variant demonstrating the most substantial improvement, reaching up to 40.0% compared to the 'Reference' variant. In the parallel direction, the 'Prepreg' variant maintained similar IBS to the reference, while the 'Fullpreg' variant showed an increase. Notably, the 'Prepreg' variant exhibited much more consistent

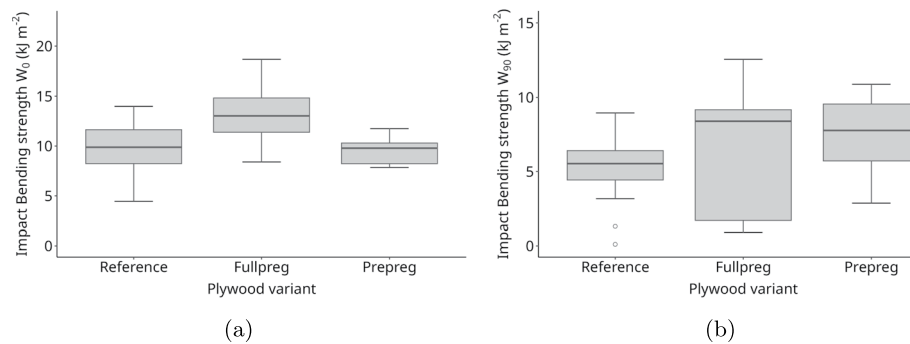


Fig. 5 Impact bending strength (kJ m^{-2}) **(a)** parallel ($\parallel$) and **(b)** perpendicular ($\perp$) to the grain of the top layers. Each boxplot represents 10 measurements (3 boards $\times$ 10 specimens)

results in the parallel direction, with the coefficient of variation (CV) reduced from 26.5% for the 'Reference' variant to 13.5% for the 'Prepreg' variant. In the perpendicular direction, the 'Prepreg' variant showed a marked reduction in CV to 37.8% from 50.0% for the 'Reference' variant, while the 'Fullpreg' variant exhibited an increased CV of 62.1%. The observed reduction in standard deviation suggests that the insertion of pre-impregnated flax fibre fabrics has a homogenising effect on the plywood. This effect could be particularly advantageous when using lower grade veneers with lower raw density for plywood production, helping to stabilise the IBS and reduce extreme deviations. The particularly strong homogenisation observed with the 'Prepreg' variant in both testing directions (CV reduction of 49% parallel and 24% perpendicular to grain) suggests that this approach offers the most reliable path toward improved material consistency. The observed increase in perpendicular impact bending strength aligns with studies on other dynamically tested natural fibre reinforcements, such as those reported by Salman et al. [42], who found improvements in fatigue stiffness and strength of laminated composites using jute fibres as reinforcement material. This assessment focused on the impact bending strength and its variability. While it provides insights into the mechanical behaviour of flax fibre-reinforced plywood under dynamic loading, it is important to note that long-term performance characteristics and fatigue behavior were not investigated in this particular study. Additionally, the microstructural mechanisms of failure during impact were not examined in detail. The enhanced perpendicular IBS and reduced variability in parallel IBS have practical implications, particularly in applications where plywood is subjected to out-of-plane impact loads or where consistent product performance is required.

The insertion of flax fibre fabrics led to a slight increase in the mean surface soundness compared to the reference, thus not negatively impacting the quality. The mean surface soundness increased by 24.8% for the 'Fullpreg' variant and by 17.6% for the 'Prepreg' variant compared to the 'Reference' variant (Fig. 6). The mean wood failure percentages were higher in the 'Fullpreg' and 'Prepreg' variants compared to the 'Reference' variant, with a proportional ratio of approximately 1:3:3.

Compared to the 'Reference' variant, the 'Prepreg' variant showed a slightly higher standard deviation of 0.246 N mm^{-2} compared to 0.186 N mm^{-2} . The results provide no evidence of deterioration in bonding quality when incorporating flax fabrics. The increase in mean wood failure percentages supports this observation. The slight increase in standard deviation can be explained by the inherent variability of natural fibres and

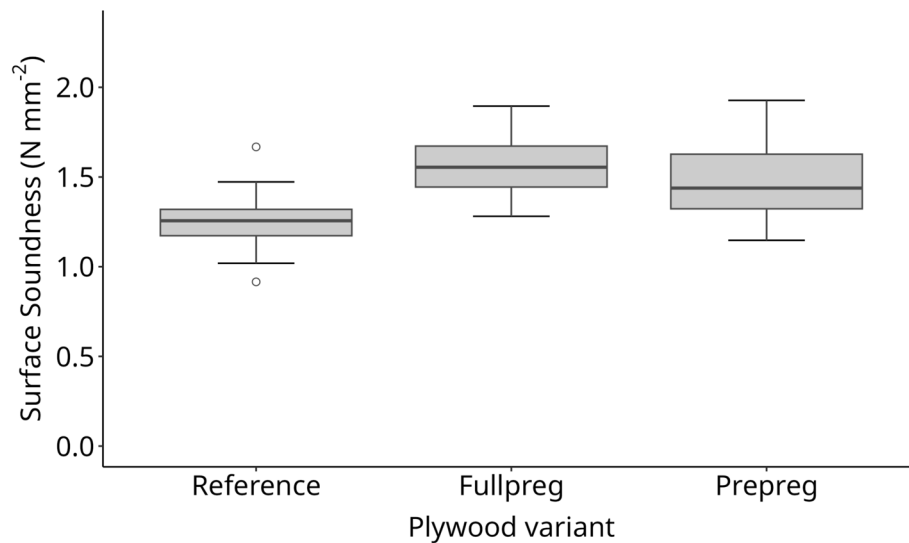


Fig. 6 Surface soundness SS (N mm^{-2}). Each boxplot represents 15 measurements (3 boards $\times$ 5 specimens)

potential inconsistencies in resin distribution during the prepreg process. These results align with comparable studies on the integration of natural fibres into wood-based materials. Jorda et al. [38] found that the shear strength of reinforced plywood was not negatively affected by the type of reinforcement material nor the adhesive amount. In contrast to some investigations that reported a decrease in mechanical properties when incorporating natural fibres within a polymer matrix [43–48], this study demonstrates an improvement in surface soundness and thus provides no direct indication of a negative impact on overall bonding quality. It is important to note that this assessment was limited to surface soundness and did not include other bonding-related properties such as tensile shear strength. Furthermore, only a limited number of lax fibre-based reinforcement approaches were tested, which constrains the scope of the conclusions.

The thickness swelling (TS) and water uptake (WU) of the plywoods were not essentially influenced by the insertion of the Fullpregs or Prepregs. The ‘Reference’ variant exhibited a slightly higher standard deviation for WU of 2.8% compared to the ‘Fullpreg’ and ‘Prepreg’ variants (both 1.3%). Plywood incorporating fullpreg interlayers exhibited a 42.0% lower standard deviation in WU compared to reference plywood, while plywood incorporating prepreg interlayers exhibited an even more pronounced effect, with a 53.5% lower standard deviation in WU. The thickness swelling of plywood predominantly originates from the face layers. The positioning of prepregs or Fullpregs beneath the face layers therefore only marginally affects the thickness swelling. These inserts likely lead to a certain decoupling or temporal delay in the water uptake of the core layers relative to the swelling of the face layers, resulting in a lower dispersion of the results. The incorporation of prepreg or fullpreg layers appears to result in a reduced dispersion of WU measurements through several interconnected factors: The decoupling effect introduced by these layers facilitates a more uniform and regulated moisture transport into the core layers, resulting in a more homogeneous swelling process throughout the plywood structure. The prepreg layers function as semi-permeable membranes, effectively regulating moisture transport. The temporal delay in moisture uptake by the core layers serves to smooth out short-term fluctuations in ambient conditions. Dimensional stability is crucial in composites, particularly for hybrid composites, as it notably

influences their mechanical performance in load-bearing applications [49]. The dimensional stability of composite materials is related to their susceptibility to microcracking and moisture absorption [50]. Cai et al. [51] demonstrated that long-term hydrothermal ageing of flax fibre phenolic composites weakens the interlaminar shear properties through “swelling-debonding-matrix degradation-fibre degradation”. The findings provide a contribution concerning the moisture-related behavior of plywood with prepreg or fullpreg layers. This assessment focuses primarily on WU and its variability, offering insights into the mechanisms behind the observed reduced dispersion. However, the understanding of how prepreg layers function as semi-permeable membranes regulating moisture transport is limited and would benefit from deeper investigation. The reduced dispersion in WU measurements has practical implications for plywood applications where dimensional stability is crucial, potentially the overall performance and reliability of plywood products in varying moisture conditions.

3.2 SWOT-analysis

To contextualise and assess the results within a broader framework, an analysis of strengths, weakness, opportunities and threats (SWOT) was conducted based on the obtained findings, while also taking into account additional aspects (Fig. 7). These further considerations, concerning the market situation, life cycle assessment (LCA), and potential negative drawbacks related to fibre-matrix behaviour, were derived from a literature survey [52–54].

4 Conclusion

This study demonstrates the potential of flax fibre-reinforced plywood composites using LPF-impregnated bidirectional flax fabric to address the declining availability of high-grade roundwood. Both ‘Prepreg’ and ‘Fullpreg’ reinforcements show distinct performance characteristics, enabling application-specific material optimisation. However, a significant performance gap remains before industrial implementation becomes viable. Whilst measurable improvements in bending properties were achieved, the enhancement levels fall short of commercial requirements for structural plywood applications. The technique shows promise but requires further optimisation to reach performance thresholds that justify additional processing complexity and costs. Critical research priorities include: optimising fibre content and orientation to maximise property enhancement; conducting long-term durability studies under service conditions; and establishing economic feasibility through production scaling analysis. Future studies with larger sample sizes would enable inferential statistical analysis to strengthen the statistical foundation beyond the descriptive approach necessitated by the limited specimen numbers and inherent variability in veneer quality and impregnation consistency. Success depends on achieving industrially relevant performance improvements whilst maintaining cost-competitiveness within existing manufacturing frameworks. The integration of renewable flax fibres with lignin-based adhesives provides a foundation for sustainable engineered wood products, contingent upon bridging the identified performance-viability gap.

	Helpful (to achieve the objective)	Harmful (to achieve the objective)
Internal origin (product attributes)	• modest increase in density • slightly increased modulus of rupture (MOR) and modulus of elasticity (MOE) • increased load deflection • increased perpendicular impact bending • increased surface soundness • no negative effects to thickness swelling (TS) and water uptake (WU)	• potential increased standard deviations (SD) • long-term performance unknown • behaviour with changes in humidity unknown • data basis generally low • applicability to other phenolic adhesive systems unclear • slightly reduced stiffness-to-weight ratio in parallel direction
External origin (environment/market attributes)	• flax renewable resources • low additional energy consumption during production • CO₂ savings through phenol substitution by lignin • processable by established technologies • recyclable by established processes • reduced demand pressure on the timber market	• flax cultivation, harvesting, and processing expensive • flax fabric supply low • life cycle assessment (LCA) pending • high cost (€15 per m²) of flax fabric limits economic viability without further cost reduction or performance improvements • target market criteria remain unclear

Fig. 7 SWOT analysis of the results within an extended context of feasibility evaluation

Acknowledgements

The authors would like to thank Aaron Kilian Mayer for his support in defining the parameters for prepreg production and Peter Meinschmidt for his general support.

Author contributions

M.C. wrote the main manuscript text, prepared the figures, and conducted the data analysis. O.G. assisted with the experimental planning and execution. C.M. supervised the project and contributed to the conceptual orientation. All authors reviewed the manuscript and contributed to the final version.

Funding

Open Access funding enabled and organized by Projekt DEAL. This research was funded by Fachagentur Nachwachsende Rohstoffe e.V. (FNR) through the "Materialeffiziente Herstellung von Produkten aus leichtem Laubholz (MatLeicht)" project, grant number 2220HV065. The funding was received by the University of Goettingen, Department of Wood Biology and Wood Products, and the Fraunhofer Institute for Wood Research Wilhelm-Klauditz-Institut WKI in Braunschweig. This publication acknowledges support by the Open Access Publication Funds of the University of Goettingen.

Data availability

Data are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest

The authors affirm that they have no Conflict of interest concerning this publication.

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

Received: 9 April 2025 / Accepted: 19 June 2025

Published online: 21 July 2025

References

1. Xu H, Nakao T, Tanaka C, Yoshinobu M, Katayama H. Effects of fiber length and orientation on elasticity of fiber-reinforced plywood. *J Wood Sci.* 1998;44:343–7.
2. Bachmann J, et al. Outlook on ecologically improved composites for aviation interior and secondary structures. *CEAS Aeronaut J.* 2018;9:533–43.
3. Gowda TY, et al. Polymer matrix-natural fiber composites: an overview. *Cogent Eng.* 2018;5:1446667.
4. Jakob M, Stemmer G, Czabany I, Müller U, Gindl-Altmutter W. Preparation of high strength plywood from partially delignified densified wood. *Polymers.* 2020;12:1796.
5. Böhm M, Brejcha V, Jerman M, Černý R. Bending characteristics of fibre-reinforced composite with plywood balsa core. In: AIP conference proceedings. 2019;2186. <https://pubs.aip.org/aip/acp/article/2186/1/070006/667283/Bending-characteristics-of-fiber-reinforced>.
6. Sankar A, Sajan S. Manufacturing of high strength plywood composites reinforced with copper fibers. *Mater Today Proc.* 2021;47:5255–9.
7. Yang G, Park M, Park S. Recent progress of fabrication and characterization of fibres-reinforced composites: a review. *Compos Commun.* 2019;14:34–42.
8. Held C, Meier-Landsberg E, Alonso V, Nacke J. Global forest sector outlook 2050: assessing future demand and sources of timber for a sustainable economy—background paper for the state of the world's forests 2022. In: *FAO Forestry Working Paper.* 2022;31:9.
9. Auriga R, et al. Performance properties of plywood composites reinforced with carbon fibres. *Compos Struct.* 2020;248: 112533.
10. Núñez-Decap M, et al. Use of carbon and basalt fibres with adhesives to improve physical and mechanical properties of plywood. *Appl Sci.* 2022;12:5114.
11. Guan M, Liu Y, Zhang Z, Huang Z. Evaluation of bending performance of carbon fiber-reinforced eucalyptus/poplar composite plywood by digital image correlation and fea analysis. *J Mater Sci.* 2020;55:8388–402.
12. Bal B, Bektaş İ, Mengeloğlu F, Karakuş K, Demir H. Some technological properties of poplar plywood panels reinforced with glass fibre fabric. *Constr Build Mater.* 2015;101:952–7.
13. Li Q, et al. Analysis of bonding mechanism of glass fiber-reinforced bamboo plywood. *BioResources.* 2020;15:529–43.
14. Liu Y, Guan M. Selected physical, mechanical, and insulation properties of carbon fiber fabric-reinforced composite plywood for carriage floors. *Eur J Wood Wood Prod.* 2019;77:995–1007.
15. Liu Y, Guan M, Chen X, Yuan Z, Zhou M. Flexural properties evaluation of carbon-fiberfabric reinforced poplar/eucalyptus composite Plywood formwork. *Compos Struct.* 2019;224: 111073.
16. Lohmus R, et al. The effect of prestressing and temperature on tensile strength of basalt fiber-reinforced plywood. *Materials.* 2021;14:4701.
17. Vijayan R, Krishnamoorthy A. Review on natural fiber reinforced composites. *Mater Today Proc.* 2019;16:897–906.
18. Native bast fibres for buses, boards and automotive equipment. <https://nova-institute.eu/news/pr/?id=358>.
19. Lau K-T, Hung P-Y, Zhu M-H, Hui D. Properties of natural fibre composites for structural engineering applications. *Compos B Eng.* 2018;136:222–33.
20. Saal K, et al. Fiber-reinforced plywood: increased performance with less raw material. *Materials.* 2024;17:3218.
21. Moezzi-pour B, Ahmadi M, Mezzi-pour A. Physical and mechanical properties of reinforced ply wood with natural fibers. *J Indian Acad Wood Sci.* 2017;14:70–3.
22. Zhu S, et al. Recent advances on bast fiber composites: engineering innovations, applications and perspectives. *Compos B Eng.* 2024;284: 111738.
23. Baley C, Bourmaud A, Davies P. Eighty years of composites reinforced by flax fibres: a historical review. *Compos A.* 2021;144: 106333.
24. Jorda J, Kain G, Barbu M-C, Haupt M, Krišt'ák L. Investigation of 3d-moldability of flax fiber reinforced beech plywood. *Polymers.* 2020;12:2852.
25. Jorda J, Kain G, Barbu M, Petutschnigg A, Král P. Influence OD adhesive systems on the mechanical and physical properties of flax fiber Reinforced beech plywood. *Polymers.* 2021;13:3086.
26. Karri R, Lappalainen R, Tomppo L, Yadav R. Bond quality of poplar plywood reinforced with hemp fibers and lignin-phenolic adhesives. *Compos Part C Open Access.* 2022;9: 100299.
27. Prefere Resins Germany GmbH. Prefere 14w451 construction resin. Technical Data Sheet, Prefere Phenolics, Erkner, Deutschland (2019).
28. Prefere exph9500 construction resin. Technical Data Sheet, Prefere Phenolics, Erkner, Deutschland (2015).
29. Bcomp Ltd. V0 amplitex art no. 5040. Preliminary Technical Data Sheet, Bcomp, Fribourg, Schweiz (2017).
30. 1993-08: Wood-based panels; determination of density; German version EN 323:1993. Standard DIN EN 323, DIN Deutsches Institut für Normung e.V., Berlin, Deutschland (1993).
31. 1993-08: Wood-based panels; determination of modulus of elasticity in bending and of bending strength; German version EN 310:1993. Standard DIN EN 310, DIN Deutsches Institut für Normung e.V., Berlin, Deutschland (1993).
32. 1981-12: Testing of wood; impact bending test; determination of impact bending strength. Standard DIN EN 52189-1, DIN Deutsches Institut für Normung e.V., Berlin, Deutschland (1981).
33. Hao J, Wu X, Oporta G, Liu W, Wang J. Structural analysis and strength-to-weight optimization of wood-based sandwich composite with honeycomb core under three-point flexural test. *Eur J Wood Wood Products.* 2020;78:1195–207.
34. 2002-08: Wood-based panels; surface soundness - test method; German version EN 311:2002. Standard DIN EN 311, DIN Deutsches Institut für Normung e.V., Berlin, Deutschland (2002).
35. 1993-08: Particleboards and fibreboards; determination of swelling in thickness after immersion in water; German version EN 317:1993. Standard DIN EN 317, DIN Deutsches Institut für Normung e.V., Berlin, Deutschland (1993).

36. Niemz P, Sonderegger W, Keplinger T, Jiang J, Lu J. Physical properties of wood and wood-based materials. In: Niemz P, Teichinger A, Sandberg D, editors. *Springer Handbook of Wood Science and Technology*. 1st ed. Berlin: Springer; 2023. p. 281–353.
37. Gumowska A, et al. Production of layered wood composites with a time-saving layer-by-layer addition. *BioResources*. 2018;13:8089–99.
38. Jorda J, Kain G, Barbu M-C, Köll B, Petutschnigg A. Mechanical properties of cellulose and flax fiber unidirectional reinforced plywood. *Polymers*. 2022;14:843.
39. Goutianos S, Pejts T, Nyström B, Skrifvars M. Development of flax fibre based textile reinforcements for composite applications. *Appl Compos Mater*. 2006;13:199–215.
40. Textile Reinforcements Based on Aligned Flax Fibres for Structural Composites. https://www.researchgate.net/publication/237533775_Textile_Reinforcements_Based_on_Aligned_Flux_Fibres_for_Structural_Composites.
41. Borri A, Corradi M, Speranzini E. Reinforcement of wood with natural fibers. *Compos Part B*. 2013;53:1–8.
42. Salman S. Effects of jute fibre content on the mechanical and dynamic mechanical properties of the composites in structural applications. *Defence Technol*. 2020;16:1098–105.
43. Elfaleh I, et al. A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials. *Results Eng*. 2023;19: 101271.
44. Qaiss A, Bouhfid R, Essabir H. Natural fibers reinforced polymeric matrix: thermal, mechanical and interfacial properties. In: Hakeem K, Jawaid M, Rashid U, editors. *Biomass and bioenergy*. 1st ed. Berlin: Springer; 2014. p. 225–45.
45. Mohammed M, et al. Surface treatment to improve water repellence and compatibility of natural fiber with polymer matrix: recent advancement. *Polym Test*. 2022;115: 107707.
46. Neto J, Queiroz H, Aguiar R, Lima R, Cavalcanti D, Banea DM. A review of recent advances in hybrid natural fiber reinforced polymer composites. *J Renew Mater*. 2021;10:561–89.
47. Singh M, Tewari R, Zafar S, Rangappa MS, Siengchin S. A comprehensive review of various factors for application feasibility of natural fiber-reinforced polymer composites. *Results Mater*. 2023;17: 100355.
48. Mohammed M, Rasidi M, et al. Interfacial bonding mechanisms of natural Fibre-matrix composites: an overview. *BioResources*. 2022;17:7031–90.
49. Taib MNAM, Julkapli NM. Polymer matrix composites: moisture effects and dimensional stability. In: Jawaid M, Thariq M, Saba N, editors. *Mechanical and physical testing of biocomposites, fibre-reinforced composites and hybrid composites*. Cambridge: Woodhead Publishing; 2019. p. 61–79.
50. Dhakal HN, Zhang Z. Polymer matrix composites: moisture effects and dimensional stability. In: Nicolais L, Borzacchiello A, editors. *Wiley encyclopedia of composites*. 2nd ed. New York: Wiley; 2012.
51. Cai M, et al. Durable mechanical properties of unidirectional flax fiber/phenolic composites under hydrothermal aging. *Compos Sci Technol*. 2022;220: 109264.
52. Klein R. (ed.). Durable and resource-saving composite structural components based on newly pre-treated and processed bast fibers (2024). https://durobast.de/wp-content/uploads/2024/06/08_KleinRoland_Fraunhofer_LBF_CFC24.pdf.
53. Bachmann J, Hidalgo C, Bricout S. Environmental analysis of innovative sustainable composites with potential use in aviation sector—a life cycle assessment review. *Sci China Technol Sci*. 2017;60:1301–17.
54. Akin D. Flax—structure, chemistry retting and processing. In: Müssig J, editor. *Industrial applications of natural fibers structure, properties and technical applications*. 1st ed. New York: Wiley; 2010. p. 89–108.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.